Initial Investigations toward a Flexible Variable Stiffness Single Port System for Partial Nephrectomy

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Abstract:

Single port laparoscopic surgeries are the next step towards minimal invasiveness after conventional laparoscopy with several incisions. However, current conventional and single port instruments as well as robotic systems offer only a straight instrument deployment possibility, which results in limited visualization and triangulation. In the particular case of partial nephrectomy the kidney needs to be separated from connected tissues in order to be rotated and thereby improve the visualization and accessibility of the tumor. This preparation procedure demands valuable time of the surgery and in fact increases the invasiveness. In order to prevent these disadvantages we propose a novel, flexible single port manipulator with variable stiffness and instrument deployment channels. We present our vision and conduct first contour accuracy investigations on one segment manipulators with granular jamming.

Key Words: Laparoscopic Partial Nephrectomy, Continuum Robot, Granular Jamming

1 Problem

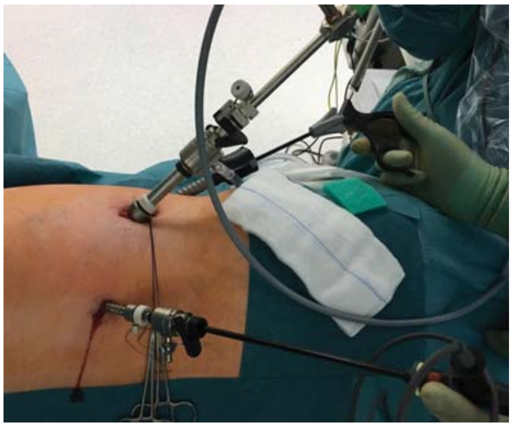

Figure 1: Conventional laparoscopic setup for partial nephroctomy.

In the past two decades conventional laparoscopy has become a surgical standard in several surgical disciplines, driven not only by reduced hospitalization, blood loss and postoperative pain levels, but also patients demand. In contrast, novel techniques such as robot assisted laparoscopy (RAL) and laparo-endoscopic single-site/natural orifice translumenal endoscopic surgery (LESS/NOTES), both potentially less invasive compared to conventional laparoscopy, developed differently: RAL has become to a world wide accepted standard for minimally invasive surgery, whereas LESS/NOTES procedures are limited to few specialized centers [1].

In this paper, we are in particular looking at partial nephrectomy. Kidney cancer is a rare malignancy with an incidence of 20 newly diagnosed cases per year per 100.000 residents, but it accounts for 6.6 cancer related deaths (according to Robert Koch Institute). Improved diagnosis of local tumors and technical improvements, such as hemostats, clips, and barbed sutures, lead to an increasing number of minimally invasive procedures for partial nephrectomy. However, current LESS approaches require an invasive mobilization of the kidney to ensure sufficient visualization. As a result, the kidney reconstruction prolongs the surgery and thus increases the stress for patients. Organ preserving approaches are highly desirable. This requires flexible visualization, in order to provide views from multiple perspectives, and sufficient angulation of instruments for tumor resection. To withstand the applied forces during the surgery the system has to provide enough stability.

The development of pre-bent instruments, flexible endoscopes, and angled camera optics address the challenges associated with single port laparoscopy partly. Can et al. [2] and Roppenecker et al. [3] proposed a single port robotic system with flexible arms enabling sufficient triangulation and instrument deployment. However the incision position is still crucial for the visualization and accessibility of the organ. Thakkar et al. introduces a flexible robotic platform for distal pancreatectomy [4] enabling deployment of several instruments. However, the reorientation of the platform is not efficient for proposed application due to sequential feeder bending mechanism. Further the working channels only accept instruments with max. 2.34 mm. Ranzani et al. [5] introduced a flexible multi-segment soft manipulator with variable stiffness for single port surgeries. However, the current design doesn't foresee working channels for instruments. To conclude, the state of the art does not provide a solution to the challenges in LESS.

We envision a flexible LESS port with two segments which can bend individually in order to allow for the deployment of the endoscopic camera and instruments on multiple tortuous paths to the kidney (see Figure 2). The flexible LESS port is envisioned with variable stiffness, such that once a desired pose is reached, the shape of the port can be locked in order to enable stable manipulation with the instruments. In this paper, we present our initial design considerations. We further present the results of an experimental analysis of variations of our port designs in terms of contour accuracy and influence of tendon tension and instrument deployment.

2 Material und Methods

Our flexible LESS port with variable stiffness is envisioned as a continuous structure following the principles of continuum robotics [6]. Bending of each segment is achieved by tendon actuation. The overall diameter of the port should be below 3 cm to comply with LESS requirements.

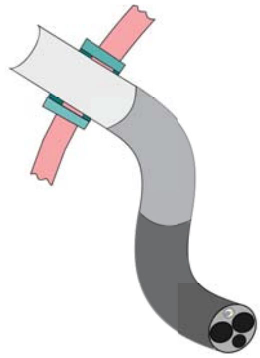

Figure 2: Vision of the flexible port with variable stiffness

2.1 Selection of Stiffening Method

Many different stiffening methods have been reported recently. Loeve gives an overview in [7]. Methods like shape memory polymers or magnethorheological fluids require harming temperatures or electrical currents for the human body [8] [9]. Designs with structural locking based on increased tendon tension [4] require high tendon tensions and do not provide constant deployment channel diameters due to sliding links. High pressure designs as proposed in [10] exhibit risk of tissue damage in case of bursting. Concerning vacuum based designs (granular jamming [11] and layer jamming [12]), granular jamming is reported as the method with highest stiffening capability [11] and has also been proposed for surgical applications [13]. Thus, we focus on granular jamming for our initial design considerations.

2.2 Prototype

We designed variations of a single segment prototype, which are based on the basic design depicted in Figure 3 (top). It consists of two round plates (base and distal plate) and a cylindrical vacuum chamber covered by a latex membrane attached air-proof between the plates. The membrane has an outer diameter of 26 mm. The base plate provides vacuum hoses (blue). Both plates are equipped with drill holes for tendon attachment and routing. We choose a 3D-printed compression spring surrounding the membrane to provide structural support and tendon routing channels (Figure 3 bottom). The spring replaces the spacer disks and elastic backbone of conventional tendon-driven continuum robots. The outer diameter of the spring is 32 mm.

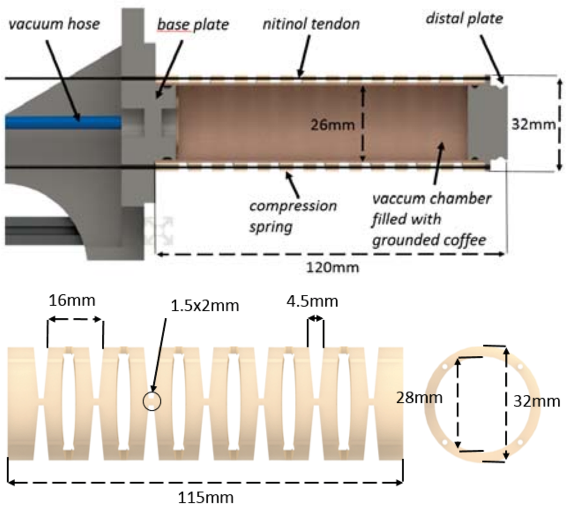

Figure 3: Cross section of basic design and spring parameters.

We choose two pairs of antagonistic tendons per segment in order to reduce the number of actuators required for bending. Hence, there are 4 tendons routed along the manipulator with 90 ° angular offset. For our initial investigation in this paper, we use a manual actuation unit. As the material for the membrane we choose latex, since it was shown as a good allrounder and most predictive material as a membrane [14]. The plates and the spring are fabricated with a MakerBot Replicator 2 (MakerBot Industries LLC, Brooklyn, USA). The spring is made of Polycaprolactone and the plates of Polyactide. NiTi wire with 0.24 mm diameter is used for the tendons. The vacuum chamber is filled with grounded coffee, as it was proven as one of the most effective granular materials for jamming [11].

2.3 Contour Accuracy Investigation

Many investigations concerning the stiffness and force generation have been performed in the past for granular jamming manipulators, however, we first address the contour accuracy of such. We investigate the influence on the contour accuracy for following characteristics: 1) Transition between jammed and non-jammed granular state, 2) Characteristic design components, such as spring, vacuum hoses etc., 3) Tendon tension increase in order to improve the stiffness of the manipulator, and 4) Instrument deployment. To investigate the influence of these parameters, we constructed variations of the basic design described in the previous section. The design variations are described in the respective following sections. For all experiments an MPZ 86.22 vacuum pump was used (hyco Vakuumtechnik GmbH, Krailling, Germany). The applied vacuum pressure was for all experiments -0.8 bar in respect to the atmosphere. The contour shape is measured by using an electro-magnetic tracking system (Aurora v2, Northern Digital Inc., Waterloo, Canada). We measure the contour shape at 7 locations along the spring (3.5, 27, 42, 57, 72, 87, 102 mm). Each location has a notch of 1 mm diameter to simplify the positioning of the electro-magnetic tool.

2.3.1 Contour Accuracy concerning Characteristic Components

Characteristic components for our port design are required to guarantee the functionality of the system, i.e. vacuum hoses routed along the chambers to the distal segments, instrument deployment channels, compression spring for tendon routing, and structure stabilization. These components posses certain stiffnesses. On the one hand, these stiffnesses shall contribute to the structure support (spring), withstand the vacuum pressure (vacuum hoses), or maintain the diameter during bending (deployment channel). On the other hand, they counteract the granular jamming due to their elastic deformation. In order to investigate this influence we evaluate the basic design (Figure 3) and 3 variations (Figure 4a-c). In (a) we route two vacuum hoses through the vacuum chamber, which enable vacuum in the distal segment independent from the first segment. In design (b) we also add a working channel of 4 mm diameter. Design (c) differs from (b) only in the diameter of the working channel which is 6 mm. All hoses and working channels are made of polyethylene.

We bend the manipulator in one plane with angles of 30 °/50 °/70 ° and perform two shape measurements. First, we apply vacuum to the chamber after bending and measure the contour shape. Second, we loosen the tendon such that only the granular jamming counters the stiffnesses of the characteristic components and measure the contour shape again. We define the error as the Euclidean distance between corresponding points of the two measurements, and determine the mean error and standard deviation at each measurement point. We repeat the experiment for all prototypes and deflection angles.

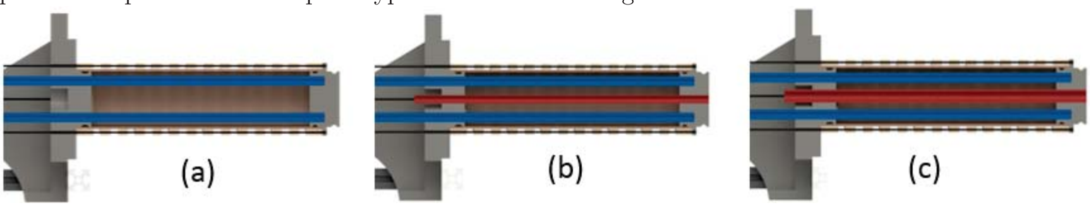

Figure 4: Basic design variations with different components. a) Vacuum hoses (blue), b) Vacuum hoses and 4 mm deployment channel (red), c): Vacuum hoses and 6 mm deployment channel (red)

2.3.2 Granular Jamming

In this experiment, we investigate the influence of the jamming transition on the contour accuracy. We use the basic prototype for this experiment (Figure 3). We bend the manipulator randomly in its 3-D workspace. The maximum bending angle is limited to 90 ° due to the spring structure. For each configuration we measure the contour after bending. We then draw the vacuum in the chamber and measure the contour again. As the last step, we release the vacuum and measure the contour the third time. Two errors are defined as the Euclidean distance of the second and the third measurement in respect to the first contour shape at the corresponding measurement points. We determine the mean error values and the standard deviation at each measurement point. We conduct the experiment at 20 random bending states of the prototype. The experimental setup is shown in Figure 5.

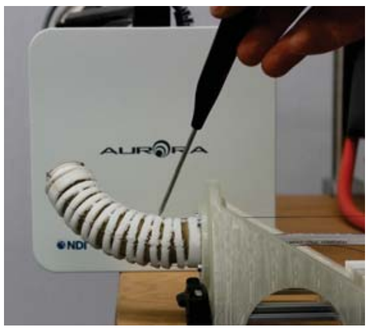

Figure 5: Experimental setup for contour measurements.

2.3.3 Tendon Tension Increase

In previous work, it has been shown that tensioning the tendons after jamming can increase the stiffness of the manipulator [11]. However, it is unknown if this method influences the contour. To investigate this behavior we use the basic prototype (Figure 3) and use the same experimental setup as for the granular jamming accuracy investigation (Figure 5). We bend the manipulator to different random angles in its 3-D workspace with a maximum bending angle of 90 °, apply vacuum to the chamber, and measure the shape. In the next step, we increase tendon tension by pulling them simultaneously (such that no further bending is induced) and then measure the contour shape again. In the last step, we release the additional tendon tension by pushing the tendons back and measure the contour one more time. The errors are defined equivalent to the jamming accuracy investigation. We evaluate 20 random bending states of the prototype. Before increasing the tendon tension we ascertain that all tendons are tensioned such that additional pulling the tendons effects all tendons. We increase the tendon tension by pulling the tendons for the same distance for all evaluated configurations. The influence of the tension increase is not the subject of this paper.

2.3.4 Instrument Deployment

Finally, we investigate the contour accuracy during the deployment of instruments. We use a prototype diversion shown in Figure 6 (left). The design includes a working channel, which consists of a low stiffness tension spring covered by silicone membrane in order to reduce the stiffness counteracting the jamming. The spring has a low stiffness such as it can't withstand its own weight, but can hold its diameter. Hence, it adapts to the curvature without significantly influencing the jamming behavior. It has a 8 mm inner diameter and wire thickness of 0.5 mm. The silicone membrane offers air-proof sheath for the channel. A close-up of the deployment channel is shown in Figure 6 (center).

This manipulator is bend randomly in its 3-D workspace with a maximum bending angle of 90 °. Once a configuration is established, vacuum is applied to the vacuum chamber. As we consider the increase of the tendon tension as beneficial, tendons are tensioned further following the protocol in section 2.3.3. After jamming and tension increase the first measurement of the contour shape is taken. In the next step, we deploy a flexible instrument through the channel such that the instrument is clearly visible outside the port (see Figure 6 (right)). After deployment, we measure the contour shape again. As flexible instruments we use two concentric NiTi tubes (straight outer and curved inner tube with diameters of 1.2 mm and 0.8 mm) and a tendon-driven continuum robot with 0.8 mm outer diameter NiTi tube as a backbone and 4 mm diameter aluminum spacer disks. For each instrument we investigate 10 random configurations. The experimental setup is shown in Figure 6 (right).

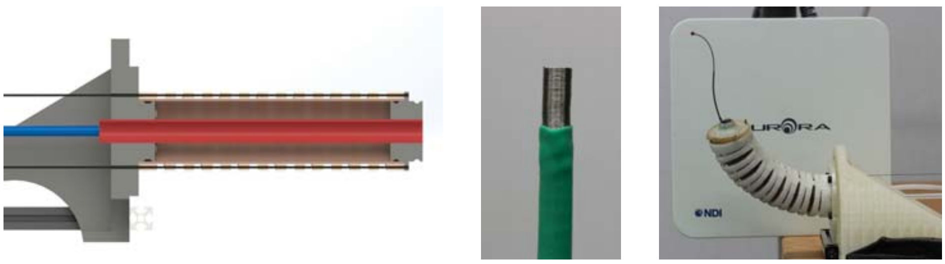

Figure 6: Deployment Port Design(left), Deployment shannel(center), Experimental setup instrument deployment with concentric tubes(right)

3 Results

The component evaluation (section 2.3.1) shows that the influence on the contour accuracy is significant. Table 1 summarizes the maximum tip errors for all four manipulators and all bending angles. The basic design (namely the outer spring) is subject to contour shape deviations for larger bending angles. Adding vacuum hoses (design a) does not impact the error in comparison to the basic design. Adding a working channel (design b) does affect the contour accuracy to some extent. The working channel with larger diameter (design c) results in the largest measured contour deviations.

The results for the jamming contour accuracy (Section 2.3.2) are depicted in Figure 7. The blue line depicts the mean error and the standard deviation after the jamming and the red dashed line the mean error and the

Table 1: Maximum errors at the tip for the component experiments.

	30 °	50 °	70 °
Basic Design [mm]	1,8	8,6	14,7
Design a [mm]	3,8	6,8	12,1
Design b [mm]	4,3	8,8	15,4
Design c [mm]	13,9	24	35,9

standard deviation after releasing jamming. No significant difference between the two measurements can be observed. In general, an increasing error tendency can be observed towards the tip.

The errors for the tendon tension experiments (Section 2.3.3) are illustrated in Figure 8. The blue line depicts the error after the tendon tensioning and the red dashed line the error after releasing the tendon tensions. Both error values are comparable. Similar to the jamming evaluation an increasing error tendency towards the tip can be observed. However the error for tension increasing is larger than for the jamming transition.

The errors for the instrument deployment experiment (Section 2.3.4) are illustrated in Figure 9. The blue line depicts the error after deploying the concentric NiTi tubes and the red dashed line the error after deploying the tendon driven continuum robot. Both instruments cause comparable contour deviations, which are smaller than those caused by the previous experiments. The large standard deviation at the second measurement point (27 mm) is caused by an outlier due to manual measurement inaccuracy.

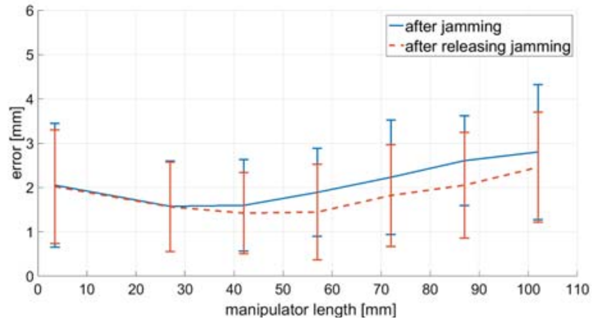

Figure 7: Jamming accuracy mean values and standard deviation: After jamming (blue) and after releasing

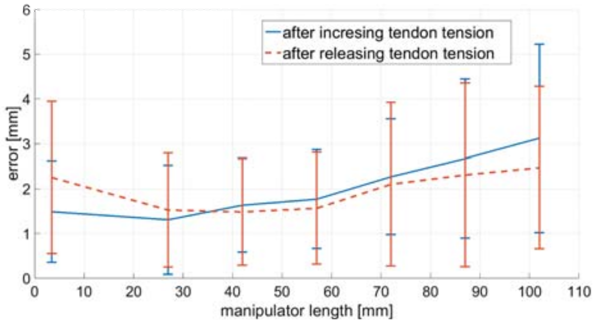

Figure 8: Tension increase accuracy mean values and standard deviation: After tension increase (blue) and after releasing tension (red dashed)

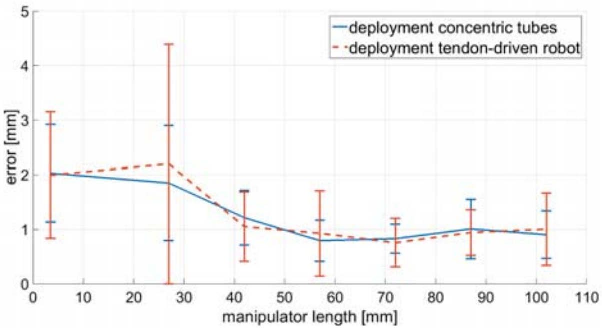

Figure 9: Instrument deployment accuracy mean values and standard deviation: tubular continuum robot (blue) andtendon driven continuum robot (red dashed)

4 Discussion

We observe that the influence of the typical manipulator components such as vacuum hoses and working channels with diameter of 4 mm do not significantly impact the contour accuracy. However, larger working channels do indeed affect the contour deviation. This, the main influencing factors are the spring which provides flexibility and structural support (Figure 3) as well as the stiffness of internal working channels. A compromise between the requirement of flexibility in order to adopt to the manipulator shape and diameter as well as number of working channels has to be found.

The jamming and increased tendon tension experimental results are encouraging as the mean error below 3 mm is negligible for the intended application considering the size of the kidney and abdominal insufflated volume. However, the slight tendency of an increase in error towards the manipulator tip may be even larger for a longer two segment prototype, which has to be proven in the future.

Shape Recovery of the initial shape after granular jamming and tension increase is not achievable with our current design. However, we do not foresee this as a problem, as the user would reposition the port after returning to the flexible state. The instrument deployment results show that the port has withstands its current shape very well. A larger variety of instruments and the manipulation (i.e. interaction forces) have yet to be investigated.

Overall, the observed errors toward the base of the prototypes show that the current design which does not foresee an attachment of the spring might need to be adapted such that no relative axial and radial displacements can occur. Furthermore, while grounded coffee shows great results as jamming material, an alternative which is biocompatible and absorbable for safe use within a patient has to be found.

5 Summary

In this paper we present initial results for a variable stiffness flexible port. Our port design enables instrument deployment and positioning in different perspectives in respect to the kidney. We investigated the influence on the contour accuracy of following aspects for the first time for granular jamming: routing vacuum hoses and working channels inside the port, transition between non-jammed and jammed granular state, simultaneous tendon tension increase in all tendons, instrument deployment through a working channel. Our results are promising and the first step toward our vision of a flexible LESS port with variable stiffness.

6 Acknowledgments

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