# Technical Requirements and Conceptualization of a Soft Pneumatic Actuator Inspired by Human Gastric Motility

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***Abstract*—This paper presents the technical requirements and conceptualization of the actuator inspired by human gastric motility. Key features of the stomach motion are explored and described in the viewpoint of engineering. A soft robotic model of the stomach is conceptualized for the purpose of in vitro simulation of the contractile motion of the stomach. Soft lithography and lost wax methods are implemented in the fabrication. Our experiments show that the proposed robot is able to reproduce the required contractile movement.**

***Keywords*— soft actuator; soft roboitcs; pneumatic actuator; human gastric motility**

## I. INTRODUCTION

Human gastric motility is central to proper nutrition, reliable drug delivery, glucose homeostasis with diabetes mellitus, and gastroparesis [1]. From an engineering perspective, the stomach has the capability to mix, grinder, store, and empty the gastric contents. All these mechanical functions are achieved by the peristaltic activity of the stomach surface. The peristaltic activity consists of circumferential waves that propagate continuously from the middle part of the stomach to the pylorus. This mode of actuation is unconventional to engineering.

There is a need for an actuator that has the capacity to reproduce the mechanical function of stomach. In food and medicine research, a realistic stomach simulator can provide details of the digestion process of pharmaceuticals and food under a range of gastrointestinal conditions including the frequency, amplitude and force of contraction [2]. It serves as a controlled environment to conduct repeatable experiments. Furthermore, it offers a testing platform to analyse and validate the performance of surgical tools such as catheters and endoluminal robots developed for gastric treatment [3]. It reduces the number of in vivo tests that are costly and time-consuming

There have been a few actuators that reproduce the mechanical function of the stomach. However, those models simplify the stomach movement strongly. There is a robot stomach using a barrel and piston structure to squeeze the food [2, 4, 5]. Glassed beakers with a magnetic stir bar inside are applied to mix and massage the food [6]. Another prototype is made of a rubber surface with ropes placed around the surface to mimic the shape and function of the stomach. The contractile movement is generated by pulling the ropes. However, a rhythmic peristaltic motion is not achieved. [3]. Another example is a cone-shaped rubber tube. Four rollers move against its surface to achieve the contractile motion. However, the deforming boundary is not a circular contraction [7].

Soft robotics a growing research field [8]. The key feature of soft robotics is the compliance of its material, making it possible to achieve some functions that rigid robots cannot realise. Materials play an important role in soft robotics, because they determines fabrication, actuation methods as well as applications. There are several feasible materials for the fabrication including the soft elastomeric material hydrogel, shape memory alloys (SMA), polydimethylsiloxane (PDMS). A range of stimuli including the electrical charge, pressurized fluids and heat are applied in terms of actuation materials. The advantage of this new class of robotics is the inherent softness, making it adaptable in unstructured environments or in contact with the objects of unknown conditions. Other benefits such as low cost and ease of fabrication promote the research on their applications. A special feature of this type of robots is that a soft-bodied actuator has an infinite number of degrees of freedom. This poses challenges in the modelling, sensing and controlling of a soft robot.

The compliance of soft actuator makes it possible to achieve a large deformation similar to the contractile motion of the stomach wall. This feature contributes to the research presented in this paper. The pneumatic operation is commonly applied to manipulate soft actuators. The ease of fabrication and low cost of the material allow for an iterative design. The geometry and movement of stomach offer the quantitative and qualitative guidance to the technical requirements and conceptualization.

This paper presents the technical requirements and conceptual design of a soft pneumatic actuator inspired by human gastric motility. Key features of the stomach are explored from an engineering perspective, and the technical requirements for the soft actuator are specified. A prototype of the conceptualized soft actuator is designed and fabricated. The design is then validated experimentally.

## II. THE FORMULATION OF TECHNICAL REQUIREMENTS

The engineering design of the anthropomorphic structure is achieved by making simplifications of the biological system [9]. Some aspects of gastric motility are introduced into the mechanical field. The feature of human gastric motility is the peristaltic movement serving for the mixing, breakdown and the emptying functions. In the human stomach, peristaltic waves commonly travel through the organ and at a rate of approximately 2.5 cm/s. The waves are initiated at a low frequency of 3 cycles/min at the pacemaker located at the middle part of the stomach [10]. The boundaries of stomach offers a gentle massage on food bolus. The movement is triggered by the electric signals [11].

The technical requirements of the soft robot stomach have been developed according to the geometry and motility of the healthy stomach. Key features were summarized in the Table I. The relative occlusion of ACW (antral contraction wave) was defined as

$$\alpha = \frac{d}{D} \tag{1}$$

where $d$ is the deformed diameter and $D$ is the original diameter. The force exerted on the food bolus varies from 0.2 to 2N, depending on the fasting or fed state. The technical requirements of the force adopted this range. In addition, the air pressure inside the stomach was assumed constant, because the slight changes in the value of the pressure are unimportant factor in the digestion process. According to the model from the literature [1], the gastric area where peristalsis occurs (gastric body and antrum) can be divided in three regions depending on the levels of ACW occlusion. In the proximal region ranging from 140 to 100 mm of distance to the pylorus, the relative occlusion of ACW ($\alpha$) decreased linearly from 1.0 to 0.6. In the media region ranging from 100 to 60 mm of distance to the pylorus, the relative occlusion of ACW ($\alpha$) remained constant with a value of 0.6. In the distal region, the relative occlusion of ACW ($\alpha$) decreased linearly reaching 0.1 at the pylorus.

TABLE I. THE SUMMARIES OF KEY FEATURES

| **Main Features** | **Values** |
|---|---|
| One ACW lifetime | 60s |
| Time gap between two neighboring ACWs | 20s |
| Frequency | 3 |
| Velocity | 2.5 mm/s |
| Maximum occlusion | 80% |
| the diameter of stomach | 2-10 cm (at the fed state) |
| The force on the surface | 0.2 - 2N |
| The pressure inside | constant |
| Starting point | About 15cm from pyloric valve |

## III. CONCEPTUALIZATION AND FABRICATION PROCESS

The conceptual design of the soft robot stomach is implemented by using conventional 3D computer-aided design (CAD) software such as Creo and Solidworks. The fabrication process largely depends on the chosen material. Since the soft robotics is a young research field, the design and fabrication methods are mainly based on the intuition and the empirical experience of experts. There are mainly three types of fabrication processes. They are lamination-based casting, retractable pin casting, and lost wax casting[12]. The selection of fabrication methods relies on the design structure and technical requirements.

The elastomer material is selected for this research. The main reasons is that this type of material has the capacity to achieve a larger deformation than other types of materials. A pneumatic system is developed to operate the actuation.

### A. Conceptual Design

A three-dimension conceptualization was shown in Fig. 1.The stomach shape was designed as a series of circles with varying diameters. The rings as a framework were connected together to form the three-dimensional shape of the stomach. Based on this view, the conceptualization of the robot stomach represented an axisymmetric tubular geometry with a centerline and six auxiliary planes perpendicular to it. This shape was generated by joining each circular slices in auxiliary planes that are perpendicular to the centerline. Moreover, the centers of these circles were on the centerline. Actuator modules were developed by mimicking single slices as shown in Fig.2. This design was derived from the idea that a stomach robot can be regarded as an array of sliced modules stacked together along and normal to an imaginary central line.

The ring-shaped actuator was the single module of the actuation. One circular air channel was inside the module in Fig. 3(d). The vertical cross section of the module was a

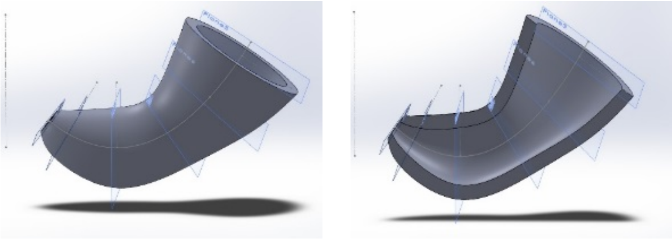


Fig. 1. The conceptual design of the soft stomach robot.

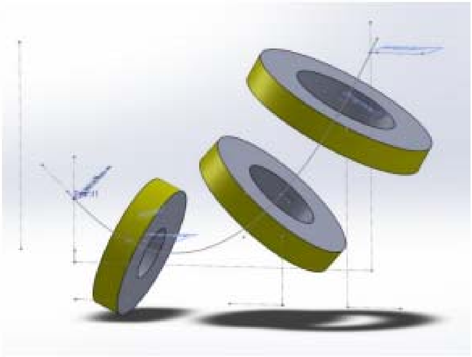
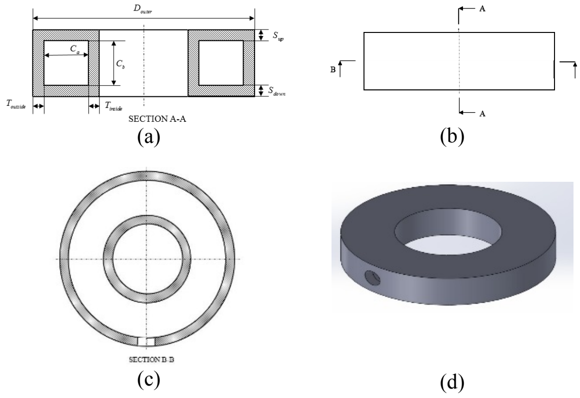


Fig. 2. A series of single layers made up of a stomach robotics

rectangular with two squares, and the horizontal cross section is an annulus as shown in Fig. 3(a) and 3(c), respectively. The detailed sizes of the design were summarized in the Table II. The sizes determined by our intuition fall within the range of average stomach. The benefit of this design was to keep the pressure constant on the chamber surface compared to that of the multiple chambers in one module. Despite this advantage, the inherent delay of air transportation may cause the uneven deformation during the inflated process. The circular contraction depends not only on the constant pressure on the inside chamber surface, but also the isotropic properties of the material. The soft actuator was placed in a rigid housing, which constrained the motion of the outside wall of the cylindrical module.

A three-layer module was designed, which comprised three single modules stacked together concentrically. The cross section of this module in the vertical direction shows in Fig. 4. The intention of developing this version were to identify the effect of neighbouring modules with different pressurized air inside and to determine how to coordinate them to form the motion similar to that of the stomach. The inside diameter and the outside diameter refer to the diameter of inside and outside wall respectively and the sizes of them were the same with that of the one-layer module. The chamber spacing was the thickness of the wall of neighbouring chamber, which was 10mm in this case.



(a) (b) (c) (d)

Fig. 3. The one layer actuator design.

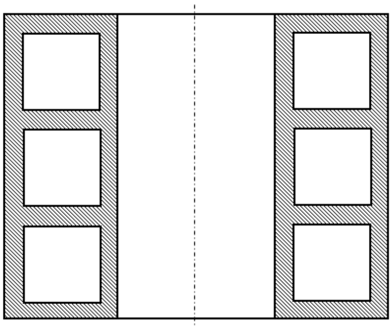


Fig. 4. Schematics of three-layer module.

TABLE II. THE SPECIFICATIONS OF THE MODEL

| Name | Size |
|---|---|
| Chamber size $C_a \times C_b$ | 10x10 mm$^2$ |
| Inside diameter $D_{inside}$ | 40 mm |
| Inside wall thickness $T_{inside}$ | 10 mm |
| Chamber spacing $S_{up}$ $S_{down}$ | 10 mm |
| Outside diameter $D_{outside}$ | 60 mm |

### *B. The fabrication of the conceptual design*

The material for the fabrication is silicone rubber (Smooth-Cast, Eco-flex 0030), a type of elastomer. The uncured rubbers are mixed with the ratio of 1A:1B by volume and cured at the room temperature. It takes four hours to turn the uncured rubber into desired models against moulds.

The fabrication of the one-layer module took two steps. The first step was to pour the uncured mixed rubber into the mould and to form the upper part of the module with one open chamber. The second step was to seal the chamber by placing the upper part above a bath mould filled with uncured rubber. This type of silicon rubber has the feature of gluing together without changing the properties. In additional, the air inlet was formed by the pillar-shaped part of the mould. All these moulds were 3D printed using ABS material. The schematics of this process was shown in Fig. 5. The rigid housing wraped the model to constrain the movement of outside wall and the inside wall remained flexible.

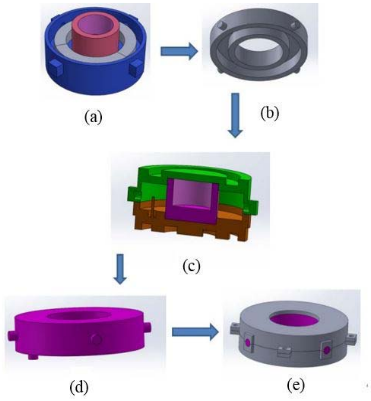


Fig. 5. Schematics of the single layer fabrication process

The lost wax method was applied to create three-layer module with the same diameters. The similar fabrication method as that of single layer was applied. However, the resultant surfaces were not smooth and seams were evident due to the misalignment in the glued process. The main fabrication process contained three steps as shown in Fig. 6. The first step was to create the three layers with open chambers against the customized mould. The second step was to create the wax moulds. The wax moulds were cast in the moulds fabricated by the rubber, because the rubber moulds have the capacity to accommodate the fragility of the wax. The third step was to form the outside surface of the model with three wax moulds sealed inside. The model at this stage containing the wax was to boil in hot water. This operation did not cause any noticeable changes to the properties of rubber. As the datasheet shows, the material can sustain temperatures of up to 200°C. Prior to the boiling step, three holes were pierced on the surfaces of each layer. The molten wax flowed through the holes. The tubes were glued to the chamber through each holes The final model was placed into one rigid housing to constrain the outside wall movement as shown in Fig. 7.

## IV. THE TEST SETUP

Two tests were conducted to validate the concept. The first test was on the one layer model. The experimental setting included one syringe, one ruler and one camera. This test gave the qualitative understanding about the performance of this model under pressurization. The test was to press the synergies to inflate the single layer actuator. The preliminary test was conducted as shown in Fig. 8.

The next test schematics is shown in Fig. 9. The pneumatic system included two on-off normally closed valves. The valve can be switched at the voltage of 24V. In addition, there was one pressure sensor detecting the inside chamber pressure at the frequency of 50Hz. In addition, one camera was right above the chamber capturing the movement. The deformation of the acuator was extracted from the video by the software ImageJ. This software is accepted by the soft robotics research. The measurement process is first to draw the basic scale and then to draw the line which is desired to measure. The software and mthod is accepted in soft robotics.

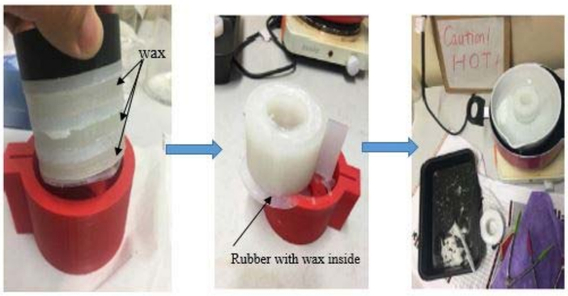


Fig. 6. The process of the lost wax method.

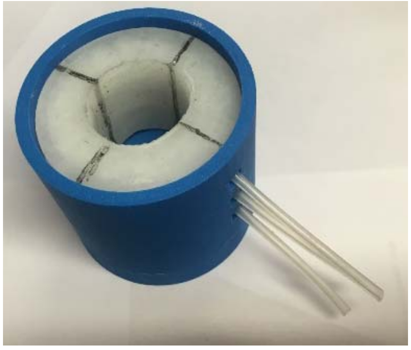


Fig. 7. The physical prototype of three-layer actuator.

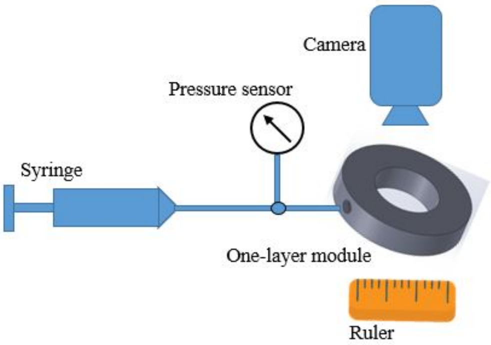


Fig. 8. The preliminary test on the one-layer module

The protocol of test two was about the valve sequencing. The programme controls the inflation time and deflation time of the pneumatic system. The camera right above the chamber filmed the whole process of deformation. The air source, a the mini motor pump was always on. Valve one V1 was responsible for allowing the pressurized air flow into the chamber. Valve V2 was responsible for the deflation. Initially, V1 and V2 were off for 0.25s. Then V1 was on and kept on for 0.25s, after which V1 and V2 kept off and the Arduino recorded the pressure during 0.25s. Due to its frequency of 50Hz, a set of twelve values were recorded to calculate average pressure. Then V1 turned on for 0.25s and then off sealing the chamber and the pressure sensor measured the values. This process was repeated five times, so five sets of pressure values were recorded during inflation process. After the inflation process, the V1 was always off. V2 was manipulated to release the air inside the chamber. The V2 was on for 0.25s, after which V2 was off and the pressure sensor began to record the pressure during a period of 0.25. After that, V2 was again on for 0.25s and then was off for 0.25s during which he pressure was measured. This process was also repeated five times. The inflation and deflation were achieved one round.

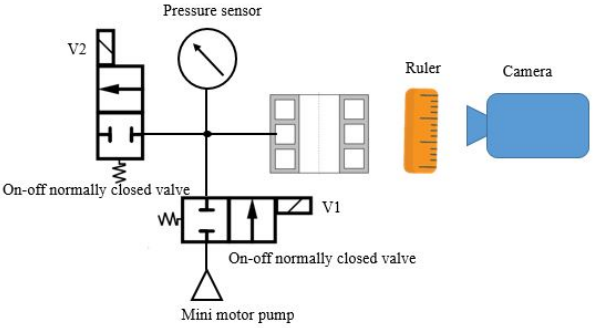


Fig. 9. The schematics of the experiment on the three-layer module.

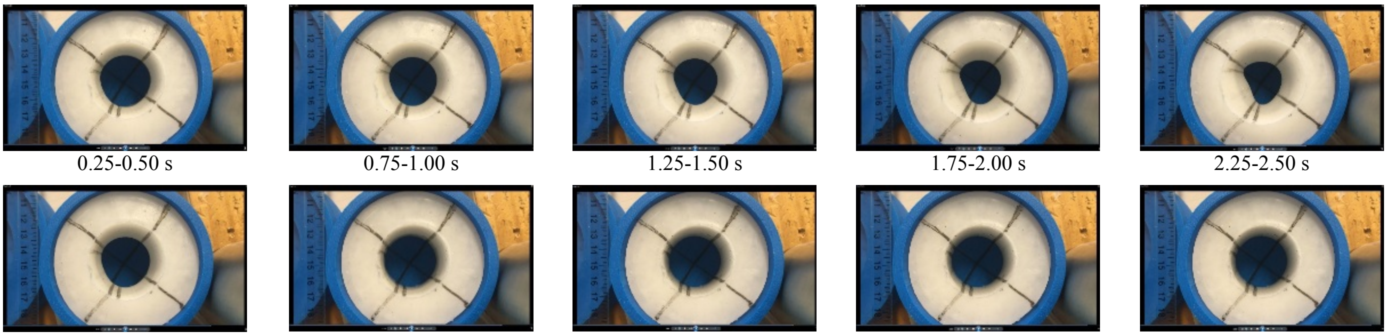

0.25-0.50 s
0.75-1.00 s
1.25-1.50 s
1.75-2.00 s
2.25-2.50 s
2.75 – 3.00 s
3.25 – 3.50 s
3.75 – 4.00 s
4.25 – 4.50 s
4.75 – 5.00 s

Fig. 10. The deformation process of the three-layer module.

## V. RESULTS AND ANALYSIS

In the first test on one-layer module, the qualitative understanding on how it deforms was obtained. Initially the inside wall contracted in a circular shape and then the contracting surface deformed arbitrarily because the air chambers expanded in the limited space.

The degree of deformation of three-layer module depended on the inflation time as shown in Fig. 10. This process started from the isotropic deformation. The linear deformation in the circular shape was of our interest in this research, because the deformation of the target organ mainly was circular shape. The relationship of pressure and surface deformation is plotted in Fig. 11. According to the data recordings, the inside diameter decreased from 4 cm to 2.5 cm when the pressure rose to its peak at 17.5 KPa. The occlusion ratio was achieved to near 40% in this case, while the value was expected to be within the 0% - 80%.

## VI. CONCLUSION

This paper described the technical requirements of the proposed soft robotic stomach and presented one conceptual design of ring-shaped actuators. The fabrication methods were discussed. The preliminary test was conducted which shows the feasibility of the required contractile movement. To improve the initial design, a number of design variables will be tuned and the range of the commanding pressure will be found.

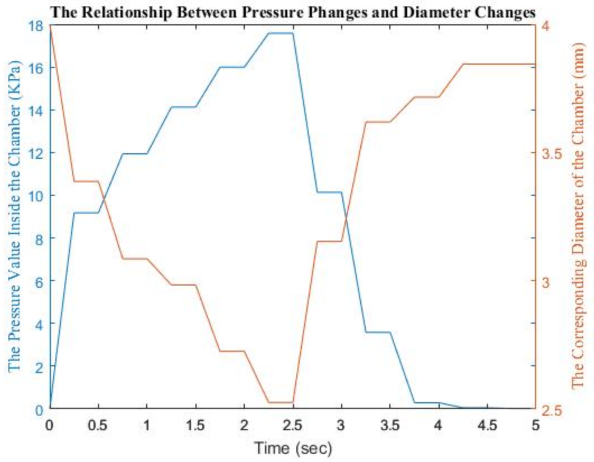


Fig. 11. The relatinoship between pressure changes and diameter changes

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