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A flexible instrument for robotic assisted minimally invasive esophagectomy

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Abstract. The paper presents a medical flexible instrument for esophagus stapling that can be integrated in robotic assisted esophagectomy. Starting with several considerations required for esophagectomy surgery, the forward kinematic model of the instrument is presented, followed by a numerical and a graphical simulation to validate the mathematical model of the instrument. A 3D printed mockup is developed in order to test the design of the instrument while simulating the stapling procedure.

Keywords: medical instrument, robotic-assisted surgery, kinematic modeling, esophagus stapling.

1 Introduction

Esophageal cancer ranks 9th globally among the most common types of cancer and 6th in terms of mortality rates. Annually, more than 500,000 cases of death are reported worldwide, with 16,640 cases in the United States alone. The mortality rate is reported to be 87.13%, affecting 14,500 individuals [1, 2].

One effective way to eliminate cancer, in addition to neoadjuvant therapy (chemotherapy and chemoradiotherapy), remains the resection of the diseased tissue [2-4].

The surgery for resection of esophageal cancer has evolved over time, with surgical interventions ranging from open procedures, where a large incision of up to 250 millimeters is made, to minimally invasive approaches. Minimally invasive techniques involve a minimal number (4-5) of incisions, typically ranging from 10 to 20 millimeters in diameter, and may also include robotic assisted surgery. These approaches aim to reduce the patient's hospitalization time, blood loss, postoperative trauma, pain, and result in a cosmetically superior outcome compared to classical surgery [5, 6].

To mitigate the disadvantages of classical surgery and improve the advantages of minimally invasive esophagectomy (MIE), a new technique was developed namely robot-assisted minimally invasive thoraco-laparoscopic esophagectomy (RAMIE). Based on the advantages presented in [7, 8] the RAMIE technique also come with a series of dis-

advantages like: poor intraoperative workspace for instruments, high price for surgery, poor pulmonary functioning generated by the thoracoscopic approach, less dexterity of the instruments, and the use of the rigid instruments. One of the major drawbacks during the MIE is the limited intraoperative workspace, where the surgeon has to manipulate several medical instruments with poor dexterity (current instruments used are stiff or have a low dexterity) in order to perform all the procedural steps of the surgery. To overcome this disadvantage and to increase the dexterity of the instrument and the workspace, this paper presents an innovative flexible instrument (patent pending [9]) used for esophagectomy. The medical instrument uses the RCM (Remote Center of Motion) principle, and its design includes several bends actuated using cable joints to allow bending of the tip of the instrument inside the patient to perform stapling of the esophagus before the anastomosis.

Following the introduction section, the paper is structured as follows: Section II, defines the surgical task and the instruments required for esophagectomy, Sections III and IV present the kinematic model and 3D modeling of the articulated instrument, and Sections V and VI present the workspace generation and the 3D printed prototype of the articulated instrument, concluding with the conclusions of this work.

2 Considerations regarding the esophagectomy procedure

There are several methods to perform the MIE procedure:

- Transhiatal esophagectomy [10] -where the surgeon performs two incisions, one at the abdominal level and the other one at the cervical level.
- IvorLewis esophagectomy [11] -is a two-phase surgical procedure. The first phase is the abdominal approach where the esophagus is accessed via abdomen and the second phase implies stapling the esophagus for anastomosis using a thoracic incision. Currently the instruments used in this step are rigid or their dexterity is less, instrument presented in this work contribute to improving dexterity during tissues suture.
- McKeown esophagectomy [12]- involves mobilization of the thoracic esophagus with lymph node dissection (performed thoracoscopically or through an open approach), exploration of the abdomen, mobilization of the stomach with lymph node dissection, and finally, creation of a left cervical incision for anastomosis.
- Thoracoabdominal esophagectomy [13] - for many years, the left thoracoabdominal esophagectomy has served as the conventional method for resecting and reconstructing the gastroesophageal junction. This approach offers better visibility for dissection, placement of the esophageal substitute, and execution of the anastomosis.

For developing the flexible instrument, the Ivor Lewis esophagectomy approach was considered, being one of the common methods used currently in Romanian hospitals, unfortunately, only conventional procedure is performed, but esophagectomy can also be robotic assisted using the da Vinci Xi robot [14]. The medical protocol for robotic assisted Ivor Lewis esophagectomy approach is presented in [11] and the entry ports required for abdominal phase and thoracic phase are presented in Fig.1. Due to large number of instruments used during the procedure, the workspace is considerably limited, thus requiring specially designed instruments, to perform specific and personalized tasks, with

respect to the medical protocol, in order to reduce the time spent in the surgery, improve the outcomes of the surgery, reduce risks caused by instrument malfunctions (improper stitches, unsuccessful anastomosis) and allow fast post-operative recovery. In this scope the instrument presented within this paper, is specially designed to allow esophagus sectioning by stapling. Due to the fact that the stapler is inserted in the thoracic volume through an 8 mm port, the range of motion regarding the angular displacement of the instrument with respect to the RCM point is considerably limited by intercostal space that does not allow large amplitude motions, requiring a special instrument, able to bend beyond the point of RCM in order to allow stapling of the esophagus.

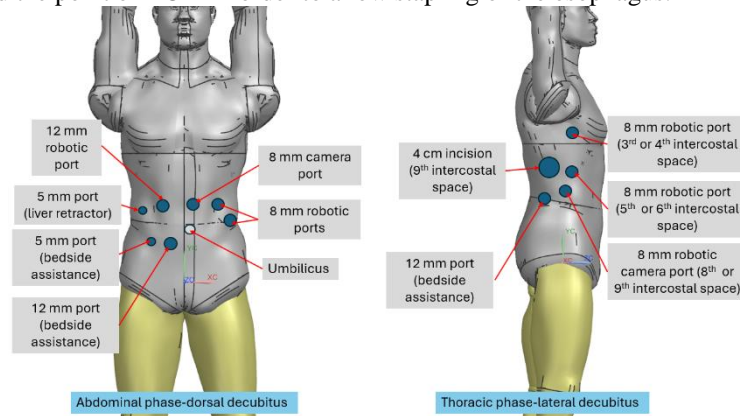


Fig.1. The ports placements during robotic assisted Iver Lewis esophagectomy.

3 Kinematics of the flexible instrument

Based on data presented in the previous section of the paper, Fig.2 presents the kinematic scheme of the flexible instrument designed for esophagus stapling before anastomosis. The instrument has 5 degrees of mobility. First motion (Motion 1) allows revolving the instrument around its longitudinal axis (OY), this motion is required in order to change the position of the tip of the instrument after inserted through the trocar and is performed using q_1 active joint. The second motion (Motion 2) represents the flexible part of the instrument, being a cable actuated mechanism that allows bending of the tip of the instrument using around revolute joint R_1 . The motion is performed using active joint q_2 that rotates the cable pulley for bending the instrument. The third motion (Motion 3) is performed around R_7 revolute joint being also a cable mechanism actuated using q_3 active joint. Motion 4 is the opening/closing motion of the stapler, also a cable mechanism actuated by q_4 , and Motion 5 is the stapling motion, where a special mechanism slides inside the jaws of the stapler in order to perform the sectioning and the stapling of the esophagus, this motion is performed using q_5 joint and a wire transmission.

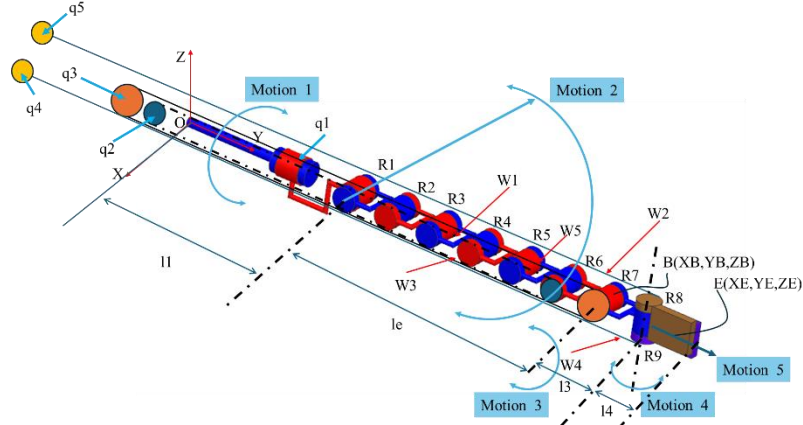


Fig. 2. The kinematic scheme of the flexible instrument.

The parameters of the flexible instrument are illustrated in Fig.2 where l_1 is length of the rigid segment, l_e is length of the bending elements, l_3 is length of the segment between revolute joint $R7$ and the base of the stapler, and l_4 is length of the stapler. Regarding the lengths of the active instruments used in robot-assisted surgery, they range between 420 - 470 mm. The maximum insertion of instrument into the patient's body is limited to 270 mm, and the flexible length of the instrument is between 60 - 130 mm ($l_e - l_4$) [15-19]. To define the motion of each flexible element of the instrument the kinematic scheme from Fig. 3 is used. Point O_0 represents the end of the rigid part of the instrument, and the flexible part of the instrument up to the last revolute joint before the gripper is composed of 6 flexible elements. The diameter of each element is 10 mm and the distance between two consecutive elements is constant. The bending of each element can be defined by two angles: ψ is rotation around the Z_0 axis, φ is bending angle around revolute joint, θ is the bending angle for the flexible part, L_1 and L_2 are the lengths of the flexible element for OX and OZ axis.

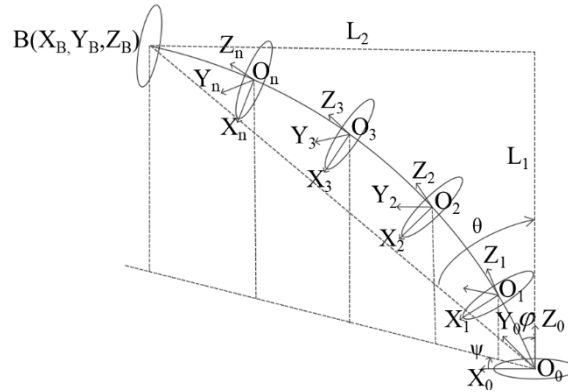


Fig. 3. Kinematic scheme of flexible instrument.

The forward geometric model of the bending section is computed using the coordinates of the point O_0 in order to determine the coordinates of the last bending elements. The length between two consecutive elements is noted with l_e and the position of each k -element of the bending section can be obtained using Eq. 1.

$$\begin{cases} X_k = l_e \cdot \sin \varphi \cdot \cos \psi \\ Y_k = l_e \cdot \sin \varphi \cdot \sin \psi \\ Z_k = l_e \cdot \cos \varphi \end{cases}, k = 1 \rightarrow n \quad (1)$$

where: $\varphi = 2 \cdot \theta / (n + 1)$ and $\psi = \arctan(Y_k / X_k)$

The coordinates of point B (the revolute joint of the last bending element) are:

$$\begin{cases} X_B = L_2 \cdot \cos \psi ; \\ Y_B = L_2 \cdot \sin \psi ; \\ Z_B = L_1 \end{cases} \quad (2)$$

$$\text{and } L_1 = \frac{l_e}{n} \cdot \frac{\sin((n \cdot \varphi)/2) \cdot \cos((n+1) \cdot \varphi/2)}{\sin(\varphi/2)}, L_2 = \frac{l_e}{n} \cdot \frac{\sin((n+1) \cdot \varphi/2) \cdot \sin(n \cdot \varphi/2)}{\sin(\varphi/2)}$$

The second motion generated by the q_2 is given by Eq.3.

$$q_2 = L_1 \cdot \tan^2(\theta) \quad (3)$$

where: $\tan(\theta) = L_2 / L_1$

4 CAD of the flexible medical instrument

The flexible instrument (Fig. 4) was modeled using the Siemens NX program and the material chosen for the instrument is ABS. With respect to the medical protocol for Iver Lewis robotic assisted esophagectomy the diameter of the instrument is 10 mm to be inserted into a trocar of 12 mm and the overall length as 465 mm.

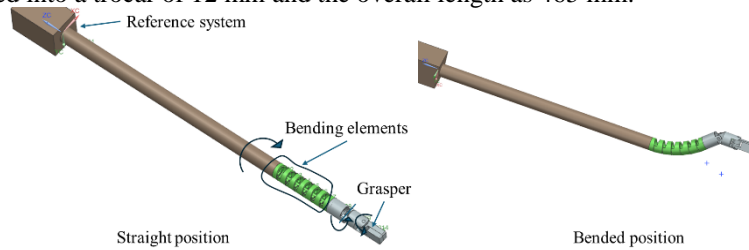


Fig. 4. Modeling of the articulated instrument with the revolute joints and the stapling mechanism.

The bending elements of the instrument are connected through revolute passive joints and are driven by cables running along designated paths from the initial element to the last. Each element includes a section with a ten-degree angled surface to facilitate the bending of the instrument. In the right part of fig. 5 the cable paths are presented. Path $W1$ and $W3$ are for instrument bending (joint q_2), path $W2$ and $W4$ are for stapler actuation and stapling operation (q_4 and q_5) and center path $W5$ is for the stapler orientation (joint q_3). Fig. 6 presents the workspace boundary of the flexible instrument, the workspace is almost half a sphere of radius R , where R represents the length of the instrument

from R_2 to the tip of the instrument. Along the bending of the flexible elements of the instrument, additional dexterity is given by revolute joint q_3 which allows various orientation of the stapler within the intraoperative workspace.

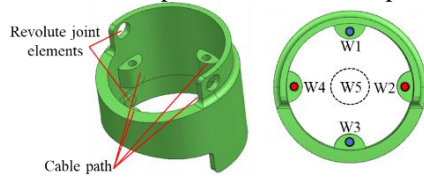


Fig. 5. Bending elements of the instrument.

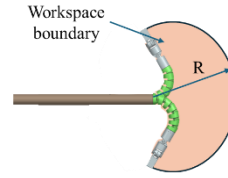


Fig. 6. Workspace boundary of the instrument

5 Simulation of the flexible instrument tip

To validate both the mathematical model and the design of the instruments, several simulations were conducted. This involved a MATLAB simulation employing the mathematical model of the medical instrument, the simulation material has not been defined in MATLAB, alongside a graphical simulation using the CAD representation of the instrument. Both simulations used same input data namely the coordinates of the initial point of the tip of the instrument C_1 ($X_{C1}=57.30$ mm, $Y_{C1}=-0.9$ mm, $Z_{C1}=-554.61$ mm, $\varphi_{C1}=-41.82^\circ$, $\psi_{C1}=10.19^\circ$) and the coordinates of the final point C_2 ($X_{C2}=-17.62$ mm, $Y_{C2}=121.51$ mm, $Z_{C2}=-430.81$ mm, $\varphi_{C2}=36.77^\circ$, $\psi_{C2}=89.86^\circ$). The trajectory of the tip of instrument between the two points is illustrated in Fig. 7.

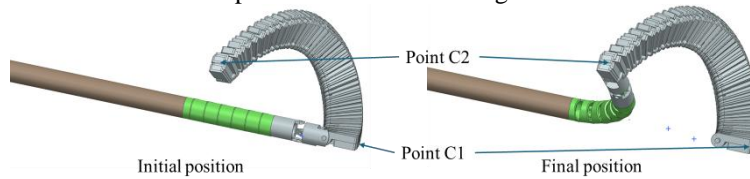


Fig. 7. Simulated trajectory of the tip of the instrument

Data extracted from these two simulations (Siemens NX and MATLAB) were parsed to a MATLAB program where were graphically represented in Fig. 9.

Fig. 8 illustrates the displacement, velocity, and acceleration of the tip of the instrument. Additionally, data from the graphical simulation is overlaid on the same graph using a black dotted line. While there is not a perfect overlap between the two sets of data, the variances are minimal, and both simulations exhibit a similar curve profile, confirming the efficiency of the mathematical model and the design of the instrument.

Also, for validation purposes, a prototype of the flexible instrument was manufactured using Stratasys Fortus 380mc 3D printer, the 3D printing being made with ABS. For the prototype a 2:1 scale was used in order to check the functionality of the instrument. The prototype of the instrument and the mock-up used to test the instrument functionality is presented in Fig. 9. The functionality of the instrument was tested by inserting it into a testing mockup, and the grasping and manipulation of the tissue were performed using its tips. The instrument behaved accordingly, encouraging further development on a 1:1 scale, adapting the instrument tip to the actual stapler, and laboratory test using the actuated instrument.

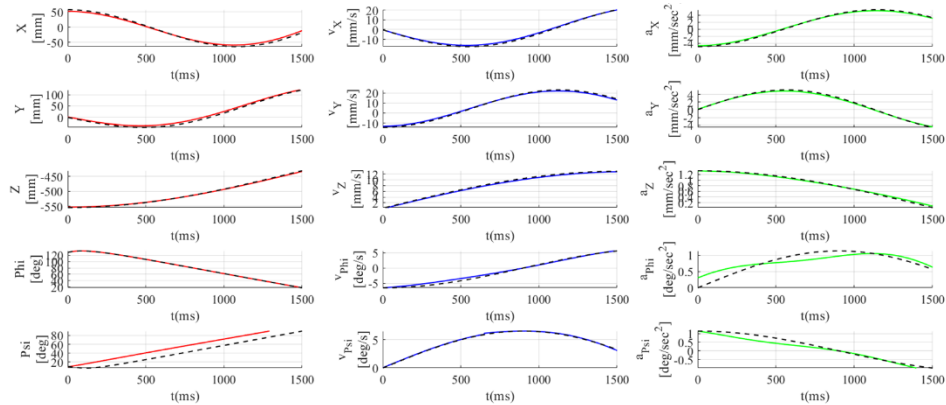


Fig.8. Time history diagrams of the coordinates, velocity, and acceleration of the instrument tip

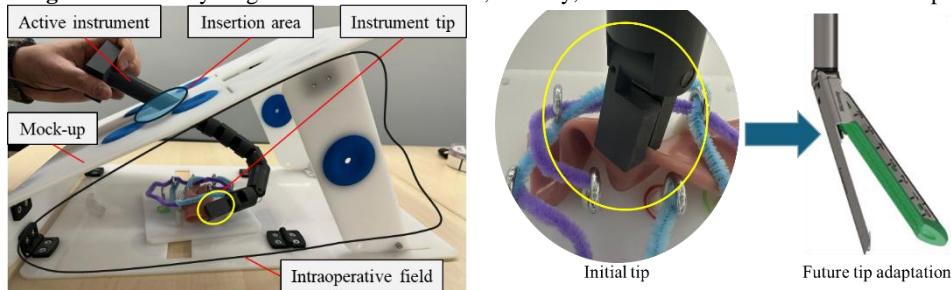


Fig.9. Testing the functionality of the proposed instrument

6 Conclusion

This paper presents an innovative flexible medical instrument designed for minimally invasive esophageal surgery. By incorporating several cable-actuated bending elements, the access for the esophagus stapling procedure is improved, allowing bending of the stapler around two axes after passing through the RCM. The workspace definition of the instrument was achieved based on kinematic modeling and CAD design, generating promising results that encourage further developments. The validation of kinematic modeling and the functionality of the instrument were conducted through simulations in MATLAB and Siemens NX. Future studies will focus on prototyping the instrument using biocompatible materials (the instrument will be printed using Stratasys J5 MediJet 3D printer) and adapting it with the tip of a real stapler, developing a control system for the final prototype, and testing the instrument under laboratory conditions.

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