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Design of a Soft Bio-Inspired Tissue Transport Mechanism*

Vera G. Kortman[1], Jovana Jovanova[2] and Aimée Sakes[3]

Abstract— **In the medical field, it is essential to remove delicate tissues from the body without damaging them or disturbing the surroundings. Current tissue transport mechanisms depend on the tissue composition and shape of the transported tissue, which results in problems such as clogging. This study presents a soft transportation mechanism for tissues inspired by the longitudinal muscles associated with the peristaltic movement of the gastrointestinal tract. The mechanism is designed as a conveying toroid that turns itself inside out in a continuous motion. A fabrication method was developed to manufacture a small-sized silicone toroid, filled with lubricating liquid. Comparable to the peristaltic movement, the silicone toroid adapts its shape to the transported tissue which results in a soft seal around the tissue. The toroid conveys the tissue while locking it at a stationary spot. A prototype was built to evaluate the transport efficiency of the conveying toroid in differently curved pathways. The preliminary experiments showed good transport efficiency, revealing the potential of the proposed soft transport mechanism for medical, and other transport applications.**

I. INTRODUCTION

The transport of delicate objects from confined environments is an urging topic in many industries, especially when manipulating an object remotely. Applications that require this type of transport are exploration and delicate object collection, such as deep sea mining, rescue operations, or surgery [1]–[3]. The field of soft robotics shows potential solutions for sustainable transportation of these delicate or valuable objects by gentle picking them from their surroundings and transporting them without any damage or disruption to their environment [4]. This is in contrast to rigid robotic transport systems. They are often associated with negative environmental impact and transport damage, as they lack an adaptive feature to real-world environments [5].

In the medical field, a soft transportation mechanism for tissues would be of great benefit. Treatment in many medical fields involves tissue removal from the human body. Disturbances, such as tumorous tissue or thrombus, are removed from the operational field in different surgical procedures [6], [7]. Also, suspicious tissue is removed for diagnostic purposes, which requires undamaged samples for optimal analysis [8].

The current trend is to perform surgeries minimally invasive, where small (5-15 mm) incisions are made to insert slender surgical instruments into the human body. A major downside of Minimal Invasive Surgery (MIS) is the reduced access to the operational field, which requires longer, and sometimes curved, pathways to transport the targeted tissue outside the body. Currently, the ‘golden standard’ for tissue transportation in MIS is the use of aspiration catheters. These slender and flexible catheters are able to follow curved paths toward the target tissue, where they apply a suction force to remove the tissues from the body. The main issue with these catheters is their vulnerability to clogging [9]. Clogging occurs when the friction between the target tissue and the catheter’s lumen exceeds the force that can be applied by the generated negative pressure. Research has shown that the ability to transport tissues with these devices is highly dependent on the length of these devices and the tissue composition. Furthermore, the suction force affects not only the target tissue but also the surrounding tissue, which can result in unwanted damage to delicate structures. Previous research showed alternative tissue transportation mechanisms, but their functionality was again influenced by the tissue composition [3], [10]. A major improvement in this field would be a flexible tissue transport mechanism whose transportation success is independent of the friction between the tissue and the transporting shaft. Therefore, this study aims to develop a soft tissue transport mechanism that transports tissue along while being unaffected by tissue composition or shape.

II. DESIGN AND PROTOTYPING

A. Bio-Inspiration: Peristalsis

Inspiration for our novel transport mechanism is taken from the peristaltic movement of the gastrointestinal tract. Fig. 1 shows a schematic overview of the peristaltic movement, highlighting the circular and longitudinal muscles in the tract’s wall. It is relatively easy to understand how a propelling wave of circular muscles’ contractions behind the bolus pushes the bolus forward. However, this type of transport has as downside that it needs to overcome the friction between the tract’s wall and the bolus. More interesting is the contribution of the longitudinal muscles, which is often overlooked [11]. The contraction of these muscles precedes the circular muscle contractions. They shorten the tract gradually before the bolus approaches [12]. The circular muscle contraction acts as sealing of the tract behind the bolus, preventing the escape of the bolus [13]. Prior studies hypothesized different functions for this longitudinal muscle contraction, among which are slipping the tract’s wall over

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the bolus, increasing the density of circular muscle fibers, or rigidifying the tract's wall [11]. Given is that shortening of the longitudinal muscles in front of the bolus 'pulls' the bolus towards the stomach [13]. This means that the bolus translates relative to its original position without shearing along the tract's wall. The bolus is taken along within the longitudinal movement of the tract while being sealed at a stationary spot. This transport method allows for transport without having to overcome the friction between the object and the tract's wall. This, together with the tract's ability to move the bolus in curved pathways and to shape-lock the bolus without damaging, makes the peristaltic movement promising to serve as inspiration for a flexible tissue transport mechanism.

B. *Design Requirements*

Some requirements should be met by our tissue transport mechanism to incorporate similar benefits as the peristaltic movement. In terms of reliability, the transported object should be fixated at a stationary spot to avoid movement relative to the shaft's wall. Illustrated by the peristaltic movement, this fixation can be realized by a shape-lock formed by the adaptation of the wall to the object's shape. In terms of versatility, the transport mechanism should be able to transport objects independently of their composition or shape. The peristaltic movement shows that this can be realized by fixating the object at a spot and moving this spot along the shaft's axis without shearing it along the shaft's wall.

Additional requirements are related to the mechanism's application in MIS. In terms of dimensions, the transport mechanism should fit through the small incisions (5-15 mm) made during a procedure. In terms of flexibility, the transport mechanism should be able to transport in curved pathways to enable tissue transport from hard-to-reach regions.

C. *Design conveying toroid*

We propose a design for a flexible tissue transport mechanism in the shape of a conveying toroid. A toroid geometry is created by extruding a doughnut shape (Fig. 2a). When filling a toroid with a lubricating liquid, it is able to turn itself inside out in a continuous motion. This is the main principle behind the tissue transport mechanism, where the inside of the toroid functions as transporting lumen. The toroid moves forward by everting its membrane. While doing this, the enveloping motion of the membrane transports an object through its inner lumen. When manufacturing the membrane from an elastic material, the toroid adapts to the object inside the lumen. This ability to self-adapt its shape to the transported object makes this mechanism suitable for the universal transport of tissues. Comparable to the peristaltic movement, the conveying toroid shape-locks the object in the transporting lumen by forming a soft seal around the object. Similarly, the object is translated along the longitudinal axis of the lumen while being shape-locked at a stationary spot. This makes the conveying toroid transportation independent from the tissue composition and shape.

The idea of a soft conveying toroid is proposed in earlier literature as a promising soft robot locomotion method to squeeze through holes [14], as a universal soft gripping method [15], [16], or as object transportation method [17]. In these studies, the functionality of the conveying toroid was proved by the use of commercial toys, the so-called 'water snakes'. These toys act like conveying toroids on a hand-size scale, showing the capabilities of a conveying toroid as preliminary prototypes. Additionally, a first attempt was made to fabricate a conveying toroid on roughly the same hand-size scale as a water snake, filled with water or air [17]. This prototype showed the potential of a toroid as a universal

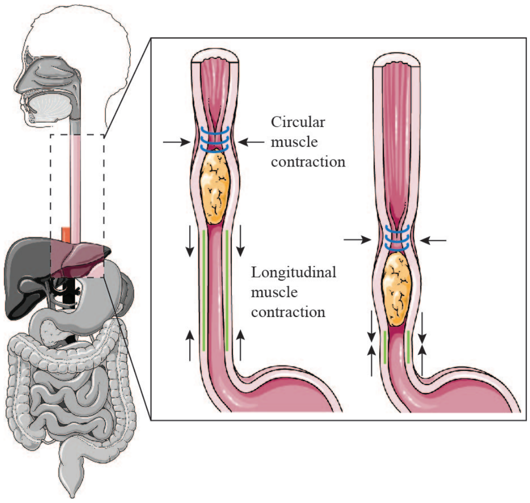

Fig. 1. Schematic overview of the peristaltic movement in the gastrointestinal tract with the circular muscles (blue) and longitudinal muscles (green) highlighted. Contracting the circular muscles seals the bolus at a fixed spot while contracting the longitudinal muscles shortens the tract before the bolus approaches. Figure adapted from Servier Medical Art, provided by Servier, licensed under a Creative Commons Attribution 3.0 unported license.

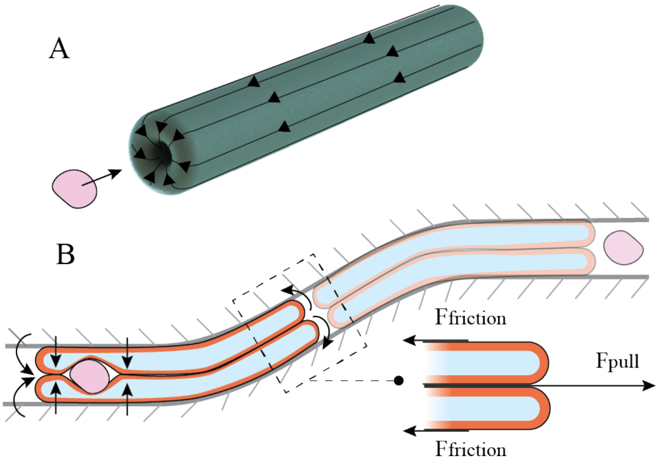

Fig. 2. Schematic overview of the design of a conveying toroid as transport mechanism. (a) The geometry of a conveying toroid. (b) Tissue transport by the soft conveying toroid, translating through an outer shaft. Friction forces ($F_{friction}$) are generated between the outer shaft and the outer membrane of the toroid. The toroid's enveloping movement is actuated by a pull force (F_{pull}) acting on the inner membrane.

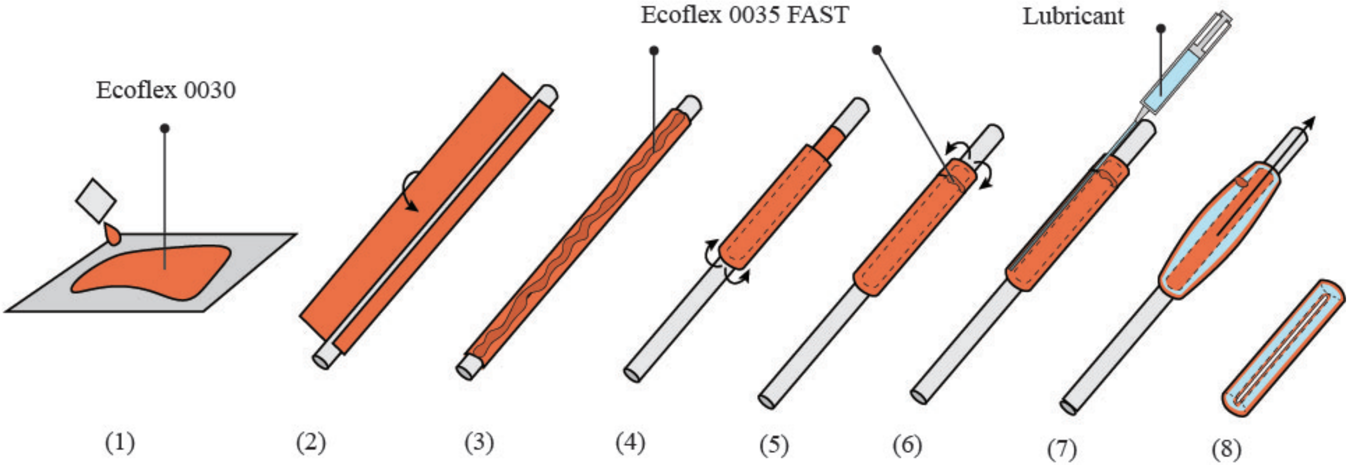

Fig. 3. Schematic fabrication steps of the conveying toroid. Steps 1-5 focus on fabricating a thin-walled elastic toroid, whereas steps 6-8 focus on filling the toroid with liquid.

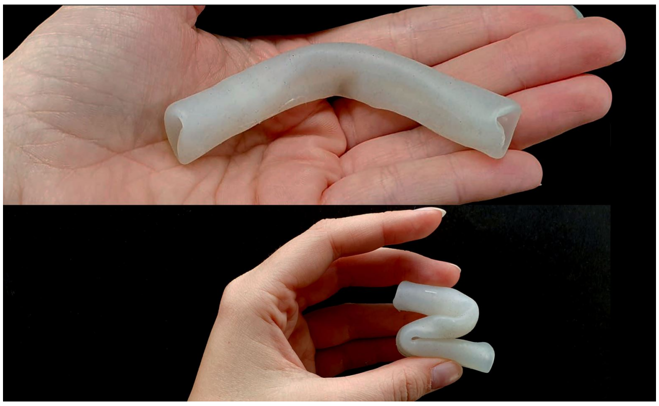

Fig. 4. The final prototype of the soft conveying toroid.

gripper, but the fabrication method was not yet designed to be down-scaled or up-scaled, nor with object transportation in mind. Concluding, the current preliminary prototypes of a conveying toroid show the potential for this mechanism, mainly focused as a universal gripping method, but are not yet designed for customization for specific applications.

To function as tissue transport mechanism, the conveying toroid is placed inside an outer shaft to translate the tissue in the desired direction (Fig. 2b). The toroid starts conveying when a pulling force is applied to its inner membrane. The toroid acts as a roller in contact with the outer shaft. Slip should be avoided to perform an optimal rolling contact. This means that it is essential that the pulling force is not larger than the friction forces between the outer shaft and the toroid. Interestingly, this results in contradictory material properties of the toroid's elastic membrane, as the outside requires high friction forces to avoid slip, while the inside requires low friction forces for smooth conveying. A material should be chosen that maintains the toroid's functionality while allowing small-scale manufacturability.

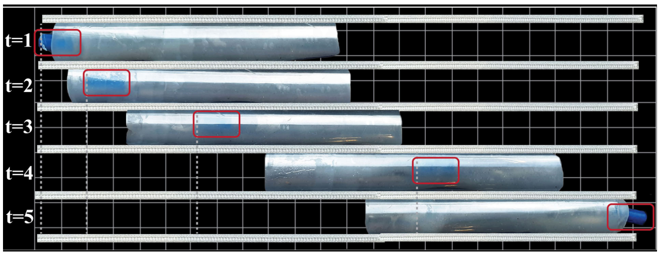

Fig. 5. The final prototype of the conveying toroid transporting a blue cylinder.

D. Fabrication

The fabricating process is divided into two parts; (1) fabricating a thin-walled elastic toroid, and (2) filling the toroid leak-free with lubricating liquid. It was chosen to fabricate the toroid's membrane using silicone due to its easy manufacturability, high friction coefficient and elastic properties. Fig. 3 shows the fabrication steps schematically. First, the uncured silicone (Ecoflex 00-30, Smooth-On) is smeared on a flat surface to create a thin and highly elastic membrane. After being cured, this membrane is wrapped around a 10 mm diameter tube with the ends joined by fast-curing silicone (Ecoflex 00-35, Smooth-On). This results in a highly flexible, thin-walled silicone tube. Subsequently, the lower end of the tube is flipped over and moved towards the top, where the top is flipped over to meet the lower end. The ends are again joined by fast-curing silicone (Ecoflex 00-35, Smooth-On). The toroid is filled with water-based lubricant to ensure low friction at the inside for smooth conveying. This lubricant is injected by a syringe, where after the injection inlet is closed by fast-curing silicone (Ecoflex 00-35, Smooth-On). Finally, the conveying toroid is rolled from the tube.

E. Final Prototype

The final prototype, with a diameter of 12 mm and a length of 100 mm, is shown in Fig. 4. The transported object is conveyed from the inlet to the outlet of the toroid, while the toroid travels its own length at the same time. This means that the object travels two times the length of the toroid, which is in this case 200 mm. Fig. 5 shows how a random object was transported through the conveying toroid.

III. EXPERIMENTAL VALIDATION

The main goal of the experiments was to investigate if the designed transport mechanism was able to transport reliably by assessing its transport efficiency ($\eta_{transport}$) for different curved pathways. The experimental setup is shown in Fig. 6. In this setup, the conveying toroid moved through a PVC outer shaft. This shaft was fixated in different angles by three shaft holders fixed to a baseplate. The conveying toroid was actuated by a pull force generated by a fiber-reinforced PVC belt driving through the inner lumen of the toroid. This type of belt was chosen because of its stiff properties to minimize elastic deformation of the belt. The belt was driven by an actuation wheel, which was again fixated to the baseplate. The actuation wheel was coated with a silicone strip to create sufficient grip with the belt. A circle of degrees was placed beneath the actuation wheel to measure the number of rotations of the wheel. A tensioning rod was added to ensure sufficient tensioning of the belt during rotation. A 3d-printed cylindrical shape with a diameter of 5 mm and a length of 15 mm acted as target object. A camera mounted on a tripod filmed the setup from above.

The transport efficiency ($\eta_{transport}$) [%] is the main performance variable of this experiment. This efficiency is affected by the slip between the belt and toroid, the slip between the target object and the toroid, and sub-optimal rolling contact between the toroid and the outer shaft. The transport efficiency was calculated by dividing the theoretical propelled belt length ($t_{theoretical}$) [mm] by the measured propelled belt length ($t_{measured}$) [mm] used to transport the target object from the inlet to the outlet of the conveying toroid, multiplied by 100% (1). The efficiency is scaled by the elongation coefficient ($\mu_{elongation}$) [-], which counteracts the effect of the toroid's elastic deformation in its longitudinal length while transporting.

$$\eta_{transport} = \frac{t_{theoretical}}{t_{measured}} \cdot \mu_{elongation} \cdot 100\% \tag{1}$$

The measured propelled belt length ($t_{measure}$) is determined by dividing the perimeter of the actuation wheel (P_{wheel}) [mm] by the number of degrees of one rotation, multiplied by the number of degrees the actuation wheel has rotated during transportation ($N_{degrees}$) [-] (2).

$$t_{meaured} = \frac{P_{wheel}}{360} \cdot N_{degrees} \tag{2}$$

The theoretical propelled belt length $t_{theoretical}$ [mm] is defined as two times the length of the conveying toroid (L_{toroid}) (3).

$$t_{theoretical} = 2 \cdot L_{toroid} \tag{3}$$

The transport efficiency was measured for a straight pathway, a 45° curved pathway, and a 90° curved pathway. For every pathway, five measurements were performed. To obtain an equal start position for every measurement, the target object was inserted at the tip for its full length before the start of a measurement. The wheel was rotated to pull the belt through the conveying toroid. The measurement was terminated when the tip of the target object reached the proximal end of the conveying toroid. A camera filmed the measurements from above. Analyzing the video footage gave the number of degrees the actuation wheel had rotated during every measurement.

The transport efficiency for the three different pathways is visualized in Fig. 7. The average transport efficiency with its standard deviation for a straight pathway, 45° curved pathway, and 90° curved pathway were 93 ± 5.6%, 95 ± 0.8%, and 93 ± 1.6%, respectively. A one-way analysis of variance (ANOVA) test shows no significant difference in transport efficiency between the three pathways ((F(2,12)=0.33, p=.7263). The statistical significance was set at an α value of less than 0.05. It should be noted that the object transportation was successful for all measurements.

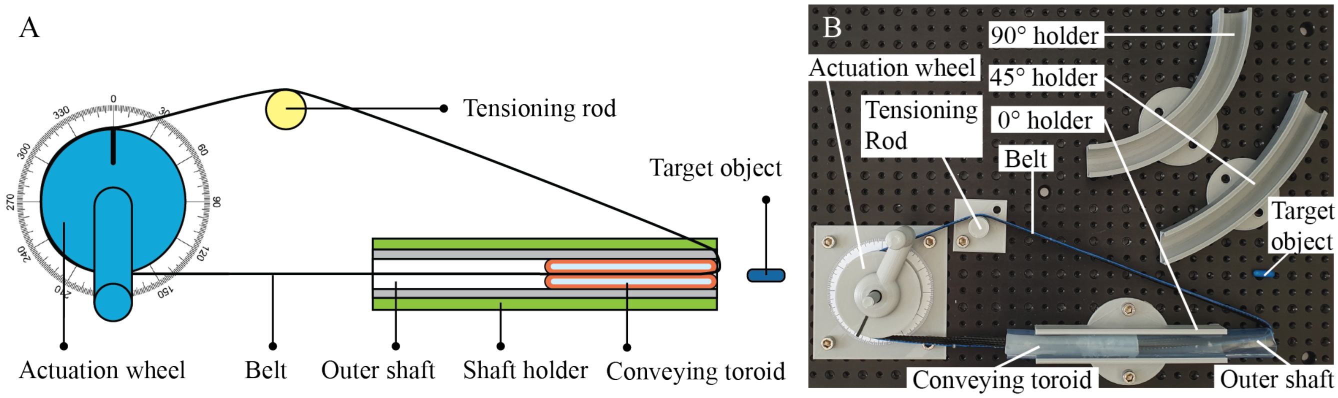

Fig. 6. Experimental setup. (a) Schematic overview of the experimental setup to measure the transport efficiency of the conveying toroid for different curved pathways. (b) Experimental setup

IV. DISCUSSION

This study shows the idea of a soft conveying toroid as a transport mechanism for tissues in MIS. This toroid transports tissue through its inner lumen by turning itself inside out in a continuous motion. The toroid is made of a silicone membrane and filled with a lubricating liquid to facilitate a self-adaptable inner lumen that deforms to the transported tissues. The tissue is fixated at a stationary spot in the lumen, while the conveying motion of the toroid brings the tissue forward. This makes this mechanism independent of the tissue composition and shape of the tissue. On this small scale, it is essential to fill the toroid with lubricating liquid instead of another type of liquid or gas. Transporting large objects might push the inner membranes onto each other, which should generate only minimal friction to maintain smooth continuous rotation.

A prototype was developed to evaluate the transporting performance of the conveying toroid in curved and straight pathways. Transporting in curved pathways would be essential during its use in MIS, as the target tissue is often hard to reach from the incision side. The experiments showed no significant difference in the transport efficiency using a straight pathway, a 45° curved pathway or a 90° curved pathway. Moreover, all transportation attempts were successful. Noticeably, the toroid appeared to stretch during transportation (Fig. 8a). This phenomenon was only observed in transportation over a straight pathway, which could be explained by the potentially larger friction forces between the outer shaft and the toroid during curved transportation. As shown in Fig. 8b, the toroid's membrane is pushed into a smaller radius at the inner side of the curve. This results in the toroid experiencing larger grip in these curved outer shafts, counteracting stretching forces. The stretching of the toroid during transportation is undesirable as this lowers the predictability of the transportation path of the conveying toroid. Another undesirable event observed during the experiments is the formation of inclinations in the outer membrane of the toroid (Fig. 8c). These inclinations hinder the continuous rolling motion of the toroid, which makes the belt slip inside the inner lumen of the toroid. Both events could be solved by pouring uncured silicone on top of a fiber mesh during the fabrication process. This would result in a fiber-reinforced thin-walled silicone sheet as the base for the silicone toroid. The integrated fiber mesh makes the toroid stiff in the longitudinal direction while maintaining its flexibility in the radial direction.

The experimental setup gave only preliminary insights into the transportation performance of the conveying toroid. A larger amount of measurements is needed to provide definite conclusions. The performance measurements could have been influenced by uneven actuation velocities. Although it was tried to maintain an equal velocity for every measurement, the manual actuation could have caused deviations. Also, the manual fabrication of the toroid could have introduced irregularities in the membrane, which might influence the interaction between the toroid and outer shaft.

The performance validation of the conveying toroid should be further evaluated by the influence of different actuation speeds on transportation efficiency. This also provides the possibility to determine the ultimate flow rate of this tissue transport mechanism, which can be compared to commercially available aspiration catheters. Additionally, the transportation performance should be evaluated using ex-vivo tissue samples with different shapes and elasticity.

The manufacturing method of the conveying toroid is suitable for fabrication in small dimensions, but also al-

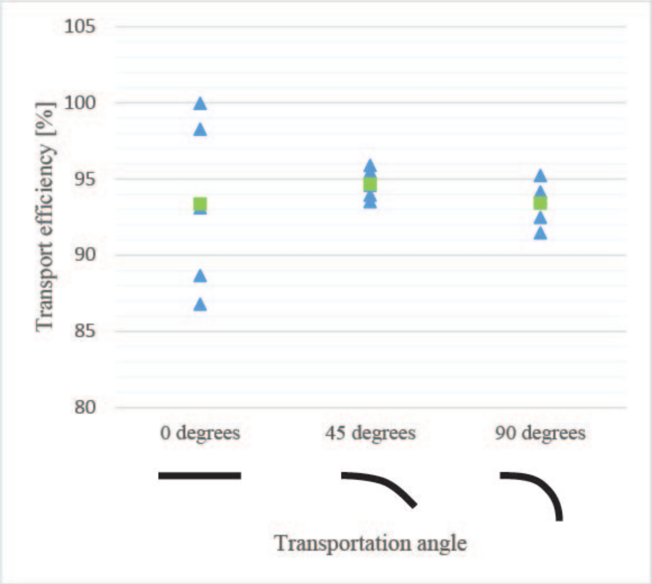

Fig. 7. The transport efficiency of the conveying toroid per transportation angle. The blue triangles represent the individual measurements and the green boxes represent their average.

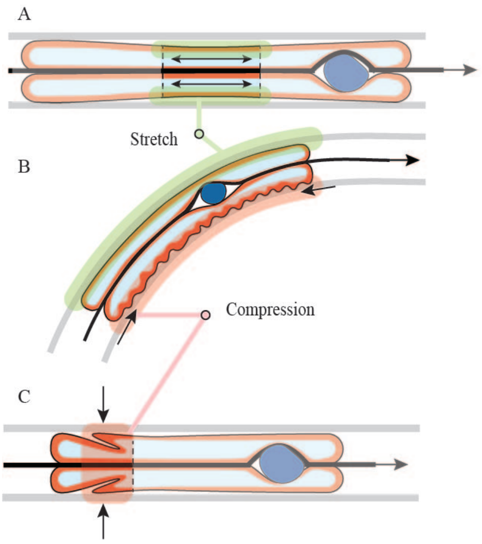

Fig. 8. Observations impeding the predictability of the tissue transportation of the conveying toroid. Parts of the membrane in stretch are highlighted in green, where parts of the membrane in compression are highlighted in red. (a) Elongation of the conveying toroid. (b) Higher grip between the curved outer shaft and the conveying toriod by smaller inner radius. (c) Inclination of the toroid's outer membrane hinders the continuous rolling motion.

lows fabrication in large dimensions. The scalability of this soft transport mechanism opens possibilities for many applications that require delicate object transport. The outer diameter could be changeable for applications in different regions of the body. Another application could be the deep seabed mining of mineral-containing nodules, which is currently associated with a negative environmental impact. The hydraulic machines used to retrieve the nodules create turbidity in the water column, crush the seabed and deposit sediments [1]. The soft conveying toroid would adapt its shape to the nodule without disturbing the surrounding sea bed fauna.

Fig. 9 shows a preliminary prototype of the conveying toroid integrated into a handheld device, featuring a future view of this tissue transport mechanism in practical use.

V. CONCLUSION

In this study, a novel solution was presented as a tissue transportation mechanism in MIS. A small-scale conveying toroid was fabricated that transports tissue through its inner lumen when translating through an outer shaft. Contrary to existing solutions, this transport mechanism works independently of tissue composition and tissue shape.

In future work, we want to develop the toroid's ability to grip the tissue before transportation. Although this study focused on the transportation mechanism of the conveying toroid, the toroid intrinsically incorporates a gripping mechanism. As described in previous research [15]–[17], the conveying toroid swallows an object inside when its tip is in contact with the object.

Additionally, steerability should be added as extra functionality of the conveying toroid to bend the mechanism actively in curved pathways. As the outer shaft forces the conveying toroid in its transport direction, this feature could be added by focusing on the steerability of the outer shaft.

These additional functionalities contribute to revealing the full potential of the conveying toroid. The simple design of the manufactured prototype shows the potential for large-scale implementation of the conveying toroid as a soft transport mechanism for tissues in MIS.

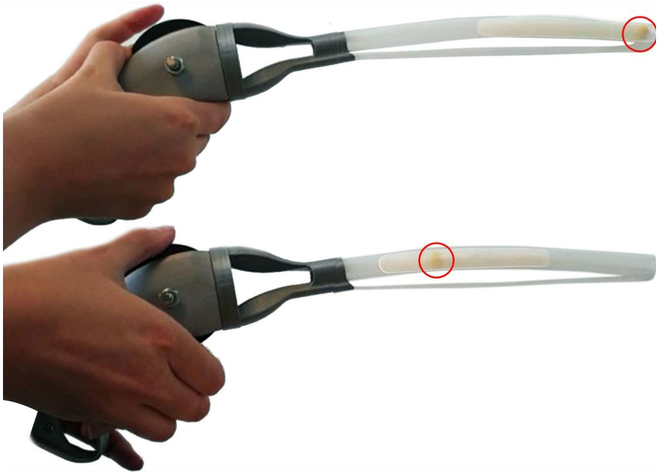

Fig. 9. A preliminary prototype of the conveying toroid integrated into a handheld device

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