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A FLEXIBLE DISTAL TIP WITH TWO DEGREES OF FREEDOM FOR ENHANCED DEXTERITY IN ENDOSCOPIC ROBOT SURGERY

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Abstract

A flexible distal tip with two degrees of freedom has been developed for endoscopic robot surgery. The flexible tip consists of a superelastic NiTi tube which can be bent from -90º to +90º in 2 directions by means of 4 cables. The improvement over previous devices is the combination of two degrees of freedom with a small diameter of only 5 mm. An additional advantage is the tool channel which enables the use of different instruments with this single device.

Keywords: *Robot surgery, endoscopy, flexible instrument*

I. INTRODUCTION

During minimally invasive surgery (MIS), the surgical instruments are introduced into the body through small incisions as illustrated in figure 1. The major advantages are the reduced trauma and shorter recovery time for the patient. On the other hand, the surgeon looses tactile feedback, direct hand-eye coordination, and also two degrees of freedom (dof) of the instrument. As the instrument can only rotate and slide through the trocar point, the number of dofs is limited to 4.

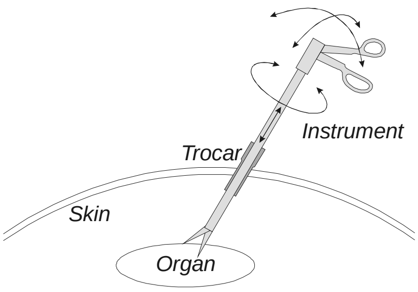


Fig. 1. Minimally invasive surgery. The instrument movement is restricted to 4 degrees of freedom.

Another important problem is the reduced accuracy the surgeon can achieve. In open surgery, the surgeon can rest his hand on the patients body to perform fine operations. In MIS, the surgeon cannot rest his hand or arm while using the instruments. Therefore, wrist, elbow and shoulder movements all add to the positioning error and trembling of the instrument tip.

Most of these problems can be solved by robot surgery using a master-slave configuration. The instruments are mounted on robot manipulators (the slaves) controlled by the surgeon through ‘joysticks’ (the masters). This allows the surgeon to perform the operation in a more ergonomic way and with higher accuracy. By feeding back the forces (measured at the instrument tip) to the masters, the surgeon can feel the interaction between instrument and tissue. Commercial surgical robots are the da Vinci™ Surgical System from Intuitive Surgical® [1] and the Zeus™ Robotic Surgical System from Computermotion [2].

To obtain higher dexterity, one or two additional dofs can be introduced at the instrument tip. Several such instruments have been developed, either with rotating joints at the tip [1,2,3] or with a flexible tip [4,5]. Most of these instruments have a large diameter (about 10 mm) or have only one dof. Specific about the instrument tip presented in this paper is the combination of two dofs with a small diameter (5 mm).

II. INSTRUMENT TIP DESIGN

The instrument tip, of which the design is shown in figure 2, consists of a flexible tube that can be bent by pulling on the cables running along its length. The 4 cables are fixed at the tip and form 2 antagonistic pairs. Each antagonistic pair controls one dof. The inner tube allows insertion of flexible instruments (like the ones used in flexible endoscopes) and separates the instrument from the cables. The fact that different instruments can be used with this single device is a significant advantage over systems where the bending mechanism is integrated in each instrument.

To enhance the bending flexibility of the outer tube, it is cut into a structure consisting of a series of rings connected by thin elastic joints. As the rings are thicker and stiffer than the joints, the torsional and axial stiffness of the flexible tube are relatively high in comparison to the bending stiffness.

Superelastic NiTi was chosen as material because of its high allowable strain, and its high stiffness and strength in comparison to rubber or plastic. A high stiffness minimises the influence of the external forces on the deformation of this flexible tip. This way, only the displacement of the cables determines the geometry of the flexible tip.

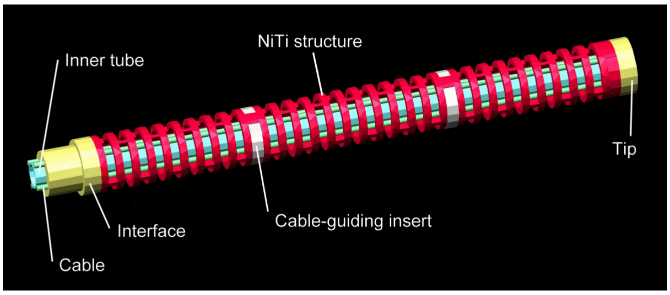
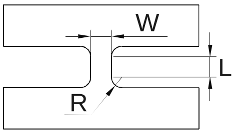


Fig. 2. Design of the flexible instrument tip.

III. FINITE ELEMENT CALCULATIONS

The initial shape of the joints is determined using finite element calculations on MSC Nastran. A non-linear material characteristic is used with an E-modulus of 40 GPa, a plateau stress of 400 MPa and a maximal superelastic strain of 8 %. The non-linear material characteristics and the large deformations require a double iteration loop. Three successive rings with intermediate joints have been modelled, with an outside diameter of 4.7 mm and an inside diameter of 3.9 mm.

The best joint geometry resulting from the finite element analysis is joint 1 as specified in figure 3. According to the calculations, an axial force of 30 N at the perimeter of the ring results in a bending angle of 12.6° and a maximal strain of 7.5 %. Figure 4 shows that the deformation is concentrated in the joints while the deformation of the rings is negligible. No stress concentrations occur at the transition between joint and ring.



Joint	W [mm]	L [mm]	R [mm]
1	0.75	0.5	0.25
2	0.5	0.5	0.25
3	0.3	0.5	0.15

Fig. 3. Joint geometries.

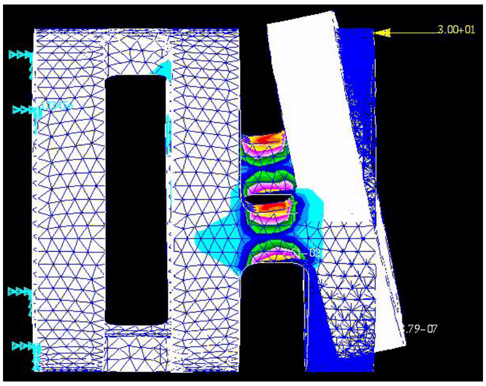


Fig. 4. Von Mises strains in joint geometry 1.

IV. JOINT TESTS AND OPTIMISATION

Tests with joint design 1 have shown fatigue within a few cycles. In order to reduce the strain and thus fatigue, the joint geometry has been changed towards smaller widths W. Three joint geometries, specified in figure 3, and two different materials have been tested.

- Material 1: a NiTi tube from Euroflex, outside diameter 4.7 mm, internal diameter 3.9 mm.
- Material 2: a NiTi rod with an outside diameter of 4.9 mm, in which a hole of 3.5 mm diameter is drilled with a hard metal drill.

Figures 5 and 6 show the results of a bending test of joints made from respectively material 1 and 2. The test object consists of a single ring connected by two joints to the original tube. The joints are produced by wire-EDM (electro-discharge machining). The surface roughness is kept as low as possible to enhance the fatigue properties.

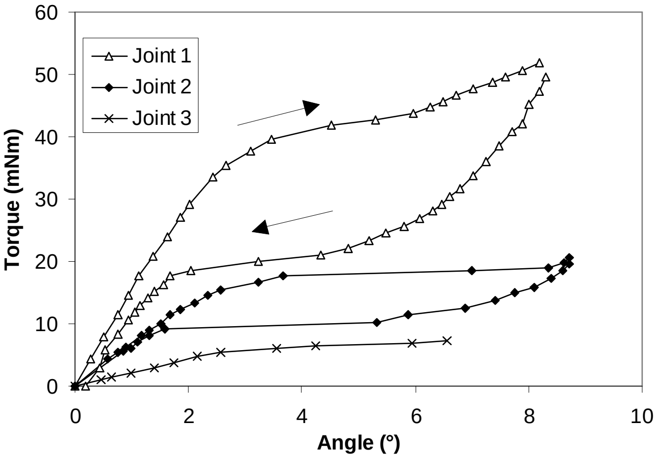


Fig. 5. Torque-angle characteristic of 3 different joint geometries for material 1 (wall thickness 0.4 mm).

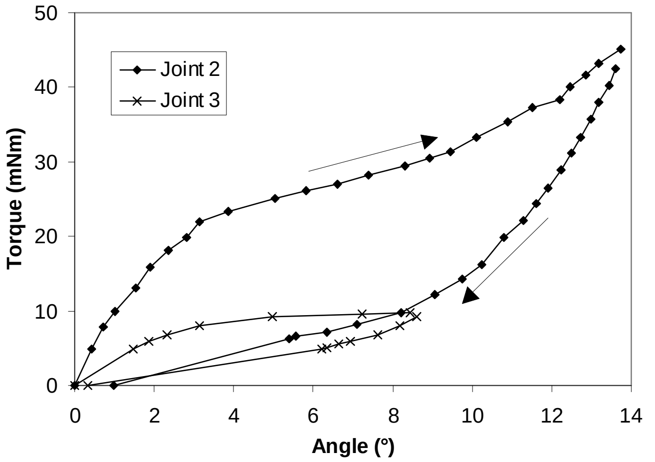


Fig. 6. Torque-angle characteristic of 2 different joint geometries for material 2 (wall thickness 0.7 mm).

When comparing the results for both materials, it is important to know that both tubes have a different wall thickness.

Joints 2 and 3 have also been subjected to fatigue tests. The results are summarised in table 1. The joints are bent alternately left and right over the specified angle (e.g. between -7.5° and +7.5° for joint 2). Only joint 3 has sufficient fatigue resistance. The bending angle will be limited to 6.0° for material 1 and 7.5° for material 2.

Table 1. Fatigue results.

Joint	Angle [°]	Strain [%]	Number of cycles	
			Material 1	Material 2
2	7.5	4.4	700	2,000
3	7.5	3.0	2,000	10,000
	6.0	2.4	6,000	-

V. PROTOTYPE 1

A first prototype of the flexible tip is made from material 1. Two times 16 pairs of joints are cut into the tube by wire-EDM. The bending angle of the joints is mechanically limited to 6° when the two neighbouring rings touch each other. The prototype thus has a theoretical stroke of 192° (-96° to +96°) for both dofs. Figure 7 shows detail views of this prototype. The rings connecting the joints are deformed to reduce the total length of the flexible part to 37 mm.

Four stainless steel cables (Berg AB018, 7x7 strands) with a diameter of 0.4 mm and a tensile strength of 178 N are placed at 45° with respect to the joints. The cables are fixed at the tip and guided by grooves in the interfacing part and by 4 special inserts. The inserts are slightly tapered to take up radial forces. The different parts are glued together.

The tool channel is a PTFE tube reinforced by a stainless steel spiral and is normally sold as a replacement biopsy channel for endoscopic instruments. The internal diameter of the tool channel is 2.2 mm.

Figure 8 shows prototype 1 in straight and bent

Fig. 7. Detail views of prototype 1 (diameter 4.7 mm).

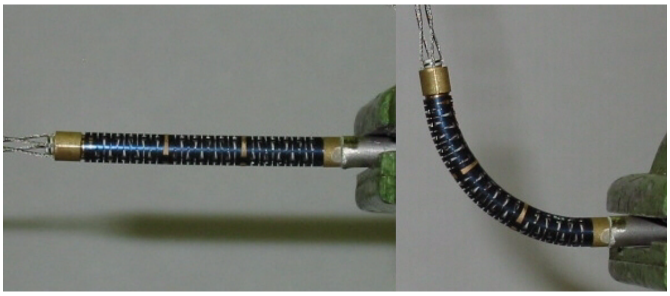


Fig. 8. Prototype 1 in straight and bent position.

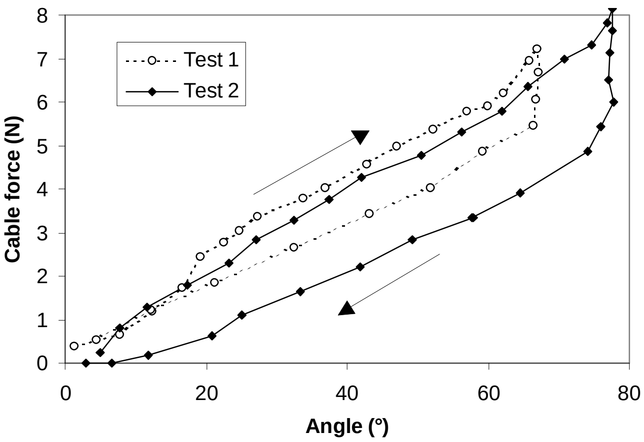


Fig. 9. Relation between cable force and bending angle for prototype 1. Only one cable is tensioned.

position. The maximal bending angle is slightly smaller than the theoretical angle. Figure 9 shows the angle over which the prototype bends as a function of the force applied to a single cable (the other cables are not tensioned). The hysteresis can be explained by the hysteresis in the superelastic material and the tool channel, and by friction on the cables.

VI. PROTOTYPE 2

A second prototype is made from material 2. This material allows a higher bending angle than material 1: 7.5° per joint. Only 2 times 12 pairs of joints are needed to reach a stroke of 180° (-90° to +90°). The main difference with the first prototype is that the cables are guided by longitudinal grooves in the tube wall. These grooves, produced by wire-EDM, remove the need for special cable-guiding inserts. The result is a shorter manipulator tip: the flexible part is only 22.5 mm long. A picture of prototype 2 is shown in figure 10.

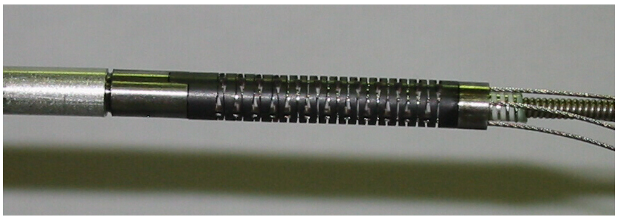


Fig. 10. Prototype 2 (diameter 4.9 mm).

VII. DRIVING UNIT

To integrate this manipulator in a surgical robot, it has to be driven by motors. Figure 11 shows the assembled manipulator with its driving unit. Each pair of antagonistic cables is driven by a DC motor with pulley. Two antagonistic cables form in fact only one cable starting at the tip, wound 1½ turns around the pulley and ending again at the tip but at the antagonistic side. The motors are mounted in a way that the cables can be tensioned. Figure 12 gives a detail view of the driving unit.

VIII. CONCLUSIONS

A flexible endoscopic tip with 2 dofs and a stroke of 180° (± 90°) has been developed. The improvement over existing devices is the combination of 2 dofs with a small diameter of 5 mm. An additional advantage is that standard flexible instruments can be inserted through the tool channel. Future work includes control and integration in a master-slave robotic set-up.

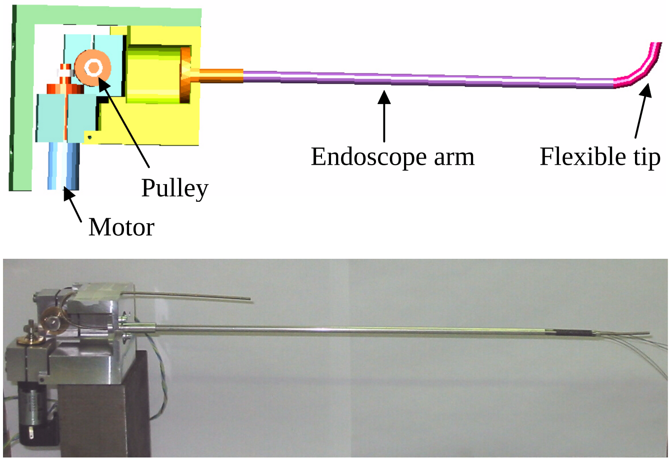


Fig. 11. The assembled manipulator with driving unit.

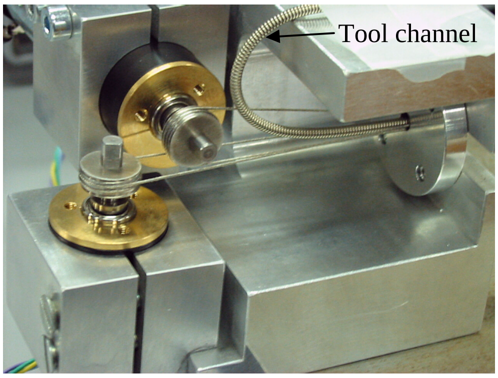


Fig. 12. Detail view of the driving unit.

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