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HOW TO BUILD A SYNTHETIC DIGESTIVE SYSTEM FOR MARVEL'S VISION

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ABSTRACT

Vision is a synthezoid (android or synthetic human), a member of the Avengers, and constantly striving to be more human. In the films of the Marvel Cinematic Universe, Vision is based on advanced robotics and bioengineering technologies. However, his body contains biological cells, and his external appearance consists of eyes, a mouth, a nose, teeth, and fingernails; traditional human attributes. Unlike humans, Vision does not eat as his metabolic energy requirements are met by a fictional alien artefact known as the Mind Stone. Nonetheless, given that Vision has eyes and a tongue, could he also have other organs? Does his body contain the organs for a synthetic digestive system? And if so, how would these organs meet his body's metabolic energy needs? In this paper, we show how advancements in soft robotics (compliant robotic technologies made from highly deformable materials) can be combined to build an artificial digestive system. We consider the primary systems of the human digestive system – the oesophagus, stomach, intestines, and waste disposal. We show that an artificial digestive system is possible, but additional technologies are needed to support the underlying soft-robotics technologies.

PROLOGUE

As he carefully reads the instructions, he fails to notice the over-boiling pot to his left. Suddenly he catches a glimpse of the pot spewing hot, red liquid all over the stove. He grabs a towel, turns down the heat, and starts cleaning up the mess. Cooking can be stressful at the best of times. And it's even more so for Vision, someone – something – that has never eaten before. Oh, how he was dreamed of the sensation of eating and tasting food! He seeks solace in the hope that his future love – Wanda Maximoff – will enjoy his first attempts at cooking paprikash.

INTRODUCTION

In the superhero genre, there isn't a typical superhero. There are human superheroes such as Steve Rogers and T'Challa. There are alien superheroes such as Thor and Supergirl. In addition, there are synthetic superheroes such as Vision – a synthezoid (or android) – who is a member of the Avengers, and the epitome of the synthetic superhero.

Vision has a rich history in the comic books. Vision first appeared in the Golden Age of Comic Books (1938 – 1956), depicted as an alien law enforcement officer. The character first featured in *Marvel Mystery Comics* (1939) #13 in November 1941 [1]. Some years later, the character resurfaced in *Marvel Super Heroes* (1967) #13 [2] and *the Avengers* (1963) #57 [3]. It is in these issues that Vision is presented as a synthezoid or synthetic humanoid. In the 1982 comic book mini-series *Vision and the Scarlet Witch* #1-4 [4–7], Vision is portrayed as husband to Wanda Maximoff (the Scarlet Witch). The couple have two children – Wiccan and Speed. In the more recent comic book series *Vision* (2015) # 1-12 [8–19], Vision creates a family in his own image. Although Vision is a synthezoid and by definition an "it," Vision is depicted as male in the comic books. Therefore, we refer to Vision using the personal pronouns "he/his/him" in this paper.

Vision in the MCU

Vision is a prominent character in the Marvel Cinematic Universe (MCU) – the most successful film franchise of all time – and his powers include flight, super-strength, and matter-phasing. The MCU's Vision is somewhat based on the comic book literature (As of Feb. 2021, Vision has featured in over 440 comic book issues). Nevertheless, MCU screenwriters have taken liberties with the source materials.

In the MCU, Vision has played an integral role, due in part to the presence of the Mind Stone in his forehead. The Mind Stone is one of the six Infinity Stones that Thanos sets out to collect in the 2018 film *Avengers: Infinity War* [20]. In the comic books, a "solar gem" can be found in his forehead rather than the Mind Stone. Both artefacts fulfil similar roles as they provide Vision's body with metabolic energy or fuel. Peculiarly, Vision does not need to eat anything, something that he points out in Episode 2 of the Disney Plus series *WandaVision* [21].

In the MCU, Vision's creation is explicitly documented. He was co-created by a host of characters including Ultron, Tony Stark, Bruce Banner, and even Thor in the 2015 film *Avengers: Age of Ultron* [22]. However, the technology needed to build or "bio-print" his body comes from Dr. Helen Cho in the form of a synthetic tissue-printing cradle technology. His body is made of three main components – biological cells, vibranium (a fictional biocompatible element), and the Mind Stone.

In the comic books and the MCU, Vision strives to become more human. For instance, in the 2016 film *Captain America: Civil War* [23], Vision wears human clothing like the other Avengers, and he tries his hand at cooking paprikash for fellow Avenger Wanda Maximoff. While cooking, Vision points out that he has problems deciphering if his culinary skills are up to scratch given that he has never eaten anything before. Although the Mind Stone provides an almost endless supply of energy to the synthezoid, this does not necessarily mean that he does not have a digestive system.

From Vision's appearance, we know that the regenerative cradle "bio-printed" eyes, teeth, a tongue, and fingernails (all body parts possessed by actor Paul Bettany). In *Captain America: Civil War,* Vision mentions that even his amygdala is synthetic [23]. As the cradle made eyes and a synthetic brain, it is certainly possible that the cradle could produce synthetic equivalents of other human organs and sensory systems. In *Avengers: Infinity War* [20], Vision is impaled with a staff by villain Corvus Glaive, causing him intense pain but does not lead to blood loss. The sensation of pain indicates that Vision has a nervous system with pain receptors.

Given the absence of blood loss, does this mean that Vision does not have a human-based circulatory system? Such a system would be imperative for the distribution of key nutrients and sustenance for the cells in Vision's body. Perhaps the vibranium bonded to the cells negates the need for nutrient transport or mineral uptake, and the fictional element might transduce the Mind Stone's energy into metabolic energy for the cells in Vision`s body. However, a real-world solution for metabolic energy for Vision could not use vibranium and the Mind Stone since neither actually exist.

A synthetic digestive system for Vision?

This leads us to the central question of this paper: would it be possible for Vision's body to extract energy and nutrients from food using a synthetic digestive system? In other words, would a synthetic digestive system generate sufficient energy for Vision to facilitate normal daily activities (beyond being an Avenger) such as walking, talking, moving, hearing, seeing, and other basic functions that are activities of daily living (ADL)? In addressing this question it's important to note that the body's metabolic energy is supplied by the molecule adeno triphosphate (ATP), which is made from sugars and involves a number of biological processes unrelated to the digestive system [24]. It is conceivable that the Mind Stone acts as a source of ATP for Vision, thus explaining why a digestive system is unnecessary for Vision. However, in reality, the Mind Stone does exist, which means we need to explore a traditional source of ATP, i.e. food. If Vision has a synthetic digestive system, what would be its structure? And would it be possible to create such a system with today's technologies?

In this paper, we will introduce current research on artificial digestive systems, and highlight the technologies that could be used to build an artificial digestive system. We will also summarise how Vision could sustain his body with the system.

DOES VISION HAVE A SYNTHETIC DIGESTIVE SYSTEM?

First, we need to address an important question: does Vision have a synthetic digestive system? The MCU's Vision has revealed that he doesn't eat food [21, 23], but that doesn't necessarily mean that he doesn't have a digestive system. However, there is evidence from the comic books that he does not have a digestive system.

In *Avengers: Age of Ultron* [22], Helen Cho's regeneration cradle technology, the artificial tissue cell Simulacra, and vibranium are used to print Vision's body. In the comic books, Vision's body is

Figure 1. Illustrations of the inside of Vision's body from two comic books issues. (A) In 1985's *West Coast Avengers* (#43) [25] Vision is shown fully disassembled. (B) In *Avengers Icons: The Vision* (2002) #2 [28] the internal components of Vision's body are shown as he phases through a fence. Here a more sophisticated robotic version is presented. Sketches drawn by the author FT and alienated due to copyright regulations.

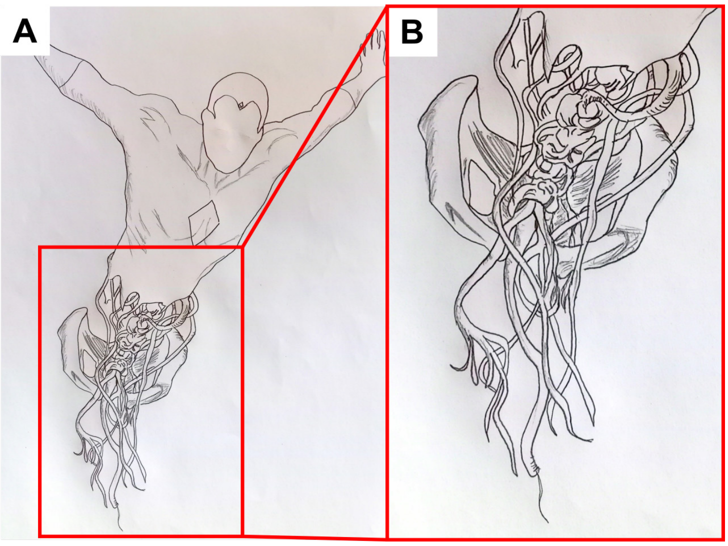

Figure 2. Illustrations of the inside of Vision's body from *Age of Ultron* (2013) #3 [30]. Vision is shown torn in half, a human-like pelvis and innards can be seen, but the vein-like tubes end in wires indicating that these are more electric wiring then intestines. (A) Full image. (B) Magnification of vein-like tubes in the pelvic region of the torso. Sketches were drawn by the author FT and alienated due to copyright regulations.

Figure 3. Vision being printed in the cradle (Avengers: Age of Ultron [22]) (Picture still from https://www.youtube.com/watch?v=4Rs9QE4wRVU (accessed 15.12.2020 13:18 CEST))

produced in different manners, and often depicts the technological advancements of the time period of the comic book story.

In the 1985 comic book series *West Coast Avengers* (#43-#45) [25–27], Vision's body is shown to be filled with nuts and bolts, resembling more a robotic system than a synthezoid (see Figure 1(A)). This can also be seen in *Avengers Icons: The Vision* (2002) #2 [28] as he is depicted to be more like a T-800 Terminator than a synthetic being with artificial organs (Figure 1(B)).

Over the decades Vision's body has become increasingly artificial through the implementation of nanotechnologies that mimic biological functionality as in *Avengers* (1998) #5 [29]. In *Age of Ultron* (2013) #3 [30], Vision's torso was detached from his legs, showing a human-like pelvis with parts of a backbone and tube-like "guts" evident (Figure 2).

The pinnacle of the evolution of Vision's body is featured in the film *Avengers: Age of Ultron* [22] where vibranium atoms bind to biological cells in Helen Cho's cradle. When the Mind Stone is placed on the forehead of the body, we see the artificial brain of the new body (Figure 3).Unfortunately, none of these scenes reveal Vision's digestive system. As mentioned in *Captain America: Civil War* [23] and *WandaVision* [21], Vision does not need to eat, which is also discussed in the comic books [8, 31].

In episode 8 of WandaVision [21] the iconic comic book scene illustrated in Figure 1 (A) was recreated at a S.W.O.R.D. facility. A group of scientists under the supervision of Tyler Hayward (director

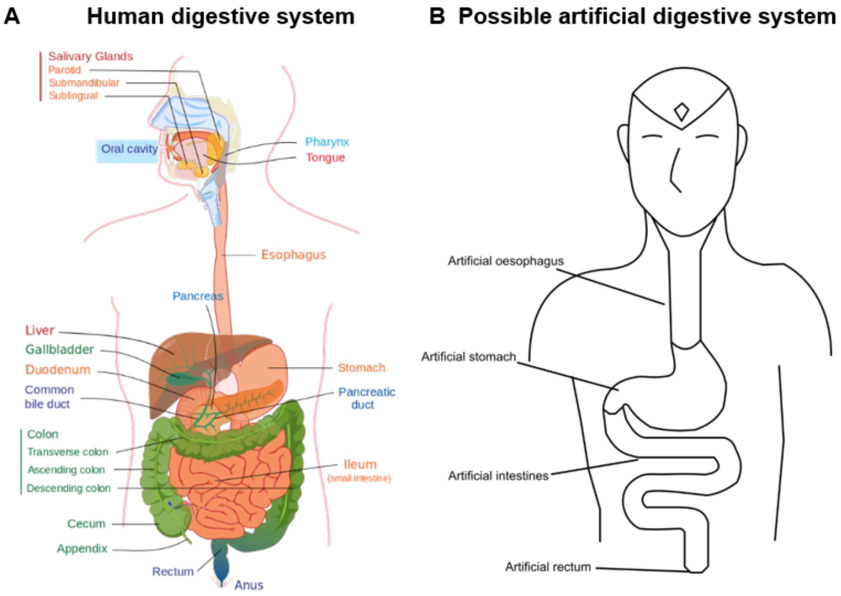

Figure 4: A) Diagram of the human digestive system. The digestive system consists of the gastrointestinal tract and complimentary digestive organs. The gastrointestinal tract includes the oral cavity, oesophagus, stomach, duodenum, colon (large intestine), ileum (small intestine), rectum, and anus. The complimentary organs are the tongue, salivary glands, liver, gallbladder, and the pancreas. Public domain graphic, no permission needed LadyofHats (https://en.wikipedia.org/wiki/File:Digestive_system_diagram_edit.svg accessed 01.12.2020 18:35 CEST). B) Diagram of a possible artificial digestive system for Vision. Vision's system consists of an artificial oesophagus, stomach, intestines, and rectum. Figure drawn by the author FT and alienated due to copyright regulations.

of S.W.O.R.D.) are shown supposedly dismantling Vision's body. From this scene, it appears that Vision's body does not have a digestive system. At the end of the episode, Hayward reveals that S.W.O.R.D. tried numerous energy sources to re-power the body, although Hayward doesn't mention if they considered a synthetic digestive system. To power Vision's body, Hayward harnesses energy from a Stark drone exposed to Wanda's powers to provide the necessary energy for the body.

Hence, evidence from the literature and films leads to the natural assumption that Vision does not have a synthetic digestive system. However, from the MCU, we know that Vision has synthetic eyes and a synthetic brain, indicating that the cradle used to make him can print synthetic equivalents to human organs. Given that the MCU's Vision most likely does not have a fully functional digestive system, Vision would not be able to survive the removal of the Mind Stone by Thanos. This leads to some key questions. How could we build an artificial digestive system for Vision? And what functionality would it need to have? Moreover, what is currently possible?

ARTIFICIAL DIGESTIVE SYSTEMS: WHAT AND HOW

If MCU's Vision wanted to have an artificial digestive system, the easiest thing would be to use Helen Cho's cradle to print one into his abdomen. However, in the real world, such technology does not exist. A viable option is to build soft robotic artificial biomimetic organs with digestive functions and an artificial microbiome based on lab-on-a-chip systems with microfluidics. Before we delve into the technical details, let's first introduce the key aspects of the human digestive system.

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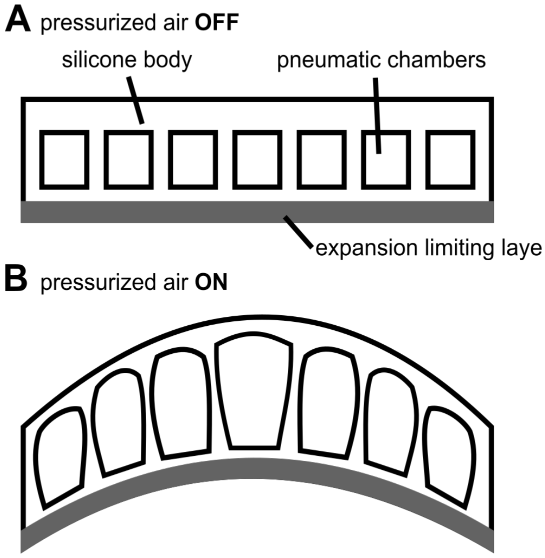

Figure 5. Schematic of a soft robotic actuator. The actuator is made from highly flexible silicone, on pressurization of the pneumatic chambers (A), the chambers expand due to the flexibility of the material and the actuator bends in direction of the expansion limiting layer (B). The expansion-limiting layer can consist of a fabric embedded in silicon, a silicone with a higher stiffness or a rigid casing. It is important that it prevents the expansion of the pneumatic chambers in a certain direction. The author FT drew figure.

Vision's digestive system would need the same basic functionality as the human digestive system (Figure 4 (B)), which consists of the gastrointestinal tract (mouth, oesophagus, stomach, small and large intestines (colon), and anus, as well as complimentary digestive organs like the salivary glands, pancreas, liver, and gallbladder (Figure 4) [32].

Food is ingested at the mouth where it is chewed and a first chemical breakdown via digestive enzymes takes place. During swallowing, the food bolus is transported through the oesophagus by peristaltic expansion and contraction of its ring musculature. After the oesophagus, the food enters the stomach, where it is broken down further by mixing with gastric acid, after which it enters the intestines. During digestion in the small intestine, the food is fully decomposed through peristaltic motions, specialized enzymes, digestive secretions, and the microbiome of the intestine. Within the intestines, the absorption of water and nutrients takes place. Afterwards, waste products are excreted via the anus [32]. Vision has parts of this system, such as a mouth, tongue, and oesophagus (see Figure 3). The critical missing parts from his digestive system are the stomach, intestines, and rectum.

Here, we propose that biomimetic soft robotic systems can be used to approximate the movement principles of the oesophagus, stomach, and intestines. Soft robotic systems are *per se* compliant systems based on flexible materials [33–37] that span a wide field of applications ranging from robotic arms, industrial grippers, walkers (tethered and autonomous) to orthoses, exoskeletons, pneumatic muscles, artificial organ simulators, and pumps [33, 38–46]. Most of these systems are based on flexible materials like silicones and driven pneumatically by expanding the pneumatic chambers. Movement and directed motions, such as bending, can be realised by attaching a strain or expansion limiting layer to the system. This ensures that the system only expands in the opposite direction, given a directed bending motion (Figure 5).

First step: Making Vision's artificial oesophagus

At present, there are only a few soft robotic artificial organ systems from which an artificial digestive system could be built. First, one would need a transport system like the oesophagus that can move the food bolus to an artificial stomach, and afterwards through the artificial intestines. The human oesophagus and intestines transport media via peristalsis (aka peristaltic movements), which can be described as circular muscle contractions propagating along a muscular tube (here the oesophagus or intestines) [43]. The ring muscles around the oesophagus contract, reducing the inner diameter

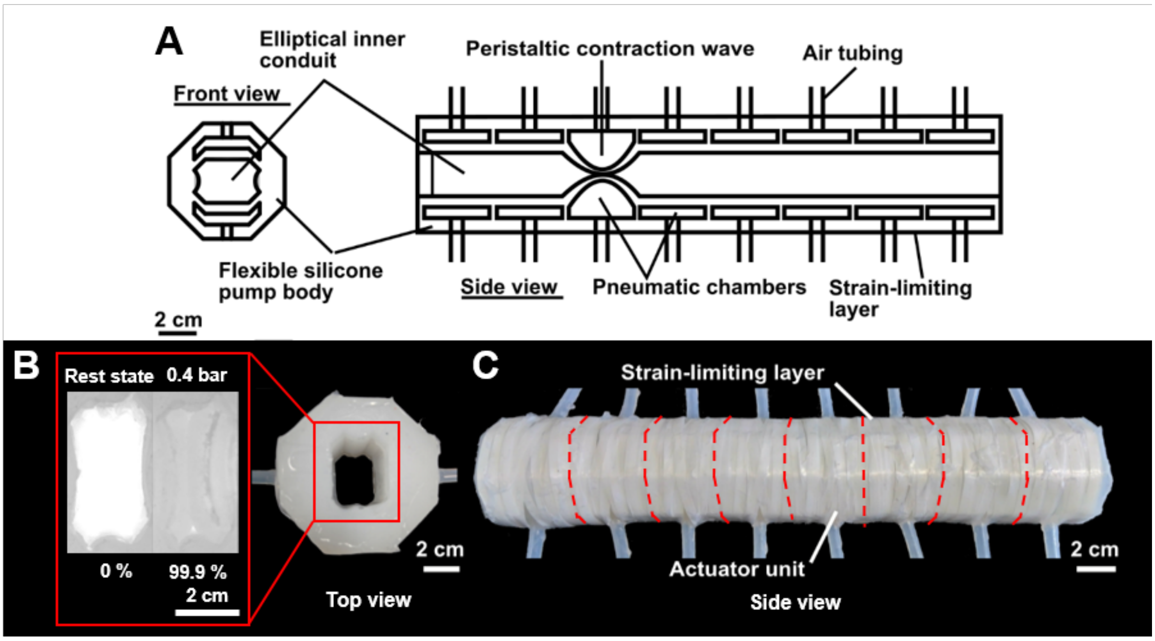

Figure 6: The silicone based biomimetic peristaltic pump (SBPP) system. (A) Simplified blueprint of the soft robotic SBPP. When the pneumatic chambers are pressurized in correspondence to the peristaltic actuation pattern, they expand and close the inner diameter. This peristaltic contraction wave travels along the tube transporting the media from one orifice to the other (adapted from [43] under Creative Commons Attribution Non-commercial License © 2019 Esser et al. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim). (B) Frontal view of a single flexible silicone ring actuator unit. The red box shows the inner conduit of an actuator unit in "Rest state" (left) and with inflated pneumatic chambers (right, 0.4 bar) closing the inner conduit. (C) Side view of a fully assembled SBPP consisting of eight actuator units with a strain-limiting layer on the outside, inward directing all expansion. Red dotted lines indicate the actuator units. © Plant Biomechanics Group Freiburg

of the oesophagus until it closes. The contraction then travels along the entire length of the oesophagus and pushes the food pulp into the stomach. Esser *et al.* developed a soft robotic peristaltic pumping system, known as the silicone based biomimetic peristaltic pump (SBPP), that was inspired by the peristaltic movements of the oesophagus and intestines. The SBPP is capable of transporting various liquids and slushes, producing a volume flow rate of over 300 l/h (litres per hour), depending on the transported fluid) [39, 40, 42, 43] (Figure 6).

This highly flexible self-priming biomimetic pumping system uses varying peristaltic actuation patterns to pressurize its pneumatic chambers and transport media through the system (Figure 6 (A)). A self-priming pumping system is a pump that generates enough suction pressure to evacuate any air from the system such that liquid can be sucked into the pump, which is positioned above liquid level, and the liquid can even be sucked into the pump against gravity [47]. When activated, the pneumatic chambers, which are integrated into the tube body that forms the inner conduit wall, expand, thus reducing the inner diameter until the conduit walls come in contact with each other and close inner conduit (Figure 6 (B)). The artificial peristaltic contraction wave then propagates unidirectional (in one direction) along the conduit length displacing/transporting any medium in the conduit in the process.

In contrast to other biomimetic tube pumps [48–50] and artificial oesophagus systems [51–53], the SBPP is fully flexible design and does not include a stiff pump casing. The flexibility of the system (up to 300% expansion) is even higher than that of

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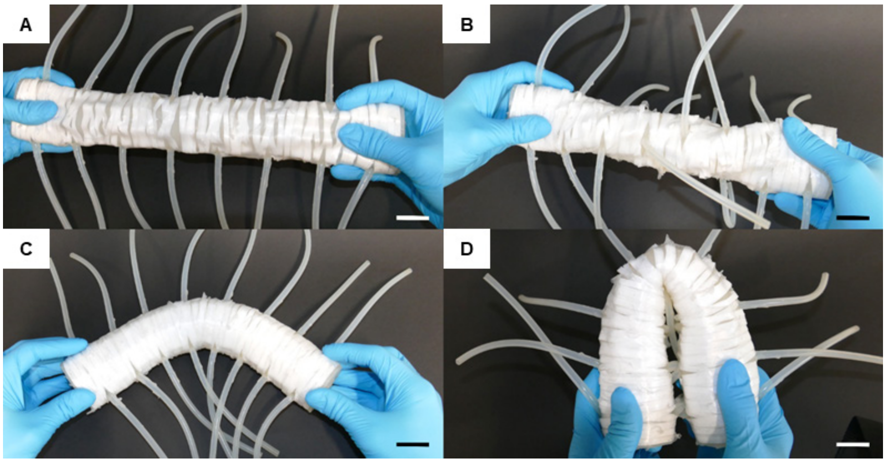


Figure 7: The SBPP can be pulled (A), twisted (B) and bend ((C) partially bend and (D) fully bend) without breaking, highlighting the high flexibility, robustness, and resilience of material and pump system. Scale bars 5 cm. © Plant Biomechanics Group Freiburg.

the biological system, as the normal oesophageal diameter is 2 cm [54] and it can be distended up to 3 cm [43] (equal to 150% expansion). However, the complex structure of the oesophagus, which consists of layers of muscle fibres (both smooth and striated) between the fibrous tissues, differs considerably from the biomimetic system. Additionally, the oesophagus cannot be twisted and bent without damaging the tissue or surrounding organs. Nevertheless, we can use the distensibility of the oesophagus for comparison as the SBPP can also expand up to 300% when pressurized. Due to the silicone material and high flexibility, the SBPP can bend, stretch, and twist without breaking. It can also adapt to almost any build space (Figure 7).

As a result of its transport capabilities and its high flexibility, the SBPP system is well suited for use in the construction of an artificial oesophagus and intestines for Vision. A number of SBPP systems could be joined together or extended by adding more actuators to replicate both organs.

Another candidate for Vision's oesophagus is the artificial oesophagus system "RoSE" developed by Dirven *et al.* from Prof. Weiland Xu´s lab at the University of Auckland, New Zealand [51–53, 55]. Dirven's work is the first complete representation of oesophageal swallowing in a biomimetic device with advanced sensory capabilities [52]. The system was developed to study the textural and rheological characteristics of modified foods for dysphagia (symptomatic swallowing disorders) patients.

The swallowing disorder, dysphagia, is often accompanied by a feeling of pressure or pain behind the sternum (the upper abdomen). It usually occurs due to dysfunction of the oesophagus, including oesophageal disease, cancer, neurovegetative dystonia, and central nervous system diseases [56]. If dysphagia is not diagnosed or treated, patients are at high risk of pulmonary aspiration and subsequent aspiration pneumonia, because food or fluids enter the lungs via the wrong route or tract. Some people exhibit "silent aspiration" and do not cough or show outward signs of aspiration. Undiagnosed dysphagia can also lead to dehydration, malnutrition, and even kidney failure. The most common symptom of oesophageal dysphagia is the inability to swallow solid food, which the patient describes as being "stuck" or "held up" before it either enters the stomach or is vomited up [56].

Dysphagia can be identified using oesophageal manometry, where a thin, flexible tube (catheter) containing pressure sensors is passed through the nose into the oesophagus. Oesophageal manometry can be helpful in diagnosing disorders that affect

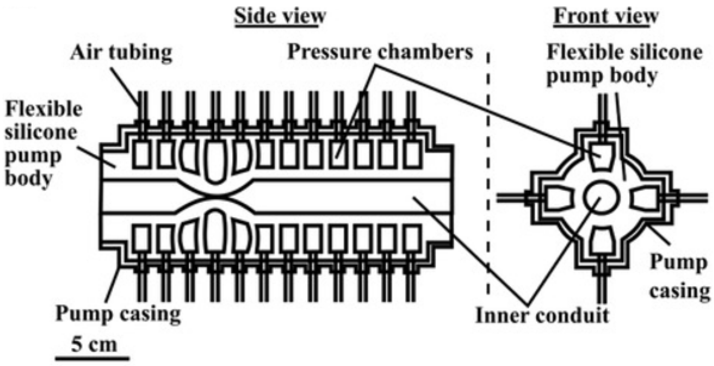


Figure 8: Sketch of soft-bodied peristaltic swallowing robot (RoSE) with its circular inner conduit. Three rows of pneumatic chambers are active per peristalsis wave (adapted from [43] under Creative Commons Attribution Non-commercial License © 2019 Esser et al. Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim).

the oesophagus. It measures the contractions, the force, and coordination of oesophageal muscles as they move food to the stomach [57].

Currently, the RoSE manometry test setup is used to measure bolus swallow pressure signals and as an *in vitro* (meaning in glass and colloquially called "test-tube experiments" [58]) testing device of endoprosthetic stents for dysphagia management. In other words, the system can mimic swallowing, which is helpful for developing swallowable foods for dysphagia patients or prosthetics (like stents) to help a patient to swallow normally. The RoSE system is a soft robotic pneumatic system outfitted with valves that enable a discrete actuation of each of the twelve rows of actuators. Each actuator is outfitted with four pneumatic chambers circularly oriented around the inner tube (Figure 8).

Vision's oesophagus would also need to be able to eject food or liquids if they were harmful. Both systems presented here (SBPP and RoSE) can achieve this by reversing the direction of peristalsis.

Vision's artificial stomach

Next, let's consider the technologies to make a stomach for Vision's digestive system. The most sophisticated artificial stomach systems have been developed in the field of soft robotics, such as the human gastric simulator developed by Ferrua and Singh [59, 60]. This system can be used to mimic and study digestion and the transport of food through the stomach. Another artificial stomach is SoGut by Dang *et al.* [61], which can be used to simulate the physiological movements of the human stomach in the study of digestion.

The human gastric simulator of Ferrua and Singh mimics the fluid mechanical conditions during the digestion of contents in the stomach [59, 60] (Figure 9). The system consists of a cylindrical, latex chamber that represents the stomach, its wall (part 2 in Figure 9) are periodically contacted by rollers (part 5 in Figure 9) to mimic the antral contraction wave activity of the stomach wall [59]. The chamber wall is pressed together by the forward, upward, and downward motion of the rollers simulating the stomach wall movement. This also helps in the mixing of the food in the stomach with the artificial gastric fluid for digestion. The system operates inside an insulated chamber maintained at 37 °C (normal internal body temperature), while facilitating the delivery of gastric juices and the emptying of artificial digested food in a continuous and controlled manner [59]. The system can be emptied with the help of a peristaltic pump through an opening at the bottom of latex chamber [60].

The SoGut system approximates gastric motility with its peristaltic contractions in an anatomically realistic way using an array of circular air chambers that generate radial contractions (Figure 10). The distinct circular air chambers inside the rigid skeletal frame can be periodically pressurized and expand inward to the stomach lumen, mimicking the peristaltic movements of the stomach wall during digestion. A lumen is the inside space of a tubular structure, such as an artery or intestine. It

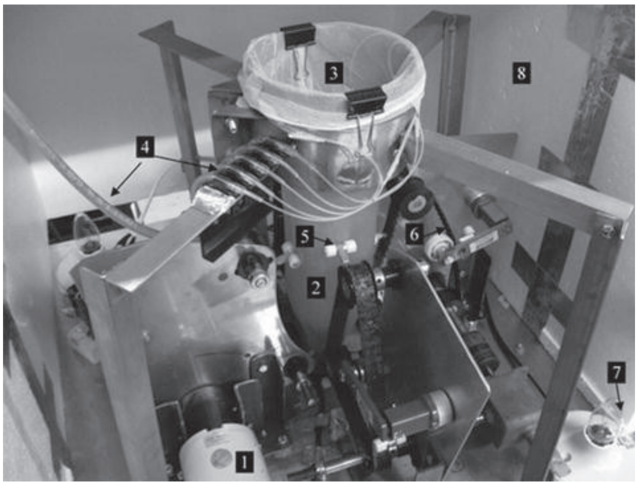


Figure 9: The human gastric simulator can digest food by imitating the stomach movement and the chemical makeup of gastric acid. The system consists of a gastric compartment (2) with a mesh bag (3) holding the artificial gastric fluid, which is distributed via secretion tubes (4). Teflon rollers (5) driven by a conveyor belt (6) powered by an electric motor (1) imitate the peristaltic movement of the stomach. An insulated chamber regulates the temperature around the setup to 37°C (7) (reproduced from [59] under Creative Commons Attribution Non-commercial License © 2015 Ferrua and Singh. Published by Springer, Cham).

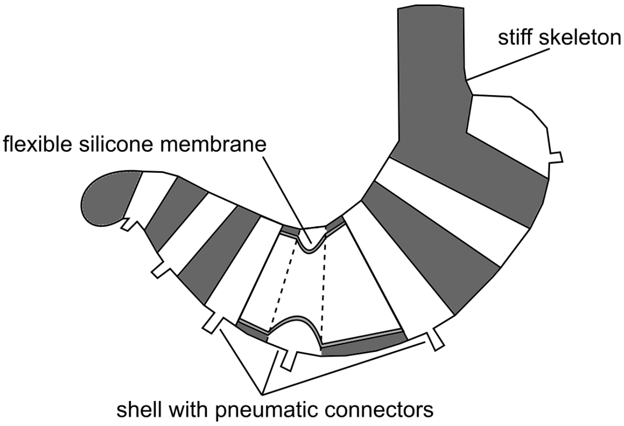


Figure 10: The SoGut system. The flexible silicon membrane is attached to the stiff skeleton. Inward directed inflation via a peristaltic motion pattern is possible in the shell segments, where a gap between the shell wall and the membrane forms an air chamber enabling pressurization via the pneumatic connectors. (Figure redrawn by author FT and alienated due to copyright regulations from [61]).

comes from Latin *lumen* meaning 'an opening' [24]. Dang *et al.* investigated the force and amplitude of the contractions when the lumen of SoGut is empty or filled with contents of different viscosities, thus simulating foods of different textures as well as the contracting force needed to process these foods using manometry (for information about manometry see previous section) [61]. The device achieves a similar range of contracting force as the human stomach, and demonstrates that SoGut can achieve *in vitro* peristaltic contractions to digest and transport food contents [61].

A combination of these two systems might not allow Vision to feel butterflies in his stomach, but it would certainly allow Vision to process and chemically digest a food bolus. In other words, Vision would be able to eat and properly digest many different types of food.

But what about the possibility of Vision being able to digest chewing gum? In Episode 2 of the Disney Plus series *WandaVision* [21], Vision accidentally swallows a small quantity of chewing gum, which affects Vision's primary systems and leads to abnormal behaviours. He acts as if he is inebriated. Animations in the episode show the chewing gum becoming entangled in a system of cogs in Vision's abdomen. Of course, this view of his internal workings is an over-simplification, as shown in Episode 8 of WandaVision. However, could an artificial digestive system based on the aforementioned systems process chewing gum?

The principal ingredients in chewing gum are gum base, sweeteners, and glycerine. Sweeteners are included to provide an initial sweet taste which vanishes with prolonged chewing, while glycerine is included to ensure that the gum retains moistness.

Gum base, which can be seen as the foundation of the chewing gum, is made from three components – resin (main chewable component), wax (accounts for softness), and elastomers (that account for the viscoelastic nature of the gum). There are natural and synthetic options for the gum base such as chicle (natural) and butadiene-styrene rubber (synthetic material also used in car tyres).

With such a variety of ingredients, some of which are synthetic, can the human digestive system digest gum if swallowed? The simple answer is no, but it will not cause an issue. While the gastric juices in the stomach may not be able to breakdown the gum, it will pass through the stomach without causing significant issue and onto the next stage of the digestive system – the intestines (see next section). Nonetheless, it has been shown that the chewing of gum can help patients suffering from issues such as gastro-oesophageal reflux, belching, and improve traditional swallowing in patients with Parkinson's disease [62–64]. In addition, chewing gum can improve mastication, general swallowing, and salivation in patients older than 65 years old [65]. Thus, if Vision were to start eating food, it might be a good course of action if he regularly chewed gum (without swallowing it) to improve his ability to initially chew, digest, and swallow food. In *WandaVision*, it is likely that the ingredients in the chewing gum are the cause of Vision's abnormal behaviour, and not the texture of the gum itself.

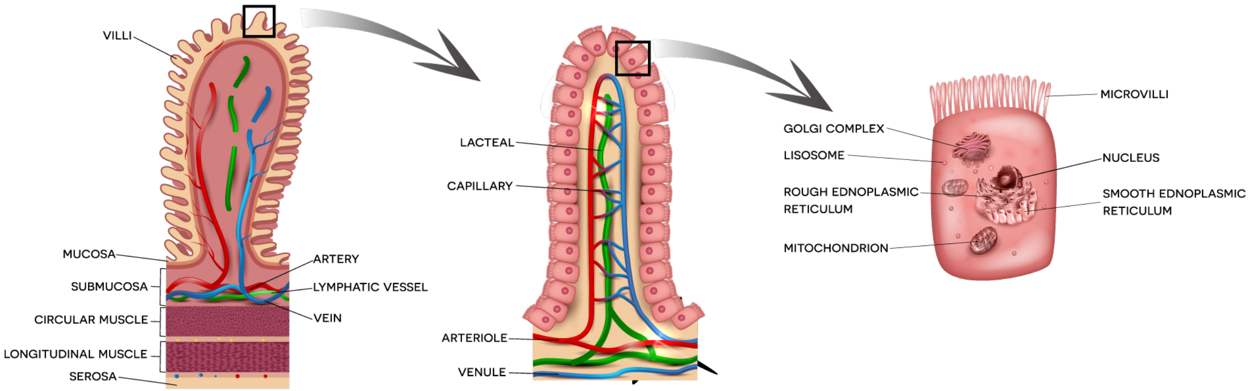
Vision's artificial intestines

Having discussed artificial stomachs, we now take a look at ways to build artificial intestines. In the human body, the intestinal system consists of two parts: the small intestine and the large intestine. Together, they help release of nutrients from food and direct these nutrients to the bloodstream. One way to build synthetic intestines would be to join together a number of silicone based biomimetic peristaltic pump (SBPP) systems. However, the inner tubular geometry would need to be adapted to the match the internal structure of the intestines.

In humans and most other vertebrates, the intestinal wall is heavily folded, with the individual folds carrying large amounts of microscopic, finger-shaped projections called intestinal villi [32]. Epithelial tissues can be found throughout the body, lining body cavities and hollow organs, and making up the main tissue in glands [66]. Epithelial tissues perform a variety of functions such as protection, secretion, absorption, excretion, filtration, diffusion, and sensory reception [66]. The epithelial cells inside the intestines are on the surface of the intestinal villi (Figure 11). In turn, these cells have even smaller extensions called microvilli (Figure 11). This provides the intestinal tract with a large inner surface area to absorb nutrients [32].

A soft robotic system that approximates scaled up intestines is already available. The Modular Endoscopy Simulation Apparatus (MESA) is an artificial colon system used for endoscopy training and outfitted with a fold-like inner tube geometry [67]. A team of scientists from Colorado University have upscaled their MESA system to double the size of a human colon, giving it a maximum inner diameter of 12 cm, an average inner diameter of 10 cm, and a length of 3 metres [67]. For experiments, MESA is placed on a tabletop XYZ movement system and outfitted with pneumatic sleeves to simulate peristaltic contractions in certain parts of the intestines. The table can be tilted in the X- (right), Y- (left) and Z- (up/down) direction. With the help of the X-,Y- and Z-stage, disturbances can be introduced to the MESA system to move the synthetic colon on the table [67]. These disturbances mimic the colon movement as well as larger intestinal contractions that experienced during colonoscopy. With the MESA system, physicians can train how to deal with such disturbances in real patients. Due to its dimensions and tabletop design, it is unsuitable as a mobile, synthetic digestive system. In effect, the system is too big to be placed in a person or Vision.

For Vision's colon, the SBPP would have to be long and include a suitable internal structure (folds, villi, glands etc.) that increases the surface area for nutrient absorption many times over. It would also need a live biofilm that supports digestion and protects the host from unwanted microbiota (that may be derived from food) [32]. Therefore, the



A FOLD OF THE INTESTINAL LINING **VILLI** **EPITHELIAL CELL**

Figure 11: Structure of a fold in the intestinal lining, a villi, and epithelial cell. (Source: Shutterstock).

inclusion of “organ-on-a-chip” technology in the macroscopic pumping systems with a live biofilm of gastrointestinal microbiota [68] and scaffolds for tissue regrowth [69–73] would be beneficial. Gastrointestinal or gut microbiota play a crucial role in the proper function of the human immune system [74, 75]. These microbiota help maintain the mucosal barrier, support digestion, provide nutrients such as vitamins, and protect against pathogens [74]. The intestinal mucosal barrier is a selectively permeable barrier that separates the external environment from the body's interior. It prohibits the passage of bacteria and toxins while permitting the flux of water, ions and solutes, including nutrients [76]. In organ-on-a-chip systems, the interaction and influence of such microbiota can be investigated, and, in some cases, even mucosal barriers can be replicated *in vitro* [77]. Organ-on-chips are microfluidic cell culture chip systems that simulate the 3D structure, function, and pathology of human organs *in vitro* [73]. They are used to study drug efficacy given that diseased tissue can be cultivated *in vitro* and examined under conditions that are similar to *in vivo* (Latin for "within the living") conditions.

There are even systems in which not only the morphology, but also the interactions of cells with micro-organisms can be investigated using organoids (smaller and simplified versions of organs) of intestinal epithelial tissue cells, like the mini-gut system of Nikolaev *et al.* [72]. In their work, the researchers used a 3D micro-device consisting of hydrogel designed to be similar to the *in vivo* morphology with folds and villi. By introducing intestinal stem cells into the device and using their intrinsic self-organization properties, tube-shaped epithelia with lumen and a similar spatial arrangement to *in vivo* cells was achieved [72].

With his system, Nikolaev *et al.* studied the regenerative properties of the mini-gut tissue by introducing controlled epithelial damage via lesions with a laser, applying a cytotoxic compound, and exposing the cells to low doses of γ-radiation. The experiments showed that the bioengineered organoids show regenerative potential.

If we applied these systems and cell cultures to the SBPP inner conduit wall, the biofilms would need to withstand peristaltic motions and be permeable to nutrients. Kim *et al.* developed a microfluidic gut-on-a-chip system to investigate this process [68]. The system consisted of two channels separated from each other by a permeable membrane, and the outer walls could be set in peristaltic motion using vacuum chambers [68]. On one side of the membrane the epithelial cell and microbial flora were grown and both channels were perfused with cell culture medium. The study revealed that a low level of fluid flow and shear stress as experienced in the living intestine are enough to promote accelerated intestinal epithelial cell differentiation, the formation of 3D villi-like structures, and increased intestinal barrier function [68]. For Vision, this process is imperative. Replicating the replacement of key digestive biological cells is crucial if Vision's proposed artificial digestive system is to function in a way similar to its biological equivalent.

In addition, these systems can be used to cultivate and analyse the microbial cells in the gut. This will make it possible in the future to design an artificial system that transports substances just like a real organ, and is capable of digesting food and absorbing nutrients, thus creating a truly artificial, fully functional organ.

These organs-on-a-chip devices show the vast possibilities of state-of-the-art microfluidic devices. These systems can mimic *in vivo* conditions and host living tissue and a microbial flora on non-living materials, which is essential for a functioning artificial intestinal wall, like the one needed for Vision's intestines. For nutrient uptake and transport, a microfluidic network needs to be included in the wall just below the surface. This system would have to be connected to Vision's artificial blood circulation system, that is if he has one of course.

Meeting energy demands

The main task of the digestive system is to break food down into components to be absorbed by the body, and thus provide cells with energy. The microbial regime of the artificial intestines, which helps in digestion, could also be used as part of a microbial fuel cell (MFC) system to generate energy. A MFC is a device that converts chemical energy into electricity using the catalytic activities of microorganisms. Although there is great potential for MFCs as an alternative energy source (i.e. in wastewater treatment process or biosensors), extensive optimization is still required to exploit the maximum microbial potential [78]. These systems are currently able to produce µW and µA [79], which is too low to power a full grown android.

For Vision, a hydrogen fuel cell would be better suited, although these systems are still under development for applications in robotics. Nevertheless, proton exchange membrane (PEM) fuel cells for mobile applications with an energy density of 4,950 Wh/kg (roughly 17,820 kJ/kg) and a run time of 99 hours are available [80]. PEM fuel cells are environmentally-friendly energy source alternatives to combustion engines. A PEM fuel cell consists of a cathode, an anode, and an electrolyte membrane. The system uses hydrogen (from a tank) and oxygen (from air) as fuel for an electrochemical reaction inside the fuel cell to transform chemical energy to electrical energy, with the only by-products being heat and water [81].

To figure out if a mobile version of this technology could power Vision's basic functions, we first need to know his basic energy demands or the energy needed for basic daily activities like walking, talking, and internal biological functions. To estimate Vision's basic metabolic rate (BMR), we consider the physical attributes of the actor Paul Bettany – who plays the character in the MCU. Bettany has a height of 1.92 metres and a mass of 90 kg. This equates to a BMR of 1,936 kcal/day or 8,097.3 kJ/day. This is roughly 15% above the BMR for an average male of 7,100 kJ/day [32].

A PEM fuel cell could provide Vision with this energy, but might not be able to provide energy to power the body's superpower attributes such as flight, super-strength, and matter phasing. An added complication with using PEM fuel cells is that Vision would constantly need to carry huge hydrogen tanks, instead of just eating food and storing the energy within his body. Clearly, this is not practical. Hence, we argue that an artificial digestive system might be the best solution. Perhaps it could be used in conjunction with ARC reactor technologies, such as that developed by Tony Stark, if such technologies ever were to exist in the future [82].

Final part: Vision's artificial rectum

If Vision has a digestive system and Vision is able to digest food and extract enough energy to sustain his body, Vision would also need to deal with waste products. Instead of just phasing it out of his body, we propose that Vision would need an end to

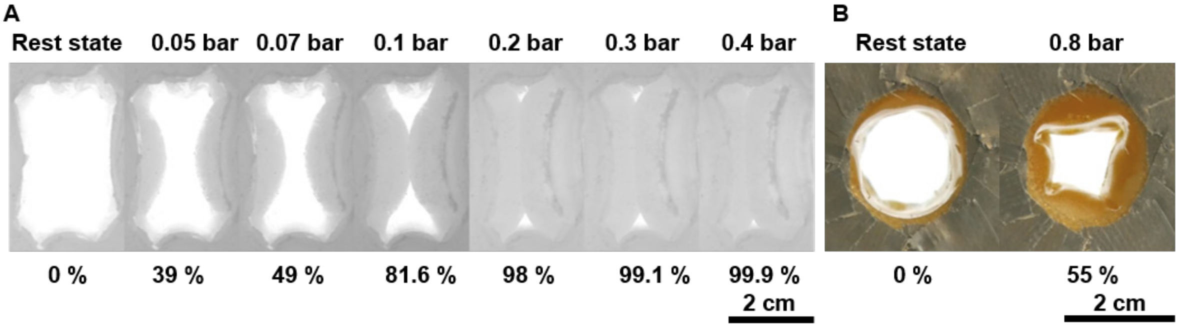


Figure 12: The closure rate of the SBPP (silicone based biomimetic peristaltic pump) (A) and FBPP (foam based biomimetic peristaltic pump) (B). (A): Closure of one actuator ring actuator in the SBPP system. As pressure increases, size of the opening decreases. A full closure is achieved with a holding pressure of 0.4 bar (adapted from [41]). (B): Closure of one circular ring actuator in the FBPP system. Maximum pressure of 0.8 bar leads to a closure of only 55% results. As a result, the less flexible foam actuators were not suitable for the pump system. (reproduced with permission from [39] Springer Nature. Copyright 2017.)

the artificial colon in the form of an artificial rectum and anus. To fulfil its duty, the rectum would need a holding capacity and anal sphincters to hold it shut.

In the human body, the rectum receives faeces from the descending colon by peristaltic motions of the intestines [32, 83]. As the rectal walls expand during filling, stretch receptors from the nervous system in the rectal walls stimulate the need to pass faeces, a process called defecation [32, 83]. An internal and external anal sphincter prevent leakage of faeces. When the maximum storage capacity of the rectum is reached, the sphincters relax and a reflex expulsion of the contents of the rectum occurs [83]. Expulsion occurs through peristaltic contractions of the muscles of the rectum [83]. The pressure generated during the peristaltic motions of the intestines is between 0.05 and 0.166 bar.

To put these pressures in context, a bicycle and a car tyre need 2.5 and 4.5 bars of pressure for standard use, while the mean basal pressure of the internal anal sphincter (IAS) (0.063 bar) and external anal sphincter (EAS) (0.064 bar) are above the lowest pressures during intestinal peristalsis. During defecation, the squeeze pressures can go above the maximum values, up to 0.163 bar (IAS) and 0.170 bar (EAS). This means that the sphincters are able to withstand the pressure during normal peristaltic motion within the intestines and can stay closed. During defecation, the pressures of the sphincters rise above the maximum pressure generated by the peristaltic motion to help empty the rectum.

From this, it's clear that the SBPP system presented earlier could also be used as an artificial bowel outlet as it can easily simulate the pressures for IAS and EAS by means of air pressure (0.05 - 0.4 bar) (Figure 12 (A)). By permanently pressurizing the last actuator unit, the system can act as a sphincter. The system can also be built with different basic materials and conduit geometries, as shown in the example of the flexible poly urethane foam based biomimetic peristaltic pump (FBPP) [39] (Figure 12 (B)). The drainage movement of the rectum and anus can be simulated by the peristaltic movement patterns displayed by the system [38, 40, 41]. These technologies would allow Vision, in theory, to experience bowel movements similar to humans. Of course, these systems would also need to include an artificial sensory system so that Vision can feel when a defecation episode has finished. In addition, this would allow the Vision's body to "feel" discomfort during defecation, which could cause serious damage to the system if left unmonitored. Finally, with such a system, Vision could become more human, something that Vision has strived for in the comic books and the MCU.

CONCLUSIONS

The combination of techniques, principles, and devices presented here could be the starting point for the development of an artificial digestive system for Vision. In combining the SBPP (silicone based biomimetic peristaltic pump) with the SoGut system and the human gastric simulator, structuring the inner conduit of the SBPP to mirror real intestinal walls (in the intestinal section), a complete gastrointestinal tract could be created. Equipping the artificial stomach and intestinal walls with microfluidic organ-on-a-chip-like tissue scaffolds could provide a fully synthetic material-based digestive system with a living tissue film and microbial flora to promote digestion of Wanda's paprikash and the assortment of cooked meals featured in *WandaVision* (Figure 13). Even defecating would be possible with the SBPP system, which would allow Vision to rid his body of digestive waste products, just like the other Avengers.

So, do the devices outlined here make it feasible to build a synthetic digestive system today for a person or even a synthetic lifeform like Vision? The answer is not *yet*.

The main role of the digestive system is to convert food into energy. In this process, the food must be decomposed and metabolised. The mechanical part of the decomposition is possible with today's soft robotic-based systems, and a living biofilm and tissue cells is a first step towards metabolisation. However, there are many more factors to consider.

For example, specific digestive juices are produced by glands that break down and decompose foods with the help of acids and enzymes, in addition to mechanical breakdown. As a result, food is broken down into its components such that the body's cells can use them as an energy source. As mentioned above, in Vision's case, this energy could also come from electrochemical reactions in a MFC system powered by food. Though a hydrogen fuel cell would cover Vision basal energy needs, to have sufficient energy to fight villains, Vision would need a more sustainable energy source, which could be provided by an artificial digestive system.

The system would also need to transmit and communicate information to Vision's “brain” so that Vision could experience hunger or even butterflies in his stomach. For this, Vision's digestive system would also need chemical- and mechanoreceptors and sensors. In humans, common triggers for hunger are blood glucose and insulin levels [32] as glucose is one of the main sources of metabolic energy. Another stimulus would be signals associated with mechano- and chemoreceptors, which sense whether food is currently in the stomach or intestine and send signals to the brain for replenishment. This is a very strong simplification of the highly complex processes. Overall, Vision would not only need a fully artificial digestive system, but also complimentary nervous and circulatory systems.

It's also worth pointing out that the human digestive system could be more efficiently designed. However, the efficiency of a human digestive system is also partly determined by the state of health and diet. An idealised synthetic digestive system does not necessarily need to match the scale and structure of its biological counterpart. For instance, supplementary digestive organs such as the liver and gallbladder could be combined into a high-efficiency universal layered component in a rectangular compartment, like a fuel cell design. Additionally, primary organs such as the stomach could also be represented as deformable rectangular structures. In the case of the intestines, the surface area is large to increase nutrient/water absorption into the body via enzymatic processes. However, such large organs would be unnecessary if the same molecular absorption processes could be captured by compact synthetic devices. Nevertheless, using the digestive system of the human body to inspire a synthetic digestive system is perfectly valid.

The presented systems can currently imitate their biological role models and transfer their principles and function to technical systems. However, they are not made from self-actuating and self-healing materials as in nature and in the human body. The development of self-actuating, self-sensing material system might reduce complexity, weight, space and energy requirements.

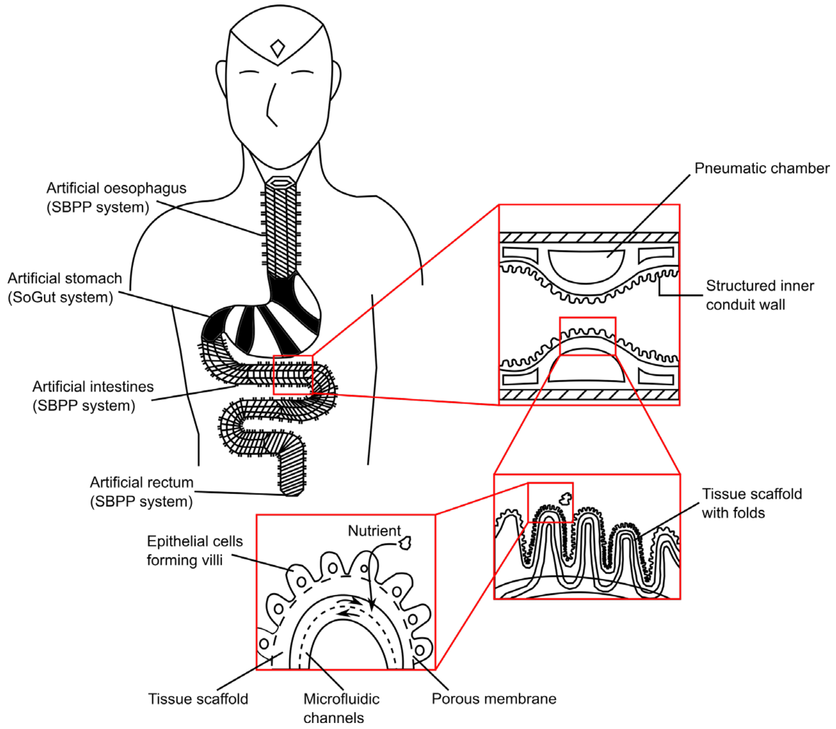


Figure 13: The possible artificial digestive system for Vision. It is built from a combination of the various systems: the SBPP (silicone based biomimetic peristaltic pump) as an artificial oesophagus, intestines, and for the rectum, and the SoGut system as an artificial stomach. The structured inner conduits of intestines are lined with tissue scaffolds growing epithelial tissue cells forming folds and villi. Beneath the scaffold layer is network of microfluidic channels imitating a circulatory system, with together with the tissue cells an organ-on-a-chip like system. Sketch developed and drawn by author FT.

Finally, we recognise that the technologies outlined here for the artificial digestive system (Figure 13) are currently far too large to be placed inside the body of a person or the Vision. Therefore, it will be some time before these technologies can be combined to create a system to adequately fit inside a human body.

OUTLOOK

In this paper, we outline how combining suitable systems and related technologies can theoretically be used to build an artificial digestive system that captures the primary functions of the human digestive system for use in Vision's body. Although significant progress has been made in the field of soft-robotic technologies for digestive system applications, a number of issues remain to be solved. For instance, such a system would benefit from the development of biocompatible self-actuating and self-sensing materials.

But, how would humanity benefit from the development of an artificial digestive system? First, these systems could serve as prostheses and provide replacements for key organs in the digestive system. Second, these systems could be used in the development of food for dysphagia patients [55]. Third, these systems could be used in the clinical treatment of patients with digestion problems.

An additional application of the technologies may be in domestic energy production. If future digestive systems could quickly and efficiently generate electrical energy from food, they could be used in the homes of the future where food scraps, kitchen waste, and biodegradable disposal substances could be processed for energy production. Such a device could contribute to the transition to sustainable and renewable energy production methods. In this way, one would have the equivalent of a home power plant. The same device could also potentially process natural raw materials like bagasse, a fibrous waste product of sugarcane that is made up of roughly 35% sucrose [84]. In addition, any excessive generated electricity could be sold to the national grid [84].

The soft-robotic systems presented here are cutting-edge, with obvious applications in an artificial digestive system that could also be used in energy generation. Hence, these technologies could conceivably have a positive impact on the fields of healthcare and energy. In the meantime, plans for an artificial digestive system that provides sufficient energy to sustain a synthezoid like the MCU's Vision are still very much a work in progress. But watch this space!

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