# **FLEXIBLE ARTICULATE SURGICAL TOOL**

**FIELD**

This disclosure relates to a flexible articulate surgical tool that provides the needed stiffness in order to be able to manipulate tissue and bear loads in anatomically confined spaces.

**BACKGROUND**

Current instruments used in minimally invasive neurosurgery (known as neuroendoscopy) are straight and rigid or slender and flexible with minimal control over the tool tip. As such, the range of motion and variety of tasks that can be performed using these instruments is limited to simple straight-line approaches, such as biopsy or the removal of small tumors within a direct line-of-sight from the surgeon's entry point. For more complex procedures which require significant freedom over the location of the tool’s tip, the only existing options involve more invasive open surgeries and large craniotomies.

Neurosurgeons have attempted more complicated maneuvers using standard neuroendoscopic equipment with the goal of expanding the scope of neuroendoscopy to other procedures currently performed using more invasive microsurgery. However, in many cases, the limited reach and range-of-motion of standard neuroendoscopy equipment limits its application. From these attempts, there is a well-defined need and published call for new instruments that function more similarly to wrist-like laparoscopic tools. The major limitation to addressing this problem is the scale of the body cavities and anatomy within the head and neck. These spaces in which surgeons must operate are very small and delicate compared to the chest, abdomen and pelvis. New instruments must be compact enough to fit inside these body cavities without dominating the space and blocking the view of the camera. Further, these miniature instruments must be strong enough to manipulate tissue without bending or deforming.

One class of existing technology that attempts to address the need for working in small volumes is notched tube compliant mechanisms. An example of such a design is shown in **Figure 1**. **Figure 2** shows the actuation of this mechanism. Here, a tube **10** made from a super-elastic material (such as nitinol) has rectangular shaped cuts or notches **12** cut into it. The remaining material at these notches **12** act like flexible hinges that can be bent without permanent deformation by applying a downward force on the inside of the tube **10** (using a cable, rod or other applied pressure).

When designing these types of joints for use in particularly small volumes as shown in **Figure 1,** where the geometric size of the instrument **205** is on a similar order of magnitude as the surgical workspace **200**, ensuring that the joint is compact is of paramount performance. Typically, this is approached by designing the mechanism’s bent configuration **201** so that it occupies as little space **202** as possible. Cutting the tube asymmetrically (from one side inward as shown in **Figure 1** and **Figure 2**) is often preferred because the tube compresses upon itself as it bends. Increasing the depth of cut **206** has the largest impact on how sharp a bending radius of curvature **203** the joint can attain in order to stay within the elastic strain region of the material. The sharpest achievable bends occur when the radius of bending of the joint **203** approaches the same value as the outer radius of the tube. To achieve this range of sharp bending, the cut depth becomes very deep, often exceeding 80% of the diameter of the tube for asymmetric notches. In these situations, the joint has excellent range-of-motion and compactness, but the overall “stiffness” of the joint, or its ability to support loads, is severely diminished. This value of 80% is based upon simulations which have been carried out by the present inventors.

In the case of asymmetric notch tubes, the directional stiffness in the front-back directions is decreased by one or two orders of magnitude compared to an un-notched tube of equivalent size and material. The method which actuates the joint, causing it to bend (cable etc.), can counteract external loads applied from the front of the joint however there is no method to counteract the forces applied from the back of the joint. This limitation hinders the practical use of these asymmetric designs, despite their advantages, since tissue manipulation requires the joint stiffness to be above a certain application-specific threshold in all directions.

There are many surgical applications in the head and neck that could significantly benefit from notched tube joint mechanisms to increase the dexterity of surgical instruments. The present inventors contemplate that one of the main reasons this technology has not been employed for these applications is because with current designs, the stiffness is too low to manipulate tissue and bear loads.

Another approach which aims to improve the compactness of symmetric and asymmetric notched tube joints involves reducing the total number of notches and the width of the spacing between notches [1]. In doing so, designers aim to ensure that the total joint length needed to achieve the desired bending angle is distributed between the fewest number of individual notches possible, resulting in fewer, longer notches. One limitation for this design is the onset of buckling when the ratio of the notch width to notch length becomes too small. Where the notch width is the difference between the tube diameter and the notch cut depth. If individual notches become too long, they exhibit bending behavior that is difficult to predict and undesirable. The present inventors also contemplate that one of the main barriers to constructing truly compact notched-tube compliant joints is the need to limit the relative length of individual notches when their widths become very small, again resulting from deep cuts.

While **Figure 1** shows the tube in which the cuts **12** have been removed just from one side of the tube, (asymmetric), tools have been produced in which the tube has been provided with slots in a symmetrical design as depicted in **Figure 2**. Specifically, **Figure 2** shows published notched tube cutting topologies [2]–[11] with the “basic” asymmetric notch shape of **Figure 1** shown in the left most image.

**SUMMARY**

The present disclosure provides a joint mechanism that is intended for working in small volumes. One application for the use of such a technology is in neurosurgery. Specifically, endoscope guided minimally invasive neurosurgery, referred to as neuroendoscopy. This technology is also relevant in any application where the dimensions of the work volume approach the same order of magnitude as the cross-sectional dimensions of the joint itself.

In an embodiment there is provided a flexible articulate surgical tool, comprising:

a) a handle, an elongate flexible shaft assembly extending distally from the handle, where the elongate flexible shaft assembly includes one or more articulable sections, said elongate flexible shaft assembly having proximal and distal end sections, said proximal end section attached to said handle, said distal end section attached to a tool configured to engage tissue;

b) said elongate flexible shaft assembly including one or more joint sections, each joint section including a generally transverse notch section extending from the outer wall of the tube, said joint section including an elongate notch section extending from said transverse notch section in a direction generally parallel to said longitudinal axis to define a first tube section closest to the proximal end section and a second tube section downstream of said first tube section, said first and second tube sections being separated by an outer strip tube section, said strip tube sectionincluding a flexible joint, an upper end of said first tube section located at a junction of said transverse notch sectionand said elongate notch section forming an inner tube section;

c) said handle being operably connected to said tool for manipulating and operating said tool and for applying external forces from a back to front direction to the one or more joint sections, wherein said elongate notch section has a diameter selected such that when the surgical tool is operated by a clinician and applies external forces from a back direction to the one or more joint sections the outer strip tube section undergoes bending and substantially immediately comes in contact with said inner tube section such that the one or more joint sections mechanically interferes with itself and self-reinforces thereby causing an increased stiffness of the flexible shaft assembly;

d) said handle being operably connected to said tool by a flexible cable for manipulating and operating said tool by applying internal actuation forces from said flexible cable to the joint segment such that one or more joint sections, comprised of elongate notch sections bend and the outer strip tube section undergoes bending and substantially immediately comes in contact with said inner tube section such that the one or more joint sections mechanically interferes with itself and self-reinforces thereby causing the strip tube section toundertake a predetermined and designed bending shape and thereby prevent buckling of the flexible shaft assembly.

The mechanical interference not only increases stiffness throughout the articulation of the joint's range-of-motion but it also serves the dual purpose of controlling the bent "shape" of the flexible portion of the joint.

A further understanding of the functional and advantageous aspects of the disclosure can be realized by reference to the following detailed description and drawings.

**BRIEF DESCRIPTION OF THE DRAWINGS**

Embodiments will now be described, by way of example only, with reference to the drawings, in which:

**Figure 1** shows a constrained workspace **200** with a notched tube joint **205**.

**Figure 2** is a view of a Prior Art surgical tool design with an asymmetrically notched tube compliant joint. The left image A. indicates the joint design initially bending from a small amount of tension applied to the actuation cable. The middle image B. shows the design further bending from more applied cable tension, and the right image C. shows the joint fully articulated.

**Figure 3** shows published notched tube cutting topologies as disclosed in references [**2**] to [**11**] with the “basic” asymmetric notch shape of **Figure 1** and **Figure 2** shown in the left most image. Here, DOF is an acronym for degrees-of-freedom.

**Figure 4** shows the mechanical closure of a square “basic” prior art notch [left] compared to a different square notch that cannot mechanically close because it would plastically deform before the edges contact. This figure illustrates the need for modifying the shape of the notch to ensure the opposing edges of the notch come into contact before the elastic strain limit of the notch material is reached. If the “basic” notch shown in the [right] image were to be further articulated to that its edges came into contact, it would become permanently deformed. Some examples of how the shapes of notches have been modified to address this issue are shown in **Figure 3.**

**Figure 5** shows a comparison of surgical tool profiles with the left panel being a prior art design, the middle panel being an embodiment showing the basic concept for a flexible tool and the right panel showing a variation of the center panel design.

**Figure 6** shows a pivoting notched tube constructed in accordance with the present disclosure showing pivoting action in mechanical interference combined with mechanical closure.

**Figure 7** shows two stiffness plots of joint tip displacement versus joint tip load where the joint tip load is based on the loading configuration as shown in **Figure 6**. Here, the series indicated **81** corresponds to the joint design **80** and the series indicated **71** corresponds to the joint **70**.

**Figure 8** shows a plot of joint bending angle as a function of the cable tension applied to articulate the tip of the joint. The plot has one series corresponding to the “basic” prior art notch design (shown in the upper left of the **Figure 8**) and another series corresponding to the present notch design (shown in the bottom right of the **Figure 8**). Both joints are capable of articulating through the same range-of-motion, and therefore, the modified notch with mechanical reinforcement and mechanical closure does not limit the maximum bending angle of the joint.

**Figure 9A** depicts a joint comprised of three serially arranged modified notches with mechanical reinforcement and mechanical closure that articulates in one degree-of-freedom in a single direction.

**Figure 9B** depicts a joint consisting of nine modified notches with mechanical reinforcement and mechanical closure that are helically arranged, along the long axis of the tube, and that articulate in two degrees-of-freedom in multiple directions. **Figures 9A** and **9B** indicate some ways in which the notches can be combined to produce more complex joints.

**Figure 10A, 10B and 10C** show three (3) alternative exemplary flexible articulate surgical tool notch topologies.

**Figure 11** shows a notched tube segment **140** with a tapered rectangular notch topology similar to those shown in **Figure 3**.

**Figure 12** show an alternative exemplary flexible articulate surgical tool notch topology combined with a locking reinforcement design.

**Figure 13** show an alternative exemplary flexible articulate surgical tool notch topology for a symmetric design**.**

**Figure 14** shows an exemplary flexible articulate surgical tool **100** incorporating the notched tubes disclosed herein.

**Figure 15** shows an alternative ring handle configuration similar to the handle design shown in **Figure 14**.

**Figure 16** shows an alternative handle design **135** where a thumb wheel **131,** which rotates around a joint **132,** is connected to a proximal end of flexible cable.

**Figure 17** depicts the notched tube designs on a robotic device. At the base of the device **210**, proximal to the tube shaft **22**, a series of mechanisms are driven to control the bending of the notched tube section **112**. Typically, the robotic devices control bending of the notched tube joint in multiple directions.

**DETAILED DESCRIPTION**

Various embodiments and aspects of the disclosure will be described with reference to details discussed below. The following description and drawings are illustrative of the disclosure and are not to be construed as limiting the disclosure. The drawings are not necessarily to scale. Numerous specific details are described to provide a thorough understanding of various embodiments of the present disclosure. However, in certain instances, well-known or conventional details are not described in order to provide a concise discussion of embodiments of the present disclosure.

As used herein, the terms, “comprises” and “comprising” are to be construed as being inclusive and open ended, and not exclusive. Specifically, when used in this specification including claims, the terms, “comprises” and “comprising” and variations thereof mean the specified features, steps or components are included. These terms are not to be interpreted to exclude the presence of other features, steps or components.

As used herein, the term “exemplary” means “serving as an example, instance, or illustration,” and should not be construed as preferred or advantageous over other configurations disclosed herein.

As used herein, the terms “about” and “approximately”, when used in conjunction with ranges of dimensions of particles, compositions of mixtures or other physical properties or characteristics, are meant to cover slight variations that may exist in the upper and lower limits of the ranges of dimensions so as to not exclude embodiments where on average most of the dimensions are satisfied but where statistically dimensions may exist outside this region. It is not the intention to exclude embodiments such as these from the present disclosure. The present disclosure addresses the above-noted loss of “stiffness” throughout the joint’s range-of-motion and provides a joint with the ability to support higher loads as its articulates, wherein its range of motion remains comparable to an equivalently sized rectangular notch.

The basic concept disclosed herein relates to shaping the notch such that the flexible portion of the joint that makes up the “hinge” comes into physical contact at one or multiple points with a more rigid section of the joint. In this manner, the joint “mechanically interferes” with itself and self-reinforces the tube as it articulates through its range-of-motion. Expressed in other terms, one may consider the prior art “basic” joint design shown in **Figure 2** as a simply supported beam that is rigidly fixed at its base and has a bending moment applied to its tip by means of a cable, wire, rod, or pressure (pneumatic or hydraulic). The topology disclosed herein breaks from this convention in that the presently disclosed designs may be thought of as providing 3-point or multi-point bending configurations. In these embodiments, the flexible portion of the joint may slide or pivot around support points that are connected to more rigid portions of the joint. Put another way, multiple rigid regions of the joint are in contact with the flexible portion of the joint “in parallel”, or “in series” or a combination thereof, to reinforce while at the same time not significantly limiting the range-of-motion of the joint as it bends.

**Figure 6** depicts the motion of a single notch in a portion of a flexible articulate surgical tool which shows one joint sub-section **20** of the tube **22** which includes a transverse notch section **24** extending from the outer wall of the tube **22** which connects to generally parallel notch section **26** which has the shape of an elongate channel section which is substantially parallel to the longitudinal axis of the tube portion **22**. It will be appreciated that the tube **22** may include more joint sections **20**. The presence of the transverse notch section **24** extending a significant way through the tube gives to tube sections **30** and **32** connected by an outer strip, or compliant joint tube section **34** such that upper tube section **32** (which leads to the end of the tube that connects to the surgical tool tip, not shown) can move with respect to the lower tube section **30**. By cutting the notch sections **24** and **26** as shown in **Figure 6**, the tube section **32** can bend in the same way that the “basic” prior art shaped notch of **Figure 2** can bend but it has increased stiffness when external forces from the back to front direction are applied to the upper section **32** as seen in **Figure 6**. This increased stiffness occurs because the compliant joint tube section **34** of tube section **22,** which undergoes bending almost immediately, comes into contact with the inner section **38** of the tube **22**. In this manner, the joint “mechanically interferes” with itself and self-reinforces. This geometry does not limit the normal articulation of the joint section **20**. Although the shape that the bent joint section **34** takes on during bending could be different than the shape of the bent joint section in joint **50**.

It will be understood that the mechanical interference could also be created by configuring the joint to interfere with another, separate rigid component within, surrounding or attached to the flexible portion of the joint. **Figure 11** depicts a compliant joint notched tube segment **140** connecting a proximal tube segment **144** with a distal tube segment **143**. The notched tube topology includes a tapered rectangular notch shape **142** similar to those shown in **Figure 3** to create mechanical closure to limit the range-of-motion of the joint before the onset of plastic deformation of the material. A separate rigid tube component **141** has been assembled concentrically within the notched tube **140.** It will be appreciated that the notched tube **140** will interfere with **141** when a tensile force is applied to the tip of the distal segment **143** by means of the actuation cable **145.** The flexible actuation cable **145** consists of a distal end rigidly fixed to the tube **143** and a proximal end that is free. When the notched tube **140** comes into contact with **141** during its range-of-motion, the internal tube **141** will mechanically reinforce the joint **140** and affect the shape that the compliant joint **140** will undertake while bending, but **141** is not made from the same material or is a part of **140.** **Figure 11** demonstrates the same principle of action of the notch topology design of **60** but this action is created from two or more separate components.

**Figure 5** shows a progression of surgical tool compliant joint notch profiles with the left panel being the prior art design of a notched joint section **50**,the same profile as shown in **Figure 2**, the middle panel being an embodiment of a notched joint section **52** as disclosed herein showing the basic concept for a flexible tool and the right panel showing a joint section **60** which is a variation of the center panel design shown at **52** that has been refined to reduce strain concentrations. All three notch configurations **50, 52** and **60** consist of a proximal tube segment **30** connected to a compliant joint tube segment **34** which is connected to a distal tube segment **32**. The notch segment **35**, representing space where tube material was removed to create the compliant joint tube segment **34** has tapered edges **33** in the middle and right panels. These tapered edges are constructed such that the distance **40** and **24** are just far enough that the top and bottom edges of the notch come into contact before the onset of plastic deformation in the compliant joint tube segment **34** or adjacent tube segments **30** or **32**. This design feature is referred to as Mechanical Closure and has been demonstrated in the prior art depicted in **Figure 3**. The elongated notch segment **26** is a thin cut section separating the compliant notch tube segment **34** from the rigid tube reinforcement section **38** attached to the proximal tube segment **30.** The elongated notch segment **26** is designed such that the compliant joint tube segment **34** is free to bend and rotate when an actuation force is applied to internal top left side of the tube segment **32** as shown in **Figure 6** where the actuation cable **25** is used to apply the bending force. The elongated notch segment **26** is further designed such that the compliant joint tube segment **34** is inhibited from moving laterally if a force is applied perpendicular to **34** in the back to front direction. The notched structure in joint section **52** includes a circular cut-out where the upper corner of transverse notch section **35** terminates at the upper right corner of the notch and this provides for reduced strain concentration at this corner during bending of the upper section **32** with respect to the lower section **30**. For notch joint **60**, this feature is included into the transition from the generally transverse notch segment **35** to the elongated notch segment **26**.

An important feature of the topology of the notch joints disclosed herein is the inclusion of a segment of the notch that is intended to create “mechanical closure.” The main concept of mechanical closure is selecting cutting parameters while producing the notches that ensure the joint’s edges come into contact during articulation, to limit its full range of motion, before the material’s strain limit is reached. This feature improves the life-time of the joint because it prevents “over-bending” and permanently deforming the notch. It also allows the notch to fully close when it is in its maximum bending position which helps to make the joint “stiffer” when it is at its full range-of-motion. This feature is distinct from mechanical interference because mechanical interference increases the stiffness of the joint throughout its entire range-of-motion, not just at the end. Mechanical closure is also important because it addresses uneven loading of many notches placed in series. Consider the prior art notch joint of **Figure 2**, where all three square notches are the same size and shape. Here, it can be observed that the notch closest to the bottom of the image, where the cable tension is being applied, closes more than the notch closest to the joint’s tip. Mechanical closure ensures that once the first notch closes, the subsequent notches can fully close as more cable tension is applied, without risking over bending the first notch.

**Figure 4** depicts two square prior art notch designs which further describe the concept and importance of “mechanical closure”. The prior notch shown on the left side of the figure can completely close compared to the differently sized and shaped square notch on the right side of **Figure 4** that cannot mechanically close because it would plastically deform before the edges contact. There are a subset of square notch geometry designs where this is possible, depending on the elastic strain limit of the material the joint is made from. In most cases, square notches cannot close on themselves without permanently deforming. To address this issue, the top and bottom edges of the notches are typically either tapered or “T” shaped, as shown in some of the designs in **Figure 3**.

**Figures 10A** to **10C** show some alternative exemplary flexible articulate surgical tool notch topologies. **Figure 10A** shows a notch topology **150** which includes a circular cut-out **152** where the upper corner of transverse notch section **151** terminates at the upper right corner of the notch and this provides for reduced strain concentration at this corner during bending of the upper section **158** with respect to the lower section **159**. The notch section **151** is tapered such that it will contact the lower portion of the tube just before the elastic strain limit of the tube material and geometry occurs. The flexible bending tube segment **153** is a compliant joint that may come into contact and slide or pivot about more rigid sections of the tube lower section **159**. These contact points are shown at **156** and **155** for example. These contact points will increase the blocking forces that the joint can support in a back to front direction. The elongated notch **157** is connected to the generally transvers notch **154** and follows an elongated curved path to reduce strain concentrations and to provide additional mobility to the compliant joint to provide a greater range of motion in bending. The elongated notch **157** is cut in a spiral or overlapping curved path pattern such that there is little resistance to rotational motion caused by the bending of the compliant joint section **153** but the opposing walls of the elongated notch **157** will come into contact and self-reinforce if loads are applied in the front or back directions. Notch topology **150** is different than notch topology **60** in that there are multiple contact points to self-reinforce and control the shape of the complaint bending segment **153**.

**Figure 10B** also shows notch topology **160** which includes two compliant bending segments **163** and **166** that are arranged in parallel in the same notch. Compliant bending segment **163** will bend if an actuation load is applied along the actuation cable **164** or if an external load is applied in the back to front direction. When the compliant bending segment **163** displaces in a back to front direction, it will mechanically interfere with the second compliant bending segment **166** which will reinforce the joint and increase its stiffness in this loading direction. Notch topology **160** differs from **60** and **150** in that it includes multiple generally transverse sub-notch sections **165** that are sizes such that they will all be in contact with each other just before the elastic strain limit of the tube material and geometry occurs.

**Figure 10C** additionally shows notch topology **170** which includes a symmetric profile with mechanical interference pins **175** that act to reinforce the shape of the complaint bending segment **173** and to guide the shape that **173** undertakes while articulating. The spacing cavity **176** allows for off-center flexing of the compliant bending segment **176** so that its range of motion is not inhibited by undesired mechanical interference. The corners **177** and **172** are curved to reduce strain concentrations.

**Figure 12A** to **12C** shows another exemplary flexible articulate surgical tool notch topology. **Figure 12A** shows a notch topology **180** which includes an upper section **185** connected to a lower section **186** by means of a flexible bending tube segment **184** that acts as a compliant joint. This compliant joint articulates by means of a flexible cable **181** that applies a bending and twisting force to the upper tube segment **185**. The notch section **187** is sized such that the bottom edge of the upper tube segment **185** will contact the lower portion of the tube **186** just before the elastic strain limit of the tube material and geometry occurs as the flexible cable **181** is articulated. The flexible bending tube segment **184** is a compliant joint that may come into contact and slide or pivot about more rigid sections of the tube lower section **186** for example when the elongated notch section **188** closes upon itself during bending. The flexible bending tube segment **184** is a compliant joint that may come into contact and slide or pivot about more rigid sections of the tube upper section **185** for example when the elongated notch section **183** closes upon itself during bending. These contact points will increase the blocking forces that the joint can support in a back to front direction. The generally transverse notch **187** is connected to the generally transverse notch **189** through a reinforcement contact locking point **182**. When an external load is applied to the tube as shown in **Figure 12C**, the upper tube segment **185** is in contact with the lower tube segment **186** through the point **182** such that the flexible bending tube segment **184** is reinforced and prevented from bending. Conversely, when a bending force is applied to the upper tube segment **185** by means of a flexible cable **181,** the cable provides a downward and rotational force that unlocks the joint such that **185** and **186** no longer connect via **182** and the flexible bending tube segment **184** is free to bend. While bending, the elongated notch **183** and **188** come into contact and self-reinforce to increase the stiffness of the joint through its range-of-motion. Notch topology **180** is different than notch topology **60** in that it combines mechanical reinforcement with mechanical closure and also with a locking mechanism to further increase the joints blocking forces in a defined configuration.

**Figure 13** shows another exemplary flexible articulate surgical tool notch topology **190** which includes an upper section **193** connected to a lower section **192** by means of a flexible bending tube segment **194** that acts as a symmetric compliant joint. This compliant joint articulates by means of two flexible cables that apply bending forces on the upper tube segment **193**. The generally transverse notch section **191** is sized such that the bottom edge of the upper tube segment **193** will contact the lower portion of the tube **192** just before the elastic strain limit of the tube material and geometry occurs as the flexible cable is articulated. The flexible bending tube segment **194** is a compliant joint that may come into contact and slide or pivot about more rigid sections of the tube lower section **192** for example when the elongated notch section **195** closes upon itself during bending. The top edge **196** of the bottom tube segment **192** has a curved profile to guide the bending shape of the flexible bending tube segment **194** as it articulates through its full range-of-motion.

**Figure 7** shows that the stiffness of a joint topology with mechanical interference added in is more stiff than an equivalently sized joint without mechanical interference. The more horizontal the slope of the line, the stiffer the design. The two tools **70** and **80** being compared are cut from the same tube, and the maximum height and cut depth of the notches in both designs are the same. In the plot, the upper series **71** shows a square design’s stiffness, corresponding to joint **70**, compared to the lower series **81** showing the stiffness for a design of the present tool **80**. These results clearly show that the notched joints of the present disclosure, shown in the lower tube **80** exhibit more desirable stiffness than the prior art notched joints **70**.

**Figure 8** depicts a plot of the cable tension (used to articulate the joints) and the bending angle of the tip of the joints. Here we see that both joints are capable of reversibly bending (many 1000’s of times) to approximately the same angle. This information is interpreted by observing that the top-right most point in each of the series is approximately at the same location in the Y-axis direction. The only difference is that the cable tension required for our joint is larger. In many cases this trade-off is not significant from design point of view because the cable or other mechanism that provides the bending force to the tip can be selected to support these higher loads, especially if the benefit is increased joint stiffness.

**Figure 9A** shows a side view of a part of a notched tube section with mechanical reinforcement and mechanical closure forming part of a flexible articulate surgical tool with several notched joints all aligned on one side of the tube to give an asymmetric arrangement of notches thereby giving a single bending direction to the tool. This configuration shows how the notches can be arranged in series to create a single degree-of-freedom joint.

**Figure 9B** depicts a joint forming part of a flexible articulate surgical tool consisting of nine modified notches with mechanical reinforcement and mechanical closure that are helically arranged, along the long axis of the tube, and that articulate in two degrees-of-freedom in multiple directions. These figures indicate some ways in which the notches can be combined to produce more complex joints.

**Figure 14** shows an exemplary flexible articulate surgical tool **100** incorporating the notched tubes disclosed herein. This instrument configuration demonstrates one embodiment that may be used for neuroendoscopy applications. In this configuration, the tool is intended to be operated using one hand while being passed through the working channel of any commercially available or custom neuroendoscope.

The flexible surgical tool **100** includes a handle **102** configured in this case to be a ring handle design to which a proximal end of flexible wire **104** is connected [12]. This ring handle **102** is constructed in this case from aluminum but could be constructed from any substitute metal (stainless steel, titanium, etc.) or plastic or other material. A distal end of the flexible wire **104** is connected to the surgical tool tip **110**, also referred to as end-effector, which for example may be biopsy forceps. This flexible wire is routed within the instrument shaft **22** that is constructed from a flexible tube. In this case, the flexible tube **22** is constructed from nickel-titanium alloy (nitinol) but could be constructed from other substitute metals (stainless steel, titanium, etc.) or plastics. Tube section **112** located just before the tool tip **110¸** and attached distally to the instrument shaft **22**,contains one or more joint sections **20**. In this case, the tube section **122** is constructed from nickel-titanium alloy (nitinol) but could be constructed from any material with super-elastic properties, including polymers. The instrument shaft **22** is connected to the instrument handle **103** by a collet mechanism **107**. The ring handle **102** is operably connected to the biopsy forceps tool tip **110** via the flexible wires **104** within the shaft **22** such that actuation of the ring handle, pivoting it about the joint **106**, results in opening and closing of the end-effector **110**.

A proximal end of flexible cable **109** is fixed to a segment of the instrument handle **103** via a clamping mechanism **103** that is fixed using set screws in this case. This connection between **109 a**nd **103** could be achieved by other means such as laser welding, or a different variation of fixation or mechanical clamping. A distal end of the flexible cable **109** is fixed to the distal end of notched joint segment **112**, proximal to the end-effector **110**. The flexible cable **109** routes within the flexible tube **22.** To actuate the notched joint section **112**, rotation about the joint **105** will apply tension to the flexible cable **109** and cause the joints **112** to close.

**Figure 14** shows the surgical tool employing biopsy forceps for removing tissue, however it will be appreciated that the surgical tool may be any tool requiring a flexible jointed section for providing the same type of stiffness as tool **100** is provided with. For example, the end-effector could be replaced with biopsy forceps, ventriculostomy forceps, grasping forceps, angled or curved scissors, bipolar forceps, guillotine knife, scalpel, bipolar coagulation electrode, burr or drill bits, ultrasonic aspirator or scalpel or laser ablation probes. The tip could also be fitted with a mechanism to deploy drugs/medications, stents, or probes or electrodes. It will be appreciated that the surgical tool could be used to position diagnostic devices for laser scanning or ultrasound. Some alternative embodiments could include the use of this technology in teleoperated surgical robotic manipulators, for example, on the tip or embedded within the body of a concentric tube robotic platform. The technology could also be attached to the tip or body of an endovascular catheter for the purposes of targeted drug delivery, stent deployment or laser ablation therapy.

**Figure 15** shows an alternative exemplary flexible articulate surgical tool **122** incorporating the notched tubes disclosed herein. This design is configured similar to **100** in **Figure 14**.In the case of **122**, the ring handle **121** is attached to the proximal end of a flexible cable **125** whose distal end is attached to the notched joint segment **112**. The ring handle **121** is used to articulate the notch joint segment as the ring handle is pivoted about the joint **123**. Through this motion, tension is applied to the cable **125** causing the notch joint **112** to bend. The trigger mechanism **120** is used to actuate the end-effector **124**, which in this case is shown to be scissors. The trigger **120** is connected to a lever mechanism **126** which is connected to a proximal end of flexible wires within the shaft **22.** The distal end of flexible wires connect to the end-effector scissors **124** such that articulating the trigger mechanism **120**, also articulates **126** which applies tension and compression to the flexible wires to open close and open the scissors **124.**

**Figure 16** shows an alternative handle design **135** where a thumb wheel **131**, which rotates around a joint **132**, is connected to a proximal end of flexible cable. The distal end of the flexible cable is connected to the notched joint **112**, such that when the thumb wheel **131** is spun, tension is applied to the flexible cable and the joint **112** is actuated and bends. A spring-loaded trigger mechanism **133** is configured such that is pivots about the joint **134**. The distal tip of the trigger mechanism **136** is connected to a proximal end of flexible wire. The distal end of flexible wire is connected to an end-effector **110** such that when the trigger **133** is articulated, the end-effector opens and closes. A finger wheel **130** is rigidly connected to the flexible shaft **22** and the finger wheel **130** is connected to the instrument **135** but free to rotate about the axis collinear with the shaft **22.** The finger wheel **130** has a dual purpose in acting as a collet to clamp the flexible tube **22** in-place, similar to **107**, and also to act to control an additional degree-of-freedom**.** It will be appreciated that the finger wheel may be spun to rotate the flexible shaft **22** and thereby change the orientation of the end-effector **110**.

**Figure 11** shows a notched tube segment **140** with a tapered rectangular notch topology similar to those shown in **Figure 3**. A separate rigid tube component **141** has been assembled concentrically within the notched tube **140**. It will be appreciated that the notched tube **140** will interfere with **141** during its range-of-motion such that the rigid tube component **141** will mechanically reinforce the joint **140** but is not made from the same material or is a part of tube **140**.

**Figure 1** shows a constrained workspace **200** with a notched tube joint **205**. The size scale of the joint **205** is similar to the size scale of the workspace **200** and therefore the space **202** that the joint **205** occupies would ideally be as small as possible. To achieve this goal, the joint radius **203** and the joint length **204** should be minimized.

The foregoing description of the preferred embodiments of the disclosure has been presented to illustrate the principles of the disclosure and not to limit the disclosure to the particular embodiment illustrated. It is intended that the scope of the disclosure be defined by all of the embodiments encompassed within the following claims and their equivalents.

**THEREFORE WHAT IS CLAIMED IS:**

1. A flexible articulate surgical tool, comprising:

a) a handle, an elongate flexible shaft assembly extending distally from the handle, where the elongate flexible shaft assembly includes one or more articulable sections, said elongate flexible shaft assembly having proximal and distal end sections, said proximal end section attached to said handle, said distal end section attached to a tool configured to engage tissue;

b) said elongate flexible shaft assembly including one or more joint sections, each joint section including a generally transverse notch section extending from the outer wall of the tube, said joint section including an elongate notch section extending from said transverse notch section in a direction generally parallel to said longitudinal axis to define a first tube section closest to the proximal end section and a second tube section downstream of said first tube section, said first and second tube sections being separated by an outer strip tube section, said strip tube sectionincluding a flexible joint, an upper end of said first tube section located at a junction of said transverse notch sectionand said elongate notch section forming an inner tube section;

c) said handle being operably connected to said tool for manipulating and operating said tool and for applying external forces from a back to front direction to the one or more joint sections, wherein said elongate notch section has a diameter selected such that when the surgical tool is operated by a clinician and applies external forces from a back direction to the one or more joint sections the outer strip tube section undergoes bending and substantially immediately comes in contact with said inner tube section such that the one or more joint sections mechanically interferes with itself and self-reinforces thereby causing an increased stiffness of the flexible shaft assembly;

d) said handle being operably connected to said tool by a flexible cable for manipulating and operating said tool by applying internal actuation forces from said flexible cable to the joint segment such that one or more joint sections, comprised of elongate notch sections bend and the outer strip tube section undergoes bending and substantially immediately comes in contact with said inner tube section such that the one or more joint sections mechanically interferes with itself and self-reinforces thereby causing the strip tube section toundertake a predetermined and designed bending shape and thereby prevent buckling of the flexible shaft assembly.

**ABSTRACT**

This disclosure discloses a flexible articulate surgical tool that provides the needed stiffness in order to be able to manipulate tissue and bear loads in anatomically confined spaces. The flexible articulate surgical tool includes a clinician operated handle, a flexible elongate tube extending from the handle to a surgical tool with the flexible elongate tube having one or more joint sections located near the surgical tool. A flexible cable connects the handle to the surgical tool. The joint sections are configured so that when the clinician activates the surgical tool, a mechanical interference is generated in the joint section and this mechanical interference not only increases stiffness throughout the articulation of the joint's range-of-motion but it also serves the dual purpose of controlling the bent "shape" of the flexible portion of the joint.

**UNITED STATES PROVISIONAL PATENT APPLICATION**

**HILL & SCHUMACHER**

# Title: **FLEXIBLE ARTICULATE SURGICAL TOOL**

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