ORIGINAL ARTICLE

Minimally invasive surgery instruments based on a four-bar linkage design

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Abstract: This paper presents a new design for instruments for use in minimally invasive surgery (MIS). The proposed mechanism features an end-effector based on a four-bar linkage, along with a hand-held device and a joint. The proposed instrument is operated using a bending motion identical to conventional bendable instruments, eliminates undesired motions.

Keywords: Minimally invasive surgery; bendable instrument; four-bar linkage

Introduction

In the last several decades, the development of minimally invasive surgery (MIS) techniques have revolutionized the way many surgical procedures are performed, resulting in smaller incisions and shorter recovery times for patients. In general, a conventional MIS consists of several procedures. First, the surgeon uses traditional surgery tools to make several small incisions, the number and location of which are determined by the specific operation and the surgeon's experience. Next, an endoscope combining a light source and an image capture system is inserted through one incision. The resulting real-time image is displayed on an external monitor. If necessary, the surgical cavity is inflated to provide more space for navigation and operation. Finally, the surgeon inserts long instruments through the other incisions for remote manipulation. The area and degree-of-freedom (DOF) of the operation are determined by the instrument design and incision location, with increased DOF corresponding with increased ease of instrument manipulation.

MIS instruments can generally be grouped into two categories (Fig. 1), with the first type having only one DOF on the end effector while the other has two DOFs. A one DOF instrument operates in only a single motion θ_1, while the two DOF instrument operates in two motions θ_1 and θ_2. However, two-DOF instrument designs are less frequently used in practice. The main structure of such instruments consists of a long bendable column rod constrained by an external tube. During an operation, the rod is extended by the manipulator and simultaneously bent by the release of the tube's constraint (Fig. 2).

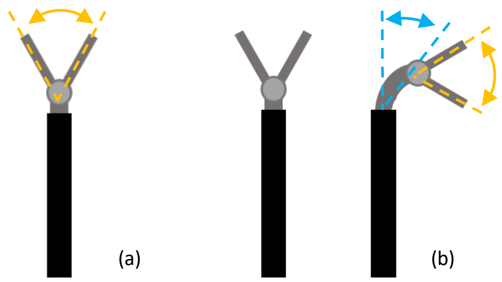

Figure 1. Two types of MIS instrument: (a) One DOF and (b) two DOF.

However, the single column structure provides insufficient stiffness, and strong force feedback on the end-effector may cause the instrument to bend, thus complicating manipulation.

MIS instruments must be small enough to fit through a small incision, but increased stiffness is also necessary for effective operation. Several studies have attempted to address this trade-off between size and stiffness. One solution was to separate the end-effector mechanism from the actuator [2], thus allowing the actuators to remain outside the surgery area, whereby the design only needs to consider the transmission mechanism [3]. Most such surgical tools are driven by wires, screws, and gear devices, with the operator using either a rotating gear mechanism on each joint or a rotating mechanism driven by a wire drive [2-5]. However, the structure of the gear and wiring device was overly complex and could not be manipulated intuitively with one hand.

Another proposed design featured a stackable four-bar linkage prototype structure which offered good loading capacity and better stiffness [6] and has been used as a transmission mechanism [7, 8], but has not yet been used in conventional instruments.

This paper presents a novel surgical instrument design with a four-bar linkage end-effector and hand-held device. The proposed end-effector design provides better stiffness, enabling the tool to smoothly cut through tissue without bending. Section 2 below describes the structural design concept, while section 3 illustrates the final instrument.

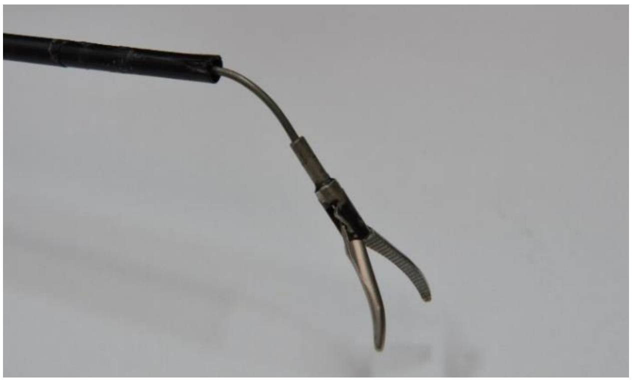

Figure 2. The two-DOF instrument generates a bending motion.

Structural design

End-effector

A novel end-effector mechanism is presented (Fig. 3), providing several features not found in the traditional two-DOF bendable mechanism (Fig. 2). First, the use of the four-bar linkage increases structural stiffness, allowing the surgeon to directly control the mechanism's movement and rotation using the hand-held device. In fact, if a force is attached to the end-effector, the device can still accurately reflect the operator's motion. The overall mechanical behaviors are much more stable compared to traditional structures. Second, the specification of the end-effector is labeled (Fig. 3). In fact, due to the tube restriction, during surgical procedures the dimensions of the proposed instrument are similar to those of less-stiff conventional MIS instruments. Finally, the use of flat components in the linkage simplifies the manufacturing process, and the flat-structure takes full advantage of wire electrical discharging machine (WEDM) fabrication processes which stack all identical pattern components for simultaneous wire cutting. In contrast, conventional instrument components are composed of complex structures that must be fabricated through separate procedures, which increases fabrication time and complexity.

Figure 4 illustrates the operation of the four-bar linkage: given linear displacement input from the left side, the joint will generate a rotation according to the kinematic behavior of the four-bar linkage.

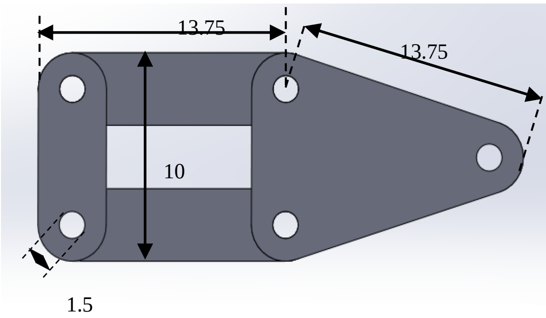

Figure 3. End-effector prototype. The design is based on a four-bar linkage mechanism.

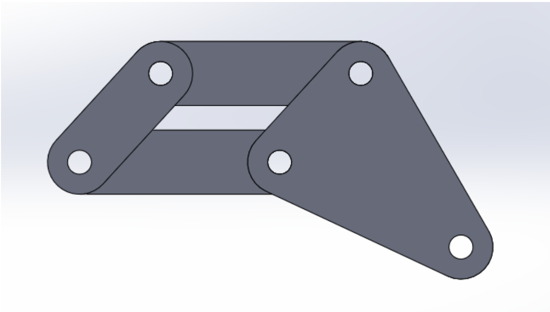

Figure 4. Motion of the end-effector.

Hand-held device

The hand-held device is used by the surgeon to control the movement and function of the end-effector through a transmission mechanism.

The hand-held device is also fabricated through

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WEDM using a flat structure. The main device consists of four flat layers, each with a thickness of 2 mm. The two inner layers share an identical design and are sandwiched between two identical outer layers (Fig. 5). The dimensions of the resulting device are similar to those used in conventional MIS.

Finally, we combined a lead screw and slider-crank mechanism to create the transmission. The lead screw transforms rotation into linear displacement, while the slider-crank mechanism transforms linear displacement into rotation, thus driving the four-bar linkage mechanism. Input combinations generated by the lead screw and slider-crank mechanism result in the compliant motion of the end-effector (Fig. 6).

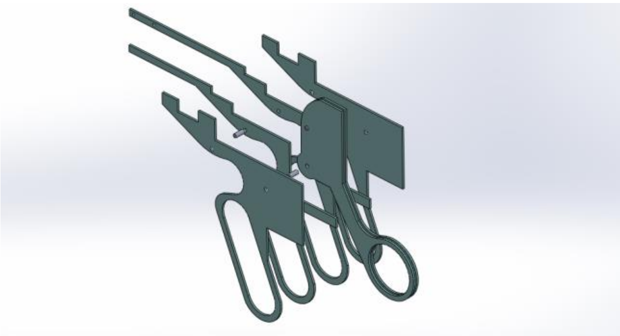

Figure 5. Hand-held device.

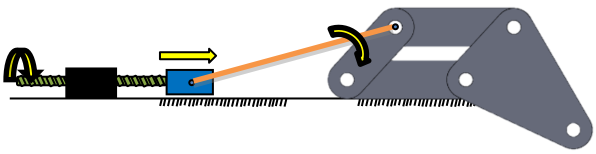

Figure 6. Combined mechanism. The overall mechanism integrates the lead screw, the slider-crank mechanism, and the end-effector to generate the compliant motion.

Joint designs

The four-bar linkage and hand-held device are both assembled in a stack formation, permanently fastened by 1.5mm diameter rivets, creating a compact and rigid overall structure.

The product

Figure 7 illustrates the manufacturing procedure. First, a 2D sketch of the instrument specification is produced using CAD software. We then use the WEDM process to machine a flat plate to create the pattern. Finally, the layers are stacked and constrained by the rivets. While surgical instruments are typically made of stainless steel, to increase ease of machining the prototype was made of aluminum with medium-carbon steel rivets. The prototype measured 40 cm long and 15 cm high, similar to conventional instruments (Fig. 8). The end-effector was produced from several WEDM-made components and constrained by rivets (Fig. 9). Notice that the fabricated end-effector differs slightly from the figure presented in the previous section. Rather than combining four components of the four-bar linkage, in practice the surgeon uses the hand-held device as a four-bar linkage base frame, thus minimizing the size of the end-effector. The four-bar linkage then is connected with a slider-crank mechanism, which transforms linear displacement to rotation, allowing the rotation angle of the end-effector to be controlled by the linear motion of the slider-crank.

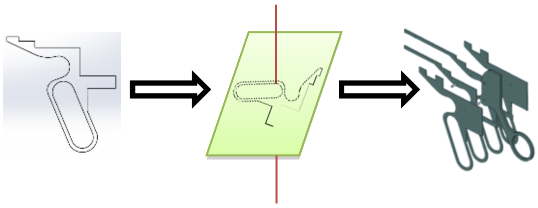

Figure 7. Three step manufacturing process.

Figure 8. Fabricated MIS surgical instrument.

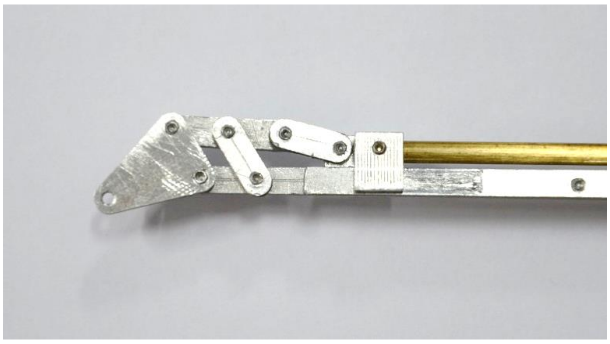

Figure 9. End-effector. The structure consists of stacked aluminum WEDM process-made components constrained by medium-carbon steel rivets.

The hand-held device consists of four 2-mm thick aluminum flat plates constrained by rivets (Fig. 10). The two inner plates control the end-effector, and are sandwiched by two outer plates to make the base frame of the four-bar linkage.

The 1.5 mm diameter column rivet required a surface finish to ensure compatibility with the hole in the instrument component. Once the rivet was placed in position, it was fastened using a center drill to constrain the linkages and other stack components.

In addition to the instrument, we also designed a motor carrier to be positioned on the back of the hand-held device. The motor is connected to the lead screw mechanism and is used to control and the overall mechanism motion (Fig. 11).

Figure 10. Hand-hold device. The structure consists of a stack of four aluminum WEDM made flat-structures.

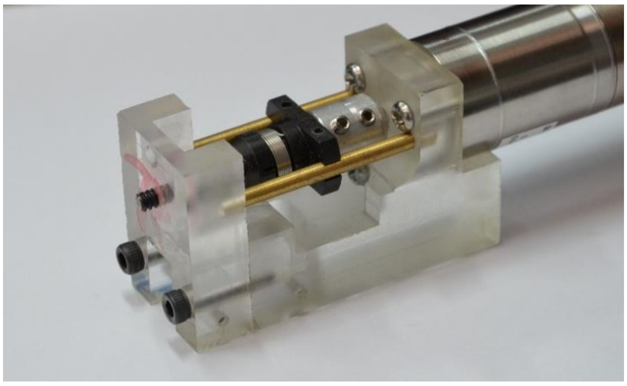

Figure 11. Motor carrier. The structure is made from PMMA, combined with a lead screw to transform displacement from rotation to linear.

Conclusion

A novel MIS instrument based on a four-bar linkage design is proposed to increase the stiffness of the end-effector and thus reduce unwanted bending characteristic of conventional MIS instruments. The end-effector and hand-held device are made of WEDM-fabricated flat plates which are stacked and constrained with joints. The dimensions of the end-effector and hand-held device are similar to those of conventional instruments. To increase ease of machining, the prototype was fabricated from aluminum, and the rivets are made from medium-carbon steel. The resulting design satisfies size and material requirements for MIS surgical components and integrates the four-bar linkage based end-effector with the hand-held device.

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