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Multi Arm Snake-Like Robot Kinematics

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***Abstract* — The next step in minimally invasive surgery is the further reduction of incisions by surgery through natural orifices (NOTES) or one single artificial incision (Single-Port). However, physicians pointed out, that those procedures are only possible if new technologies will increase the dexterity of the instruments inside of the body. Especially the missing ability to manipulate tissue from two sides (triangulation), needs to be obtained. This article is about the development of different kinematics for a Multi Arm Snake-Like Robot to manipulate flexible endoscopic instruments at the tip of a flexible endoscope. By using Selective Laser Sintering (SLS) it is feasible to create various shapes and designs, custom made for different patients. We are using flexure hinges and compliant mechanisms to create defined movements in serial kinematic structures. In the experiments, the relation between different structures and the influence of the inserted flexible endoscopic instrument are compared. The proposed kinematics are able to manipulate flexible endoscopic instruments. That proves that SLS structures get more advances towards a use for a flexible Single-Port Multi Arm Snake-Like Robot.**

I. Introduction

Today most of the surgeries to treat diseases located at the gastrointestinal tract are performed as minimally invasive surgery (MIS). This includes a great benefit for the patients, which means fewer incisions and less post-operative pain after surgery and shorter in-habilitation at the hospital. In this article, we are focused on the disciplines Single-Port Surgery, whereby an artificial incision is made, e.g., through the umbilicus and Natural Orifice Transluminal Endoscopic Surgery (NOTES) where a natural orifice such as the mouth is used to enter into the body. Performing NOTES some medical problems arise like the limited access to the body and the lack of secure closing devices. Using flexible endoscopic instruments, an angular bending motion (triangulation) of the instrument to manipulate tissue from the side cannot be realized. The technical challenge is based on creating kinematic chains and structures fitted to the medical requirements and special needs of recent operating-techniques in minimally invasive surgery. Our aim is to develop a Multi Arm Snake-Like Robot with the use of SLS. In the proposed paper we are focusing on the tip of the system and the possible kinematics of the robot arm.

II. State of the Art

A. Operation Techniques

Nowadays, different methods and surgeries are performed to treat patients with gastrointestinal diseases:

OR Techniques for Gastroenterology / Abdominal Surgery: Performing a common operation in the gastroenterology means using flexible endoscopes with one or two working channels for treatment of gastrointestinal diseases like early tumors or polyps located at the mucous membrane of the stomach. An Endoscopic Submucossal Dissection (ESD) is performed to remove injured, tumor or necrotic mucosal tissue, in one piece. Hereby flexible endoscopic instruments are used to hold, handle and cut tissue [1]. For the method Minimally Invasive Surgery (MIS), rigid laparoscopes and rigid instruments are used. Removing a tumor inside the lower end of the intestine, e.g., the Laparoscopic Sigma Resection LSR is used [2]. Using only one entry point to the body a Single-Port Laparoscopic Surgery is performed. This means using an artificial incision, e.g., through the belly button to enter inside the human body. The first Single-Port surgeries have been performed by [3] and [4] in 1998. NOTES can be seen as a combination of both disciplines only using natural orifices like the urinary bladder, the vagina, the mouth or anus [1] and [5] to enter to the body.

Research in NOTES robotics: In the field of research different robotic platforms for NOTES are described: such as ViaCath [6], Master [7], DDES and Anubis both described in [8], EndoSamurai [9], Flexible Endoscopic System [10] and others. An overview of the systems and a classification by their modularity and sterilization concept is described in [11] and [12]. Related work in the research field of Snake-like robotics [13] and [14], active cannulas [15] and [16] are not further described in this article.

Flexure hinges: In the current state of the art different design rules and methods for designing with flexure hinges are known, e.g., the compliant mechanisms and the pseudo rigid body model described by [17] and large-displacement compliant joints [18]. Also some basic design rules for Selective Laser Sintering are described in [19].

B. Drawbacks of the State of the Art

Beside the benefits for the patients, the current OR-techniques bear some challenges for the surgeons [20]. For Single-Port Surgery, the access to the body is limited using only one or more trocars. The field of view is limited through the trocar and the instruments are only working through a pivot point (the entry point to the body) and cannot provide triangulation that means to spread from the main direction and to manipulate tissue from the side. So the degrees of freedom are limited to the pivot point and the forces, that can be applied, are limited through the trocars [21]. The same challenge remains for flexible endoscopic instruments for NOTES surgery where triangulation is not possible. For the research systems the remaining problem is the sterilization. Most of the systems do not have a FDA approval [8]. Second the systems are not modular adaptable to different surgeries.

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C. Concept of the Multi Arm Snake-Like Robot System

Using a flexible endoscope as the base for the system, we proposed two concepts in [11] and [12]. In Figure 1. the endoscope (7) is extended by an adapter (5) with at least two or more hollow articulated arms (6). The flexible endoscopic instruments are running through these articulated arms and are additionally guided by a frame (1) above the endoscope.

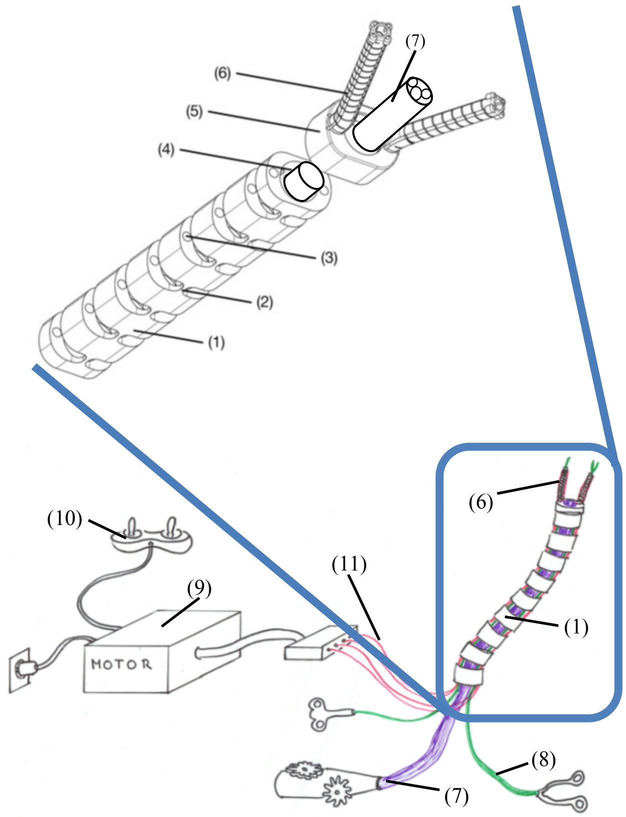

Figure 1. Concept of the Multi Arm Snake-Like Robot System with a frame (1), 1D flexure hinges (2), two instrument channels (3), one channel for a standard flexible endoscope (4), an adapter (5), manipulator arms in helical shape (6), a flexible endoscope (7), flexible instruments (8), motors (9), a joystick (10) and the actuation Bowden wires (11).

The actuation of the articulated arms is realized by Bowden wires, but actuation by push rods is also considered. The latest concept of the whole system is shown in Figure 1. This new system establishes a new manufacturing process and custom made flexure hinges within the robotic system. By using a clip mechanism, the complete system is modular and can be adapted to different flexible endoscopes up to a diameter of 11 mm.

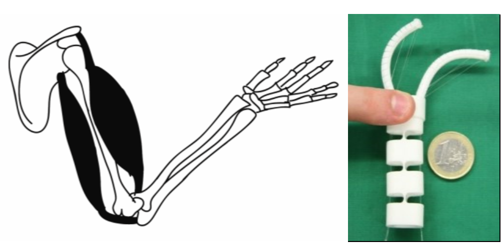

Figure 2. Nature mimicry: the actuation of the system can be compared to the human arm. The cables on the outside (muscles) are actuating the structure inside (bones).

The actuation wires are located at the outside of the structures. This is a nature mimicry (compared to the human arm muscles: the bone inside is manipulated by tendons and the muscles outside with only one force application point for each tendon). By using Selective Laser Sintering it is possible to create individualized parts, custom made for each patient.

III. Material and Methods

In this chapter the requirements for the Snake-Like Arms, the designed and realized structures and the principle of Selective Laser Sintering (SLS) are described.

A. Requirements and Principles: Real/Universal Joints

All the requirements for a Multi Arm Snake-Like Robot are based on medical and technical needs, mostly related to the SLS manufacturing process: 1) the serial kinematic chain should have two degrees of freedom: pitch (left / right) and yaw (up / down) 2) it is hollow inside to guide the flexible instruments up to Ø 2.8 mm 3) the translational movement is realized by the movement along the axis of the instrument inside the hollow arms and 4) the actuation of the kinematics is realized by four cables (Bowden wires).

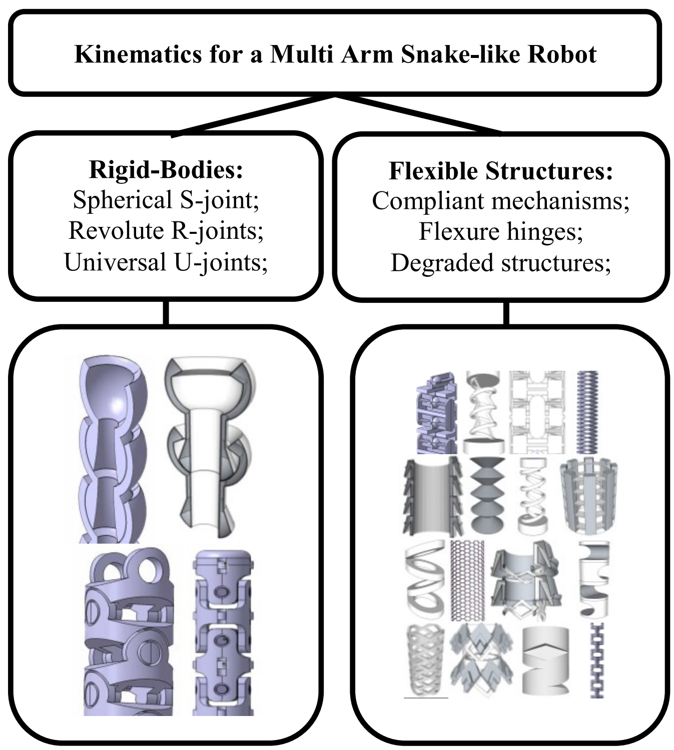

Figure 3. Overview of design principles and realized designs (lower pictures) to build a Multi Arm Snake-Like Robot: left: real joints (manufactured in one part: monolithic), not assembled or glued and right: different shapes of kinematics based on flexure hinges. Structures on the right are flexible joints based on the flexibility of the used material.

Design of the structures: Based on standard principles of basic joints, like spherical, prismatic or universal joints, we researched different serial chains of joints to develop a Snake-like structure for the robot arm. In the following section an overview of the design principles of real joints and flexure hinges and the resulting structures in CAD drawings are shown.

Rigid bodies: Spherical and revolute joints are based on rotational elements with an air gap in between. Movement gets only possible by the play between the parts.

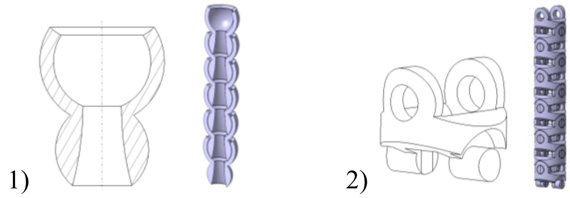

Figure 4. Rigid bodies: spherical- (1) and revolute joints (2), both designed with an air gap of 0.3mm between the moving parts. The structures should be manufactured monolitically (one piece).

Flexible Structures: Flexible structures can be created by different methods. The flexibility is realized by the flexible material properties of the structure. The proposed and tested designs of our structures as followed:

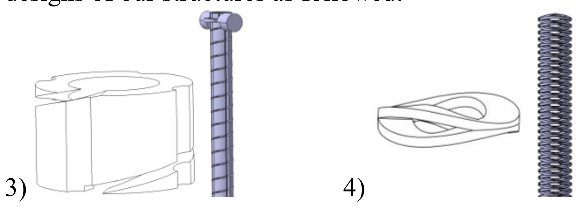

Figure 5. Flexure hinges: helical structure (3) is a cylinder with a continous helical flute, to weaken the structure and to create the necessary flexibility. The cup springs (4) are bended cup springs, the flexibility is created by the change of flexible (loose) parts and stiff (connected) parts of the structure.

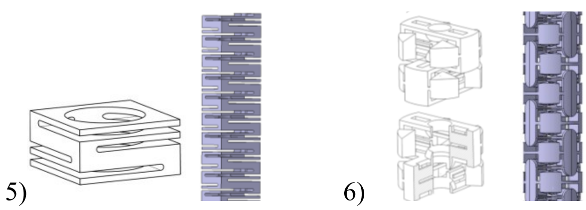

Figure 6. Compliant mechanisms (5) realized by a weakened bar and CR-joints (6) based on rotational flexure joints.

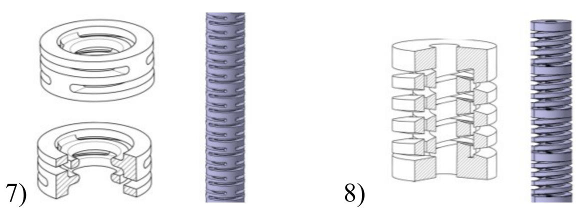

Figure 7. Circular leaf springs (7) are two plane cup springs connected with 90° shift. Two springs with shifted pitch and limited end stop are shown in (8).

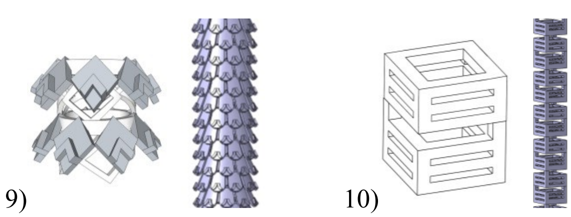

Figure 8. Fir tree principle (9) is a structure with cup springs inside and end stops at the outside and the CT-joint (10) based on translational flexure hinges.

B. Manufacturing

All structures should be realized using Selective Laser Sintering (SLS) with PA2200. Therefore the requirements are defined using this manufacturing method: The layer thickness is 0.1 mm and the minimum wall thickness: 0.5 mm. For the real joints an air gap of 0.3 mm has to be considered. Using Selective Laser Sintering it is possible to create various shapes and complex monolithic parts customized for the technical and medical demands. To manufacture the different concepts we use a Formiga P100 Selective Laser Sintering machine (EOS GmbH, Krailling, Germany).

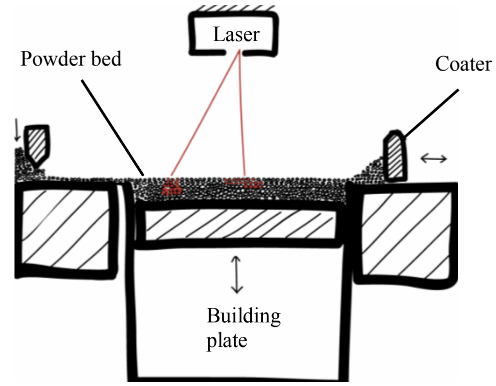

Figure 9. Principle of Selective Laser Sintering (picture source [11]).

The used material is a polymer powder named PA 2200 based on polyamide (PA 12, Nylon) with a particle size about 50 to 60 µm. This polyamide is a typical material for Selective Laser Sintering with beneficial mechanical properties and a high flexibility. The flexibility is very important designing flexure hinges and compliant mechanisms like we propose in this article. Some fundamental mechanical parameters are listed in the following table:

TABLE I. IMPORTANT MECHANICAL PROPERTIES FOR PA 2200

Property	**Value**
Melting temperature (10°C/min)	**176** °C (ISO 11357-1/-3)
Vicat softening temperature A	**181** °C (ISO 306)
Flexural modulus, 23°C	**1500** MPa (ISO 178)
Flexural strength	**58** MPa (ISO 178)
Ball indentation hardness	**78** MPa (ISO 2039-1)
Izod impact notched, 23°C	**4.4** kJ/m² (ISO 180/1A)
Shore D hardness (15s)	**75** (ISO 868)
Strain at break (X Direction)	**24** % (ISO 527-1/-2)
Tensile modulus (X Direction)	**1700** MPa (ISO 527-1/-2)
Tensile modulus (Y Direction)	**1700** MPa (ISO 527-1/-2)
Tensile modulus (Z Direction)	**1650** MPa (ISO 527-1/-2)
Density (laser sintered)	**930** g/cm³

(Based on the datasheet from EOS 2010-09-03:www.materialdatacenter.com)

After the manufacturing process the parts have to be cleaned in a finishing treatment process. Usually glass-beads (particle size up to 50 µm, and a pressure up to 2 bar) are used to remove loose powder from the production process. A great benefit of the material PA 2200 is the certification as biocompatible related to EN ISO 10993-1.

C. Realized Structures

In the next picture one can see the realized structures. All structures are designed by the principles of real joints or flexure hinges and manufactured by Selective Laser Sintering. These principles are connected to a chain of joints and the results are serial flexible kinematic chains. The length of each structure is limited to 40 mm. All structures are manufactured monolithically, which means, they are not glued or assembled together. The first two structures are based on real joints. The rest of the structures are based on different types of flexure hinges.

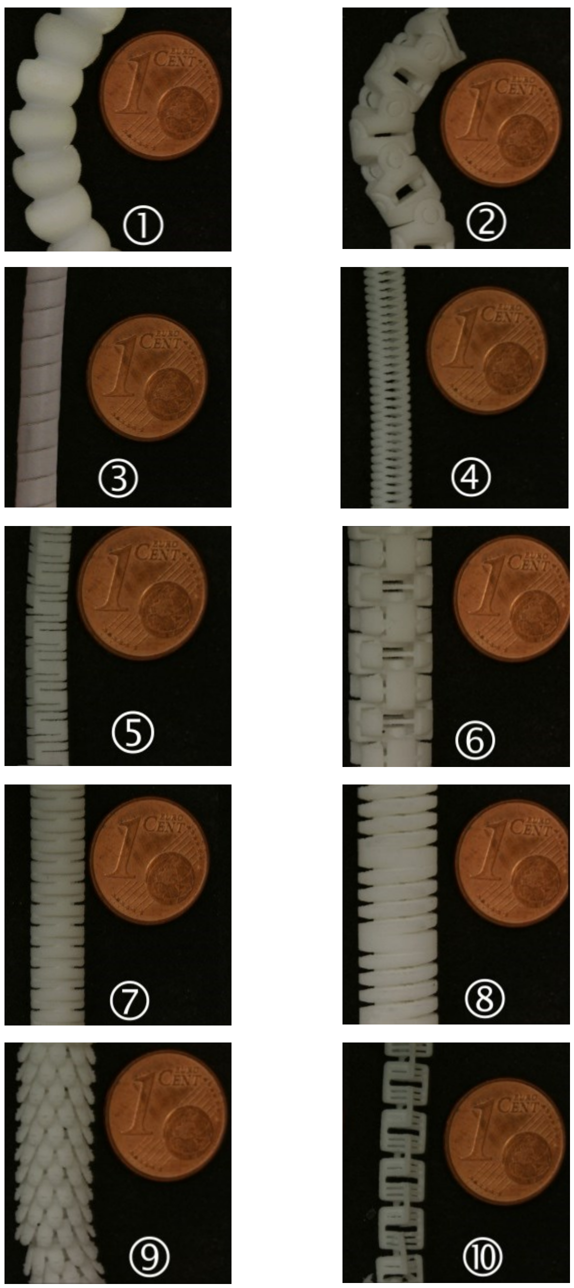

Figure 10. Realized structures: spherical joints (1), revolute joints (2), helical structure (3), cup springs (4), compliant mechanisms (5), revolute CR-joints (6), circular leaf spring (7), spring (8), fir tree principle (9) and translational CT-joint (10).

IV. EXPERIMENT

In order to compare and to verify the different concepts and realized structures of the proposed Snake-like kinematics we analyzed their behavior with and without inserted flexible instrument.

Hypothesis of the Experiment: One or more structures can manipulate a significant higher weight, up to 5 mm, than the other structures.

Methods: Five specimen of each structure were tested with an increasing weight until one of the specimen was not able to lift the weight over a height of 5 mm. Based on the cumulative probability of the binomial distribution (equation 1), five successful attempts out of five tests ensure with a significance of more than 90%, that all further specimen will be able to lift the same maximum weight with more than 60% probability. The last weight that could be lifted, is thereby the characteristic one.

$$P_{n;p}(X \leq k) = \sum_{i=0}^{k} \binom{n}{i} p^{i} (1-p)^{n-1} \qquad (1)$$

Parameters: The weight, which was lifted by the structures, was increased during the experiment by steps of 50 g. The minimum weight was the weight of the base (26 g) and the maximum weight used was 826 g. The increasing weight has to be carried above a height of 5 mm to fulfill the hypothesis.

Setup: In Figure 11 the test setup is shown. The lower end of the structure (1) is fixed to a base (4). To the tip (2) of the structure a force (parallel to the axis of the structure) is applied by using a Bowden wire (3). This force leads to a moment that bends the tip of the structure. The axis of the specimen is located in the moving plane of the actuation wire. To analyze and detect the range of movement of the structure a scale paper was mounted below the structures. The whole setup was build using the module construction kit FAC and Automat-construction system. All specimens are standardized and the setup is built up modular for a quick and easy change of specimen. For the data analysis we used a camera and the scale paper as support. The structure is actuated manually until the height of 5 mm was reached. Step by step we took a higher weight and the experiment was repeated. Five structures n=5 of each concept normed to a length of 40 mm made of PA 2200 have been tested. The experiment was repeated with each 5 structures with inserted flexible endoscopic instrument.

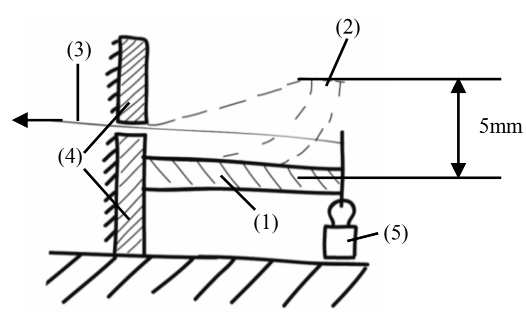

Figure 11. Test setup with tested structure (1) and the actuated tip (2), Bowden wire (3), a base (4) and the weight (5).

In Figure 12. and Figure 13. the experiment process is shown. Figure 12. shows the spiral structure with inserted flexible instrument (gripper). The gripper holds the weight. By pulling the wire the weight gets lifted. The bending movement is related to the design of the structure.

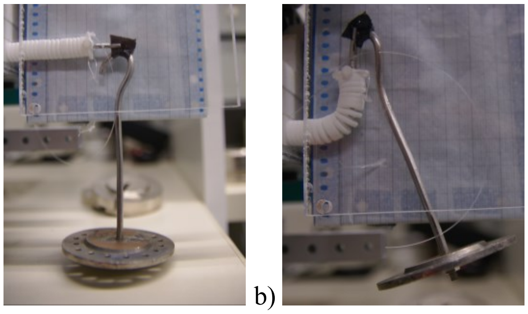

Figure 12. Spring structure (8) in starting position (a) and with the load of the base (b) during the experiment.

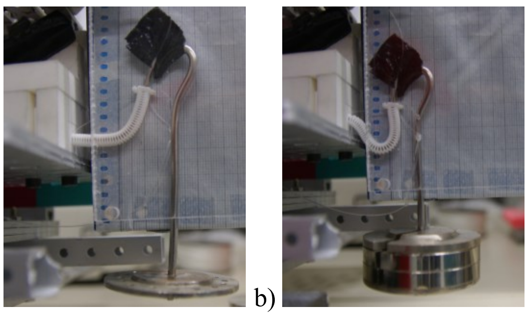

Figure 13. Spring cups during the experiment. a) with the load of the base and b) with base and a weight of 250g.

V. RESULTS

The experiments should verify which of the structure is the strongest and adaptable for the requirements of a Multi Arm Snake-Like Robot. To compare the structures the experiments have been performed without flexible instrument. To verify the structures for the task of manipulating flexible endoscopic instruments, the experiments have been repeated with an inserted flexible endoscopic instrument (a gripper).

In Figure 14. the difference between the structures and the influence of the used inserted instrument is shown. The weights, each structure can lift, are summarized. Some structures are very weak without the instrument like the compliant mechanism and not practical for the use as a kinematic for a Snake-Like Robot Arm.

Interesting are the results of the spherical joints; it is a very strong structure, compared to the others. But experiments without the inserted instruments are not reasonable for the real joints. These structures are weak without the flexible instrument and they do not have a reset force like the structures based on flexure hinges. Due to the necessary play in between the moving parts and the manufacturing process these structures are not applicable for our system. The best structures are based on the designs of flexure hinges: the rotational CR joint, the circular leaf spring, the spring and the helical structure (only with inserted instrument).

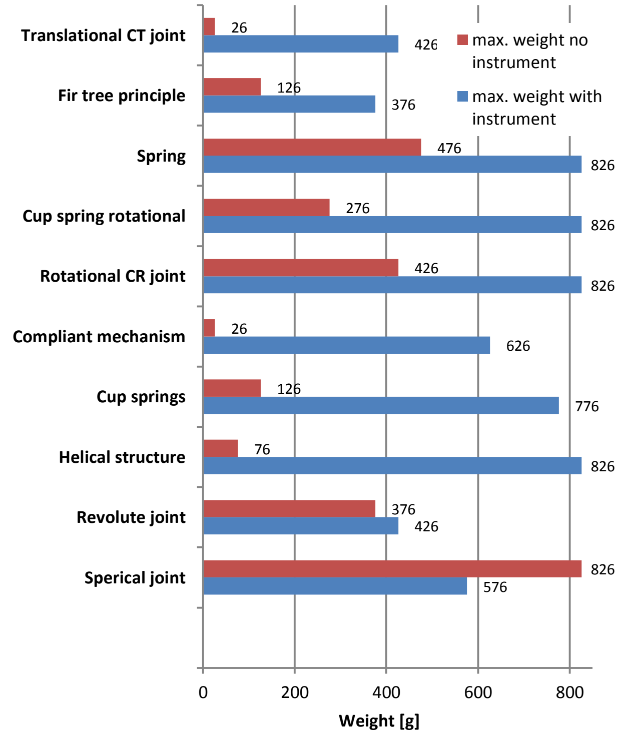

Figure 14. Results of the experiment: maximum weight load compared with all structures. Red is without instrument and blue with inserted flexible endoscopic instrument.

For three structures the failure was caused by fraction (Figure 15. and Figure 16.). The remaining structures yielded too much to lift the weight (Figure 13. b). All the structures based on flexible structures were loaded with stresses above the elastic limit and deformed plastically (Figure 17.).

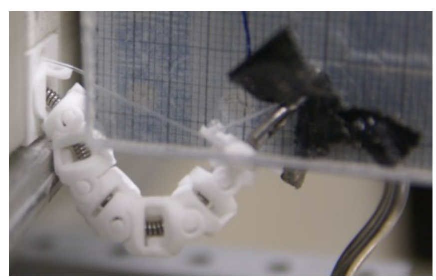

Figure 15. Broken kinematic: revolute joints with inserted instrument, broken at the shaft of the structure with a loaded weight of 476 g.

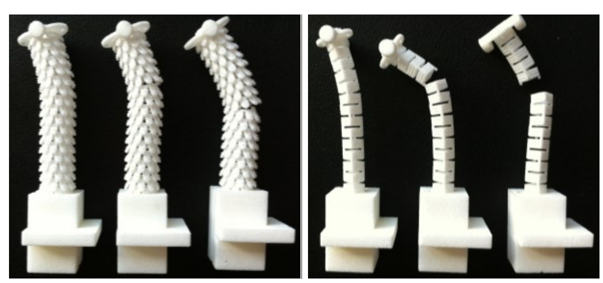

Figure 16. Specimen after the experiment; three of each type: a) fir tree principle and b) CT-Joint structure.

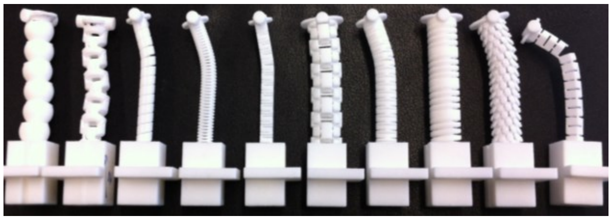

Figure 17. All specimen after the experiments: from left to right: spherical joints (1), revolute joints (2), helical (3), cup spring (4), compliant mechanism (5), CR-joint (6), rotational cup spring (7), spring (8), fir tree (9) and CT-Joint (10).

VI. Conclusion

Our motivation is designing and manufacturing a Single-Port Multi Arm Snake-Like Robot by using the manufacturing method of Selective Laser Sintering. The creation of different small kinematics adapted to the medical needs for manipulation of flexible endoscopic instruments is possible. The great range of variety shows the applicability of SLS as a manufacturing method for small flexible kinematics. Especially structures based on flexure hinges like the helical structure (3) the cup spring structure (4), the rotational CR joint structure (6) and the cup spring structure (7) are able to fulfill the task of a Snake-Like kinematic for a robot arm build to perform surgery inside the gastrointestinal tract. These structures are recommended to optimize for the next version of the tip of the Multi Arm Snake-Like Robot.

The progressed experiments have shown that the laser sintered structures can carry a weight up to 800 g. By characterizing the different structures it's possible to choose the right kinematic for the needs of surgery inside the stomach. And these results are also very important gaining towards a control mechanism for the arms of the robot.

VII. Acknowledgment

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