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Synthetic Vascular Tissue with Binary Control for Dynamic Stiffness

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Robotics and Computer Engineering

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Resümee/Abstract

Sünteetiline binaarkontrolliga vaskulaarne kude dünaamilise jäikusprofiili saavutamiseks

Selle töö raames valmistati sünteetiline binaarkontrolliga vaskulaarne kude dünaamilise jäikusprofiili saavutamiseks. Tööl oli kaks põhilist eesmärki – disainida ja ehitada vaskulaarne rakuline süsteem dünaamiliseks jäikuse muuduks ning disainida ja ehitada pehme muganduv klapp. Valmistatud rakuline süsteem ja pehme muganduv klapp näitasid vastavalt dünaamilist jäikust ning seisundi kontrolli. Need omadused annavad suure potentsiaali nende integreerimiseks ämmaemandate simulatsioonõppesse sujuvaks seisundi kontrollimiseks.

CERCS: T150 Materjalitehnoloogia

Märksõnad: Muganduv funktsionaalsus**,** pehmed süsteemid, juhtimistehnika

Synthetic Vascular Tissue with Binary Control for Dynamic Stiffness

In the scope of this work, a synthetic vascular tissue with binary control for dynamic stiffness was built. The task had two distinct objectives – design and build a vascular cellular system for dynamic stiffness and design and build a soft distributed valve. The built cellular system and soft distributed valve were characterized and showed dynamic stiffness and state control. These properties give them great potential for integrating them into midwifery simulation training for more seamless state control.

CERCS: T150 Material technology

Keywords: Distributed functionality, soft systems, control engineering

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1 Literature overview

1.1 (Soft)robotics

Various machines have been around for a while; however, bigger mechanization occurred during the 1st industrial revolution, when the steam engine was invented. This invention opened many opportunities as manufacturing technologies were less reliant on human power, as humans were now able to utilize previously unused natural phenomena. Those machines aimed to aid humans with challenging tasks, which either exhibit high repetition rates or are physically very demanding and later on for tasks that require higher precision. But as technologies evolved, the need for devices with higher control came about, and devices with higher adjustability and automatic movement started to appear. These devices are called robots, and they are designed to take over human functions[1] but have a high level of control over them by altering their physical features or later by "conventional" programming. Therefore, the design of physical features, like shape or stiffness, could be viewed as part of a robot's programming as it defines the properties of the robot by which it will fulfil its tasks. As written earlier, some machines are designed so that their movement is programmed physically, e.g. using differently shaped cams[2], as seen in Figure 1.

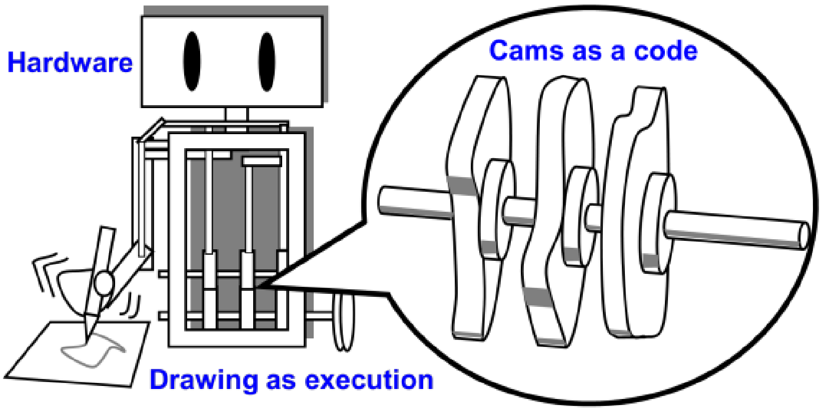

Figure 1: The concept of a drawing automaton based on cam and linkage mechanisms with three interchangeable cams. The pose of the arm linkage is controlled by three cams to trace a user-specified 3D trajectory. [2]

Physical programming also means that each feature introduces a new set of "programming" cams for the device. This means that a robot can be designed in a way where the structure, materials and design define the functionality and movement of the robot.

Over the years, robotics has evolved, and conventional robots are highly rigid metal devices designed to fulfil repetitive tasks, which are easy enough to do or require a high level of precision. However, a huge downside of those robots is the inability to adapt to their environment, and for human safety, a highly structured environment is needed in most cases.

Soft robotics used to be a discipline, which explores the world of robots made from physically softer and other highly compliant materials, which are able to absorb more energy from collisions by replacing rigid materials with compliant materials which have similar elasticity with human skin or muscles. From that point soft robotics has evolved to robots that boast high environmental compliance to enable side-by-side working with humans or situations, where conventional robots are unable to provide value and distributed functionality which can omit multiple tasks for each part of the robot.[3] This evolved definition also means, that conventional robots and soft robots can have similar production methods and the materials used do not necessarily have to be soft. The design of soft robots is more simple in essence, as exploration and studying of nature gives us inspiration from the biomechanics of different species, however, the task to incorporate those principles or mechanisms to manmade systems has proved to be more complex. Even when the underlying idea is understood, the control mechanisms of the phenomena are usually the stumbling block for taking over the principles as there can be struggles with implementation. These soft robots are used in a variety of domains, for example, in medicine, use cases have been researched in surgeries and rehabilitation[4] and manufacturing, as gripping mechanisms have already been used and industrialized[5,6] and their design is often mimicked or inspired from biomechanics.

1.1.1 Biomimicry

The evolution of humankind has always been highly inspired by nature as it surrounds us at every step, for example, first knives and axes found inspiration from dental structure of currently extinct animals[7], first flying machines made after birds[8–10] and a warship modelled after a turtle[11]. These instances could loosely fit under the term biomimicry, which is derived from the Greek words *bios* – life and *mimesis* – to imitate and is quite straight forward. However, the meaning of the idea is bit more complex. as the previously presented examples from natures' inspiration were the copies of observed phenomena, but the term has evolved and was more intended to describe a whole mind-set or a process, where naturally existing models are explored and studied to gain an advantage when designing synthetic systems, whether they be fulfilling their original functions or not.

Therefore, extensive research has to be done to find the suiting technologies for our needs and nature is here again to help us, as it does not really matter, how much research we are doing, nature has done most of the work already. The reasoning behind this is that our planet could be viewed as a research and development laboratory, with almost 4 billion years of experience[12], during which the most efficient structures and methods have remained. Therefore, it might not be reasonable to invent new technologies, but to explore nature and discover the existing, "hidden" ones. Some of the examples of such mind-set are Velcro strips, which originate from the fruits of burdock plants which have tiny hooks[13] (Fig. 2) and an building, designed with all-natural cooling, which originates from the termites' nest, as it is very sensitive to heat[7]. As Velcro is mostly being used in clothing and all-natural cooling structures are mostly buildings, it is evident that impact from biomimicry can be used in a wide spectrum of domains.

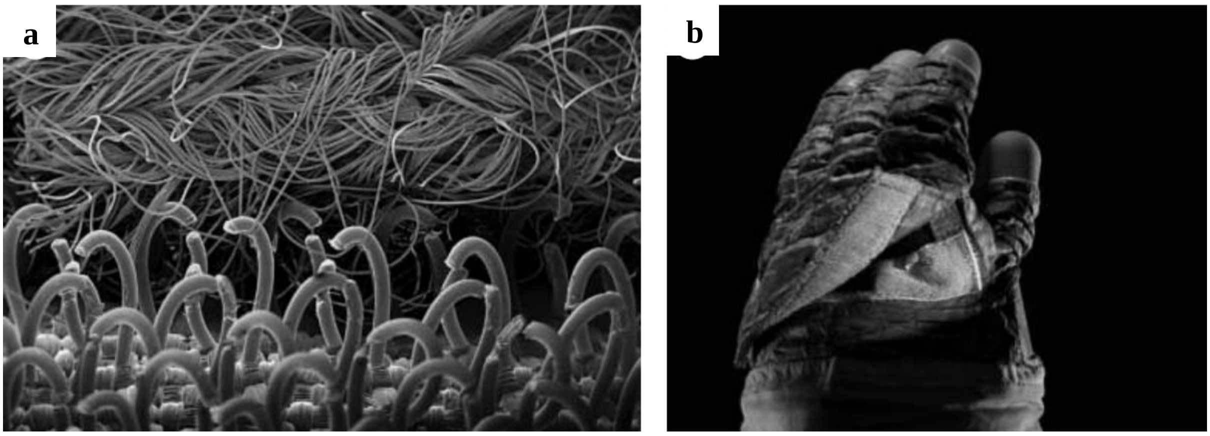

Figure 2: Example of natural adhesion and its synthetic counterpart. a) Tiny hooks found in cockleburs b) Commercial velcro strip on a glove.[13]

This wide domain spectrum and growth potential are also supported by the fact that between the years 2000 and 2015, the number of biomimicry patents, articles and research grants demonstrated a fivefold increase[14]. The first usage of the term biomimicry was introduced in the ’60s by Otto Schmitt[14], while doing research for a physical device to mimic the electrical activity of a nerve, but the term was getting more recognition with work published by Janine Benyus, e.g. *Biomimicry: Innovation Inspired by Nature*[12]. In the book, she stated that as biomimicry is taking lessons from nature as the groundwork, rather than just using it for raw materials, it is leading the path to a new age of technological development.

As most targets of interest for biomimicry are of biological origin, they should boast a high possibility of compatibility with nature it is attempting to merge both nature and man-made technologies, although this is not by default. Therefore, there is also the possibility to build hybrid systems, which could mimic nature, completed using synthetic materials, for example, soft robots. Although, there are cases where biological functions are implemented differently in regard to the original function, making the design bioinspired.

1.1.2 Bioinspired design

Bioinspired design is a slightly different term as it means to take inspiration from biological objects, but implement their usage in a novel way, while biomimicry takes a biological object and copies its build and function. Therefore, the terms are different, but despite this difference, both terms are generally used interchangeably.

Some examples of bioinspired design are soft grippers for food automation solutions[5] (Fig. 3a) and porcupine quill inspired adhesive patches[15] (Fig. 3b). In the initial example, the design of soft tentacle-like grippers has been inspired by the tentacles of octopuses, that use them for moving around the seabed. The artificial grippers are used for grabbing and repositioning randomly oriented soft food products like eggs or cakes in the production line, where using conventional robots would increase the risk of unnecessary damage and deformation of product. For the latter example, the barbs on porcupine quills were taken as inspiration for an adhesive patch, as the barbs on the quills open up and obstruct the backwards movement of the patch, holding it in place.

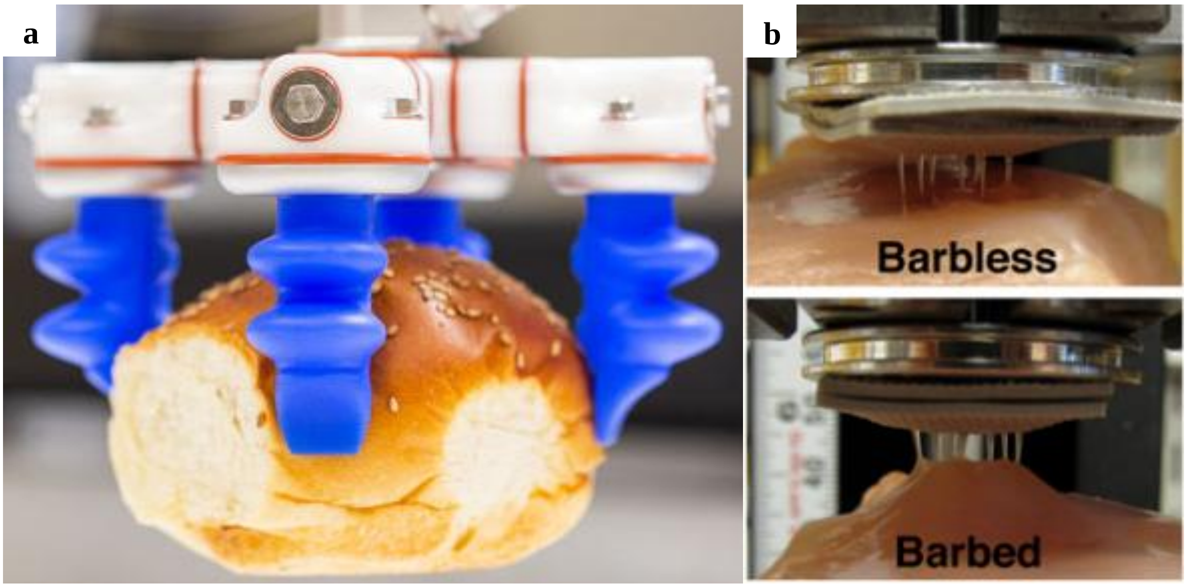

Figure 3: Examples of biomimetic adhesion. Soft grippers for food automation solutions[5] and porcupine quill inspired adhesive patch[15].

Therefore, biomechanics, that is already familiar to us, is also applicable to different principles rather than what nature has intended, which gives designing of soft robots a new dimension, as new use cases can be found for already known mechanics.

1.2 From nature to soft robotics

1.2.1 Biomechanics

Biomechanics is meant as the mechanical aspects of biological structures, for example movement mechanisms inhibited by different stimuli caused by some external cues from the surrounding environment. The observable biological systems are everything from mammals to plants and other growing and evolving organisms, therefore covering all parts of nature. The field is closely linked to biomimicry and bioinspired design, as studying biomechanics can introduce novel ideas in unexpected areas, but can also be used to study systems for better understanding or utilization of the observed phenomena.

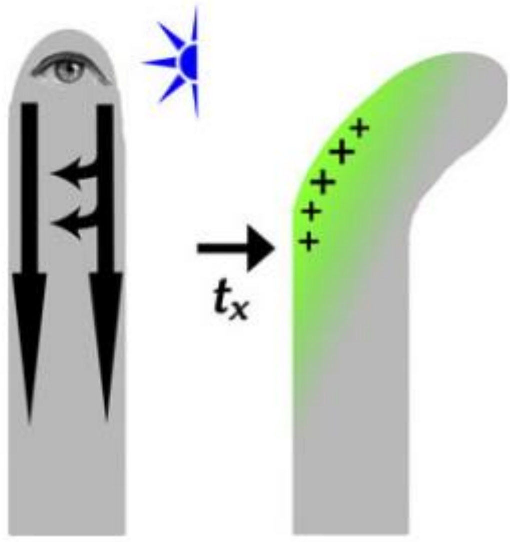

Figure 4:Movement mechanics of a coleoptile. One side of the coleoptile is exposed to a light source, which influences the coleoptile from top to bottom, inducing hormone movements from exposed side to the shaded side, which summons movement towards light. [16]

For humans, biomechanics mostly revolve around the elongation and contraction of muscle fibres to conduct useful work. For conventional robotics this mechanic is solved by using electrical motors to inhibit movement. Muscles also exhibit distributed functionality as apart from helping humans move, it also protects the inner organs and supports the human body. Even though plants are more static in their nature, biomechanics can be observed, e.g. some plants are able to turn towards or away from sunlight as seen on Figure 4[16]. In this case it is predicted that hormones are to be found on the shaded side of the plants' inner structure, which drops the pH level locally. This decreases the rigidness of structure, allowing the rise of Turgor pressure in the cell due to water and elongates one side of the plants stem, causing it to tilt towards sunlight.[17]

As soft robotics often mimics or is inspired by nature, biomechanical function can often be seen. Biomechanics also enables to mimic systems that resemble biological objects, e.g. humans, animals and etc., which can have various medical use cases.[18–21]

1.2.1.1 Turgor pressure

Turgor pressure is created by the water inside the plant which pressures the cell membrane against the cell wall. When pressure is high, the cell membrane is pushed against the cell wall, expanding it (Fig. 5). This is caused by the osmotic movement of water, which is trying to ensure an equilibrium between different spaces inside the stem, causing flow of water between spaces when necessary. The values of this pressure can range anywhere from 0.1 MPa to over 3 MPa[22] and it can potentially be measured by fine-tip pressure probing[23].

As turgor pressure has the power to expand the cell wall, use of the method has been investigated, e.g. Must *et al.*[24], where a tendril like soft robot was actuated by electrical stimulation of osmolyte. It was found, that the turgor pressure did not only change the outer dimensions of the robot to induce movement, but also showed variation of stiffness for the tendril. Due to this, the presented soft robot was able to compliantly interact with changing environment by being able to adapt in a dynamic environment and also the dynamic stiffness during usage to be able to grab different objects, exhibiting distributed functionality.

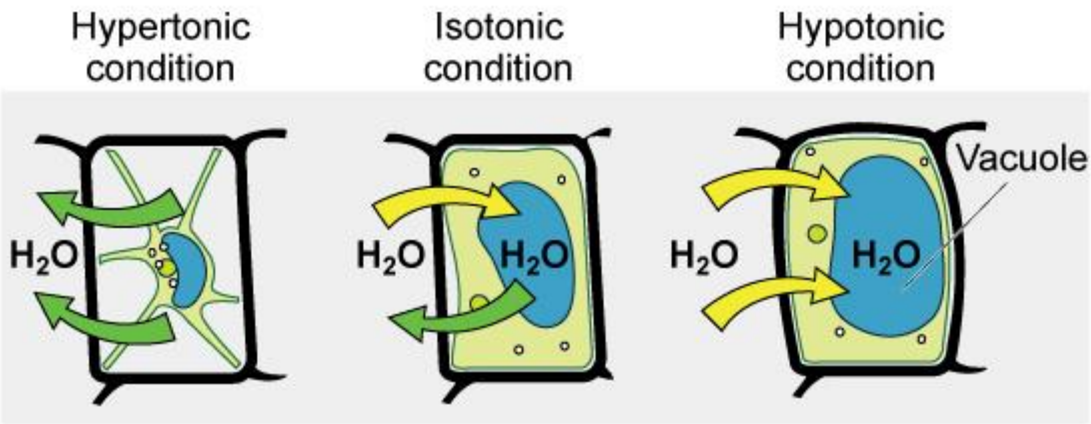

Figure 5: Three states of osmotic movement inside plants cell. Hypertonic condition corresponds to water flowing out, isotonic condition to equilibrium and hypotonic condition to water flowing into the cell. [25]

1.2.2 Distributed functionality – material level action

Conventional robotics often omits single functionalities to its parts, making them easier to comprehend and build, but making the fit to a complex system more challenging while also increasing the cost for different failures in the system. As in, when a single functionality component fails, it can be expected that this functionality is lost as no other component can take it over. For example, when the control functions, e.g. microcontrollers, are replaced with material level logic, those conventional control mechanisms are redundant and the complexity level of the soft system will drop as all necessary controls are in the material morphology and fault tolerance will be higher due to distributed functionality.

This way novel soft systems can be made that have the ability to mimic human bodies and functions, without using the rigid methods of conventional robotics, where many solutions consist of bearings, motors, pumps and wires. Mimicking the necessary functions using soft robotics would enable construction of highly compliant robots, that would replicate the distributed functionalities of human body making it more life-like and enabling the higher usage of such devices in medicine to replicate a convincing simulation environment.

Soft systems with distributed functionalities also need a control system, however they are usually made specifically for a robot to achieve compliancy and highest performance, one example of this is a soft valve. Producing any kind of changes in a biological or a soft robotic system assumes the use of control mechanism(s) to produce the anticipated result. Transportation of fluids is very common for biological objects - water, oxygen, blood or other compounds often need passage to a necessary location, which is why different valves are present in biological systems, e.g. plants[26] and the human heart[27]. Production of a valve is not considered something too difficult as a singular system, but making it part of distributed functionality system can create more challenges.

1.2.2.1 Natural distributed valve

One example of a distributed valve can be taken from poppy ovaries. Poppy ovaries are globular structures, that have poppy seeds growing inside. The inner structure is semi-compartmentalized to radial clusters and during growth the ovary is getting subsequently bigger until the seeds inside are ripe. As the ovary is closed off by a stigmatic surface composed of rays that are fused to the edge (Fig. 6), during ripening the ovary dries during which small pores between the ovaries and the stigmatic cover open.[28] During heaving caused by wind, the seeds begin to drop out of the ovary, dispersing in the area and is defined as poricidal dispersion. Due to such structure, the ovary is able to open up pores around the whole radii and disperse the seeds in all direction leading to better coverage for the plant. The principle of the mechanism could be translated to a valve to open and close multiple openings around a radius simultaneously.[29]

Figure 6: Globular poppy ovary, with a stigmatic cover and pores between the ovary and the cover.[30]

1.2.2.2 Example of a soft valve

Ideally, the incorporation of functions into the structure would be solved using a homogenous structure, which would be seamless and more durable. However, this poses great challenges to the production technologies, therefore alternative methods are used, e.g. laminate systems. Pontin *et al.*[31] constructed a laminate system, where inflatable membranes had a built-in control mechanism, which had the task of isolating leakages in the system from the main pneumatical circuit. They incorporated a soft control valve in between the different laminate layers (Fig. 7) and when the soft valve was pressurized, the control channel expanded, resulting in closing of the topological structure and subsequently isolating a broken area from the pneumatical circuit, to maintain pressure in the system. As control systems are essential parts of every robotic system, this seamless integration could be hugely beneficial.

As mentioned, fluid transport is detrimental for biological systems, therefore, integrating such soft control systems to simulation systems, would enable the design of more realistic simulation systems.

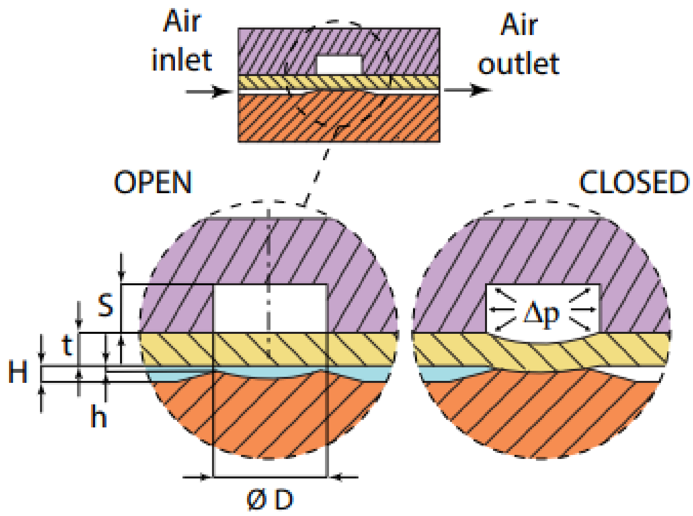

Figure 7: Soft control valve built by Pontin et al. D - diameter of control chamber, S - height of control chamber, H - height between yellow middle layer and base of orange bottom layer, t - thickness of yellow middle layer, h - height of the tip on the orange bottom layer, Δp – increase of pressure inside the control chamber.[31]

1.3 Simulation training: Mimicking human body in soft robotics

Studying biological systems and mimicking their functions enables the creation of realistic representations of objects or occurrences found in nature. As most objects in nature are distributed, mimicking these can be quite challenging. There can be different intentions for mimicking, solving a problem using nature or trying to copy nature directly. For example, previously mentioned Velcro falls to the first category as the intent was adhesion, not seed distribution, however, various humanoids fall to the latter as the intent is to create as human-like system as possible, for example, in medical simulations.

Simulation training is a hands-on approach where real-life methods are drilled during the learning process to gain more experience and knowledge through a bigger amount of repetitions to produce situational cues for faster adaption to a real-life situation. It allows the practitioners to have a better understanding of the field and allows greater pace for obtaining knowledge through accumulation of practical skills.

As medicine is dealing with life-threatening or quality-of-life altering decisions, it is considered a very high risk environment, therefore, it is expected that specialists have excellent skills in their discipline. This is done by emphasizing both theoretical and practical learning methods, where theoretical knowledge is embedded by practical operations to ensure the high-quality of medical professionals. One thing that stands out in the medical education is the amount of supervised practice-hours needed to graduate from educational institution and obtaining official credentials before they are able to receive patients solo.

1.3.1 Necessity of simulation

One method to give more practice for the students is to use simulation training, where the aim is to create a safe environment which has resemblance to a real-life situation. Medical simulations can be in form of walking through a set scenario using standardized patients or by using technologically enhanced simulations, with latter having better situational repeatability due to lower human factor and being available on-demand, which gives the students more opportunities to obtain practice hours on a topic. Combining technologically enhanced simulations with traditional practice has shown association with better learning outcomes.[32]

Therefore, incorporating simulation training to traditional practice methods has the potential to decrease the amount of medical malpractice cases by giving the students more practice hours due to better availability, but also giving already practicing medical professionals the opportunity to refresh their skills voluntarily or by assessing the medical competency after a set interval[33].

To achieve those goals, novel simulation methods have to be researched and bioinspired robotics could be a good start, as it tries to mimic the biomechanical properties found in nature, which are often under observation by medical personnel, making these solutions ideal for creating controlled near-life-like distributed functionality simulations.

Some scenarios, which are to be simulated could consist of chest compressions, observing human breathing, neurological or physical cues about the change of medical condition, broken bones, etc. All of them are dynamic in nature, meaning that the complexity of the system is high, which will pose great challenges on conventional robotics.

1.3.2 State-of-the-art of robotics in simulation training

There are various types of medical simulation devices available, with physical devices being around initially, but the development of virtual- and augmented reality technologies has opened the door to a wide variety of new training methods.

One of the more conventional physical devices is the SimMan® 3G (Fig. 8a), which is a life-size robotic manikin, that boasts high resemblance to a real human body. The aim of the patient simulator is to offer training on multitude of different medical procedures and patient cases by displaying different neurological and physiological symptoms as well as pharmaceutical responses to various drugs. This enables the user(s) to completely plunge into the patient case and navigate the situation by engaging with the manikin through measuring different vital indicators, e.g. blood pressure and pulse. The manikin is also able to show signs of respiration through bilateral and unilateral chest movement and allows physiological testing, e.g. movement of different parts of the body, like limbs and jaw. The chest movements, airway modes and fluid systems are driven by an internal compressor with a small internal reservoir with an additional port to support outside compression systems. Airway systems also use different bladders to simulate the chest movement for breathing, pneumothorax and lungs while there is a chest compression string for pushing back the chest during CPR. The detection of drugs is done my marking the syringes with RFID tags which will be read by the manikin to call out preprogramed actions. All transportation of gaseous or fluidic media is conducted over tubing system around the body to lungs, nose and bleeding ports.[34]

Figure 8: Examples of medical simulation systems. a) SimMan® 3G is capable of displaying a wide range of neurological and physiological symptoms[34], b) ImmersiveTouch creates a 3D-model of different scans for better understanding and interaction through VR[35].

The development of technology has enabled to create augmented reality (AR) and virtual reality (VR) environments for medical education purposes. The aim of AR is to enhance the user experience by overlaying computer generated virtual imagery to exactly overlay physical objects in real time[36] and could be used to obtain additional information of a situation or provide higher level of cooperation when marking areas in AR for multiple participants. While AR aims more to assist, VR plunges the user to a new reality where they can interact with the environment. This way visualizations or simulations of more complex patient cases can be made, which should decrease the probability of malpractice cases due to better preparation. One example of such system is the ImmersiveView and ImmersiveSim systems, which are able to translate various patient scans into a 3D model (Fig. 8b), that can be manipulated in AR or VR[37]. This way the user is able to have a new perspective on the gathered scans and make more informed decisions on a patient case or demonstrate the situation to a patient to give a better understanding. The simulation software can be used to plan different medical procedures by simulating it beforehand, through marking important areas or walking through the proposed methods for the procedure.

1.3.2.1 Example: robotic cervix for midwifery training

Midwifery is considered a practice-based medical field, in which the practical part should make up half the curricula as the main prerequisite for being a competent practitioner is confidence[38], therefore, acquisition of practice hours is of great importance. During active labour, the midwife is constantly assessing the condition of the patient to determine the need of intervention or other following actions. An integral matter for this is the stiffness of the cervix, which is subject to change during labour and it is sensed using palpation techniques by the midwife. This means that no numerical values are obtained and the analyzation and decision will be made from past experiences like training period under a supervisor or past patients, placing great importance to the quantity of practice hours. Using means of simulation training is immensely beneficial due to the repeatability and on-demand availability of the system.

Figure 9: Example of a simulation device in midwifery. Noelle version of Gaumard's Childbirth and Neonatal Resuscitation Simulator. [39]

Currently, one system used for simulation training features the use of a life-like robot manikin (Fig. 7), which is able to replicate most aspects of labour. It features an automatic labour system where the neonatal is pushed out using a metal rod, which is able to rotate the baby to match different scenarios, while some labour phases need to be changed physically to correctly represent a new situation. From the mothers' perspective, the manikin is able to give some neurological and physiological feedback, e.g. chest movements, eye and eye-lid movements, blood pressure and pulse. Those vital indicators are created by pressurized systems using pumps, e.g. bladders, electrical motors or sound cues, therefore using methods mainly found in conventional robotics. It is also able to distinguish different drugs administered using RFID's, when they have been previously documented and added to the software.[39]

The simulator enables to work through the entirety of labour process and it is programmable to go through different scenarios, therefore, it is able to create a diverse learning environment, where the users cannot only focus on a single task, but are stimulated to see the full picture. This way the users are more familiar with their theoretical knowledge and motor skills, which creates the prerequisites for a successful labour and lower the probability of misconduct.

1.3.3 Limitations

During the labour, among other vital indicators, the midwives have to measure the stiffness of the cervix, to assess the labour phase and prepare for upcoming stages. For the previously mentioned robot the current solution is to change out the simulated cervix to obtain change in stiffness to match the labour phases. This makes it impossible to palpate the dynamic change for the simulation robot and therefore pauses are needed during the simulation the change out necessary parts. Halting the simulation process could leave the students without the necessary references regarding that situation, therefore, being able to seamlessly facilitate the dynamic change of stiffness is an important part in making the process wholesome. Not only would solving this challenge enable to make the use of the system easier, but it would also make the training process more fluent and increase the resemblance to a real environment even further, by enabling the device to seamlessly interact with the surrounding environment.

2 Original solution

In this chapter, the original solution for a soft robot is presented, that is able to change the systems' stiffness dynamically. This task was divided into smaller objectives to focus on a single functionality. Later on hypothesis will be made and the design principles for the soft robot will be discussed.

2.1 Objective #1: Cellular system for dynamic stiffness

The objective is to create a cellular system, inspired from the build of plants, which through a control mechanism will be able to dynamically change its stiffness to match the situational needs. The system will feature a binary control system through a valve which is able to open and close all the cells inside the robotic cervix locally using fluids inside the control system. When the body of the robotic cervix's cell is probed, the pressure inside will increase similarly to Turgor pressure as discussed earlier, therefore, creating dynamic stiffness change. Similar phenomena can also be observed then pressuring a cell from bubble wrap, where the inner pressure of a cell creates a repulsion force when pressured.

To be able to feel a change in stiffness due to repulsion force while pressing on the cell, the systems' matrix would need to have marginal effect in the repulsion force, therefore, a soft matrix would need to be used. The intention is not to increase the volume of fluids inside the cell, but to trap the movement of fluids from the cell to create repulsion force inside it, that would create the effect of increased stiffness in the system (Fig. 10) and expanding the cell walls for the structure. When a valve is open, then the cells are connected to the ambient environment and the stiffness will be lower, and with a closed valve it will be higher, therefore, the system only needs energy for the control mechanism to open and close the valves, but will not change the pressure in the valves directly.

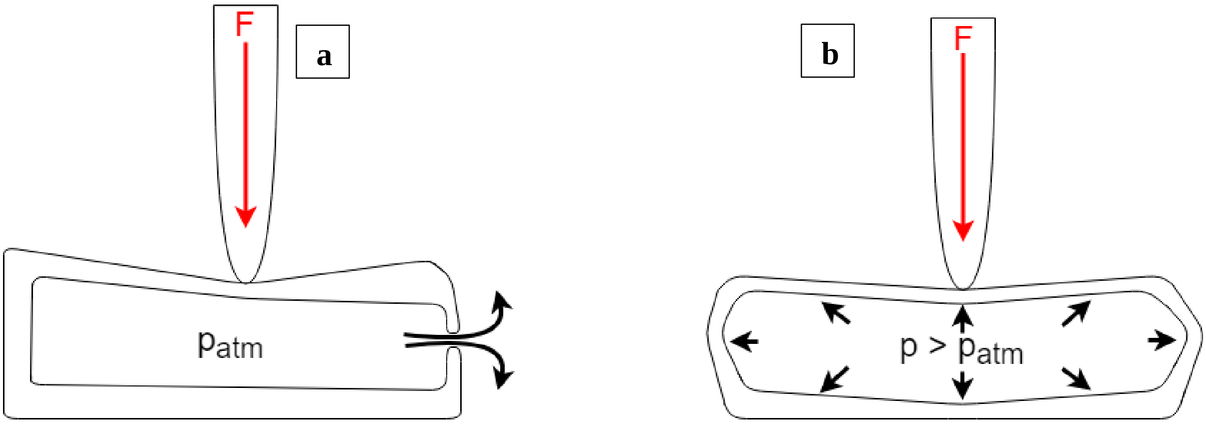

Figure 10: Description of the vascular cellular system for dynamic stiffness. Probing an a) open-ended cell will result in low repulsion forces due to equilibrium with the ambient environment, therefore, ambient pressure is preserved b) close-ended cell will result in repulsion forces as the fluid has nowhere to go, increasing the inner pressure, similar to Turgor pressure. Ambient pressure is denoted with p_{atm} and increased cell pressure with p.

The cellular structures needed can be found in the poppy ovary, which has radially compartmentalized seed clusters around the radii, as seen in Section 1.2.1.2 about the mechanics of poppy ovaries. For the solution used in this work, one end of the cell will be permanently closed, while status of the other end can be controlled. Taking inspiration from such build would be able to give the soft robot a solid structure, while enabling the dynamic change of stiffness due to the cells, which corresponds to the distributed functionality principle.

2.2 Objective #2: Design of soft distributed valve

To enable control over dynamic stiffness change, a soft valve is needed to control the flow of gas inside the cells. The valve is taking inspiration from the poricidal seed dispersion of poppies and is controlled by a single-tube pneumatic system, which will inflate the valve, opening all cells simultaneously, while enabling free fluid flow between the cells and outside environment as in Figure 11.

The main challenge with this objective relies on the distributed functionality, where due to compliance with the rest of the system, the valve would need to be from a soft material to become uniform with the main body. Additional constraint to the system is the need to switch all the cells at the same time. The initial, easier way would be to control each single cell by inserting tubes to them and having an outside control mechanism. A more sophisticated solution would be to build a soft valve which is able to switch all the cells simultaneously, without using any rigid materials, which would stand out from the significantly softer matrix. Using a tubular system for each cell would demand an off-the-system pump to pressurize the cells to an appropriate level, but this increases the complexity of the system and lower the compliancy due to the control system becoming so complicated and difficult to use, therefore, a single control signal is preferred. More in-depth discussion about the control system type is found in the upcoming section about design.

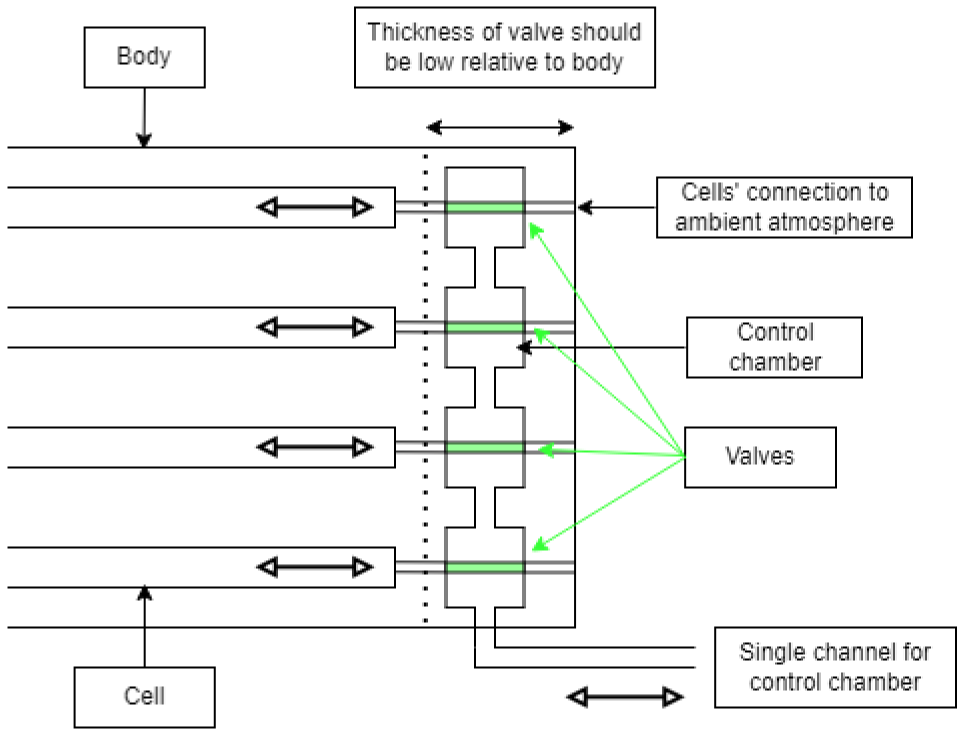

Figure 11: Concept of the soft valve for Objective #2. A single control signal is able to connect or disconnect the cells from the ambient environment simultaneously.

To build such a control mechanism, the part would need cover the entire bottom part to manipulate the status of cells. This could be done using a control chamber, which is pressurized according to need and the chamber swells up due to the excess fluids, causing a change of state for the cells by either connecting or disconnecting from the ambient environment. Dropping the control signal in this case would cause the valve to close the cells due to loss of energy and by switching between the states, one should be able to present a dynamic stiffness profile on a soft matrix. The two parts are then joined together, by casting an anchor like element between the parts to hold them in place.

2.3 Hypothesis

By switching the state of the valve from Objective #2, it is possible to produce dynamic stiffness change collectively in the cellular, distributed functionality soft robotic system created in Objective #1.

2.4 Design

Non-homogeneous joints are one of the weakest links of such structure as they break the uniform nature of rest of the robot and using adhesives to link them together will have lower strength. For this reason, ease of manufacturability and lower deviation from the intended dimensions, the robot was designed to feature as few parts as possible. Therefore, due to manufacturability, the soft robot was designed as 4 separate parts – lid, body, valve membrane and valve base.

2.4.1 Manufacturing

As the system design assumes a soft matrix, 3D-printing and casting were the main methods considered. One of the future scopes, which will be introduced later, of this work is the integration of fibres into the soft matrix, which cannot be done using 3D-printing, leaving casting as the method of choice. To create a human tissue-like matrix, silicone Dragon Skin 10 NV by Smooth-On Inc[40] is used due to its similarity.

Casting silicone creates the need for moulds for non-planar parts in the assembly. One of the implementation focuses was the ease of manufacturability, by having low part count for assembly and the usage of poka-yoke principles, single direction assembly, which would enable easier assembly, while also lowering the risk of defects during casting due to not allowing incorrect assembly by design. For these purposes, the moulds for revisions were designed in a way to allow a single assembly direction, using radial guide elements to direct the parts to correct positions on one or both ends of the mould.

The moulds were created using 3D-printing as the batch quantities are small and revision changes were frequent, it also offers sufficient accuracy along with ease-of-use and low cost, therefore, this method was chosen to create the moulds needed for this thesis.

2.4.2 Body

As the system has to facilitate the dynamic change of stiffness, they need to have empty deformable spaces or cells in the outer shell of the soft system, similar to Figure 5. The walls of outward surfaces cannot be too thick or the system will become more stiff, resulting in lower relative change of stiffness and the cells for the soft system were designed as single-ended channels of almost length of the robot, resembling vascular channels. For manufacturing purposes, the body of the robot will have open ended cells to allow fixing the position of the mould from both sides of the body, permitting better repeatability during casting. For testing and manufacturing simplicity, the main shape used for the system was abstracted as a cylinder.

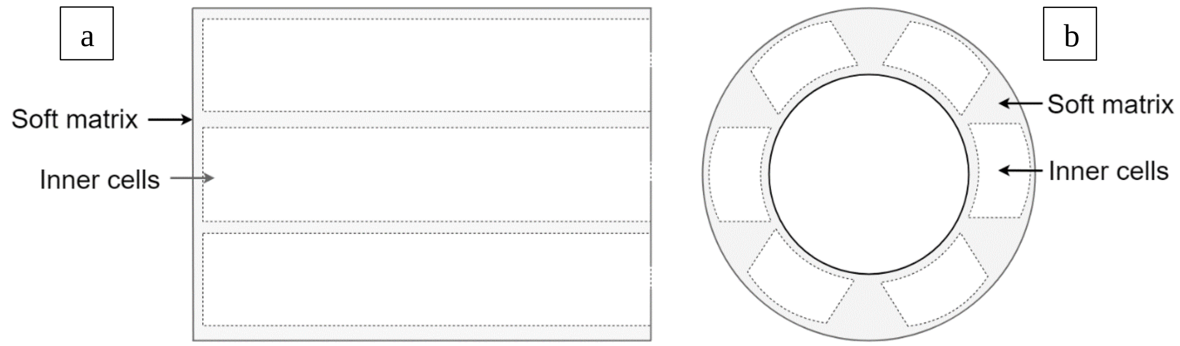

Figure 12: Vascular design for the systems' body as radial cells around the radius, shown as cross-sections from the a) side and b) top.

For additional structure, the system will feature vascular cells around the radii of the system as in Figure 12b, which are connected to the ambient environment via soft distributed valve. When closed, this structure would create repulsion forces due to increased inner pressure in the cell when closed, creating dynamic stiffness change in the system. The structure will be designed to facilitate stiffness change more towards to outer surface of the system rather than between the cells, by creating thicker boundaries between cells relative to outer surface, allowing palpation to be performed.

2.4.3 Lid

Body of the system features openings on both sides of the vascular structures. A lid was designed to permanently close off one end of the body, to enable state control over the other end for dynamic stiffness. For better placement the lid features smaller dimensioned guides (Fig. 14), that fit to the cells and making a more uniform connection to the system due to increased surface area for the adhesive. As the lid itself will not be palpated, the thickness of this part can be an order of magnitude higher, 2 mm, to allow stronger structure at the tip of the system. The smaller openings for the cells will be controlled by a soft valve.

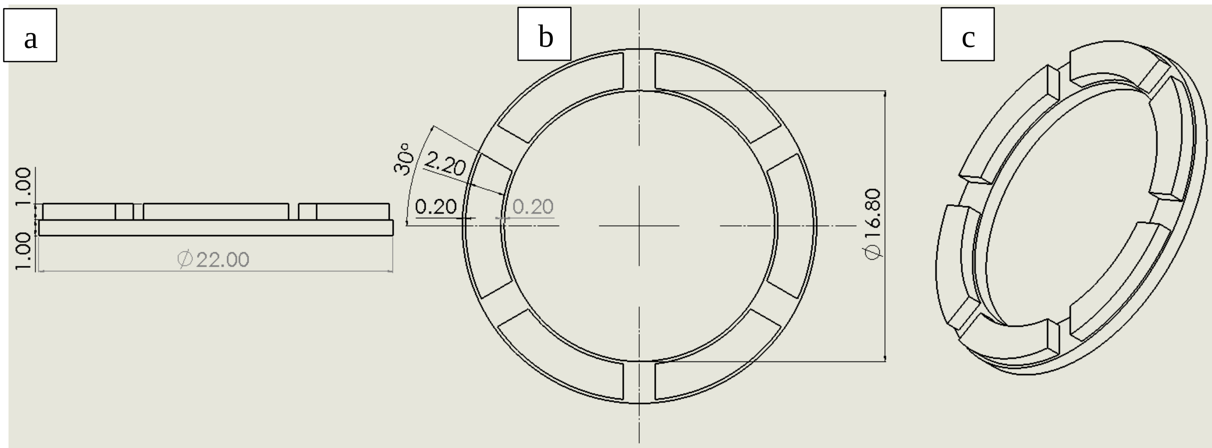

Figure 13: Views of the lid: a) side view b) bottom view c) isometric view

2.4.4 Valve

Four designs were considered for building the control mechanism of the valve:

a) Each cell is connected to a single pump via a tube (Fig. 15a)
b) Each cell is connected to a single valve via a tube (Fig. 15b)
c) All the cells are connected to a pump via tubes (Fig. 15c)
d) All the cells are connected to a valve with distributed functionality (Fig. 15d)

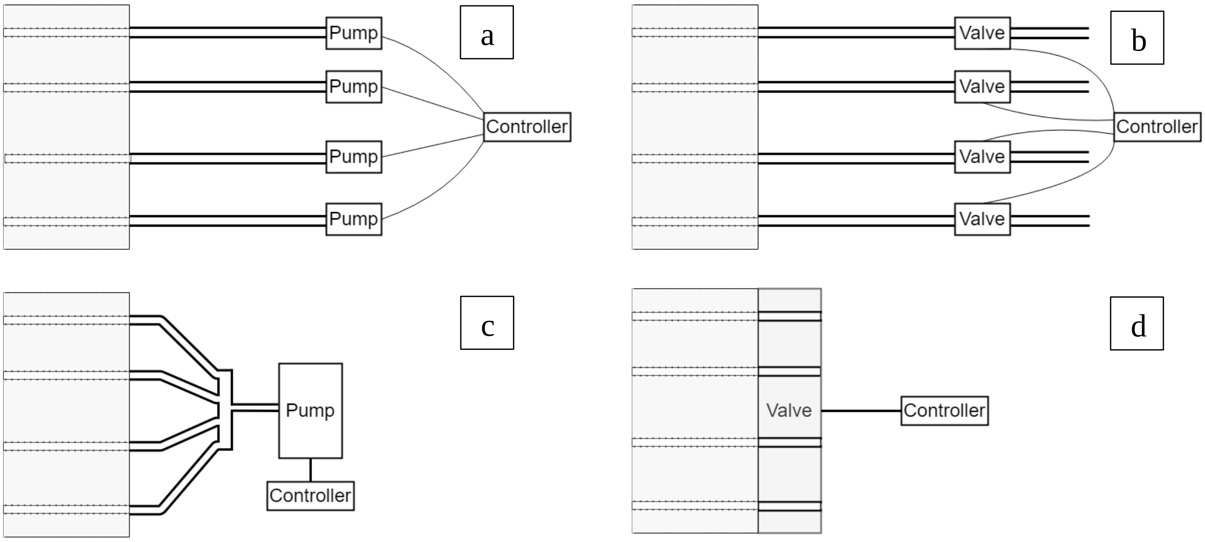

Figure 14: Design ideas for a soft distributed valve: a) Control pump for each cell via tubes b) control valves for each cell via tubes c) single control pump for controlling of all the cells simultaneously d) single control valve integrated to the system to control all cells simultaneously.

The first two designs required an outside controller to direct the work of the pumps and valves (Fig. 15a and 15b), while also featuring an inconvenient tubular system making the system more complex and less compact as more external modules are needed. As there is no explicit need to obtain varied stiffness for the cells, the need for external pressure systems (Figure 15c) becomes redundant, lowering the complexity of the system. To be able to sense the dynamical change of stiffness, it is unnecessary to control the exact value of the cell pressure - only the cell states need to be differentiable, which can also be achieved with a central valve controlling all the cells at the same time (Fig. 15d). This enables the use of a distributed functionality valve, while also dropping the need for a noisy pump, which could become a distraction during the simulation. Using the principle on Figure 15d also allows to design a system where the valve is seamlessly integrated to the system after assembly, which corresponds to the distributed functionality concept, therefore, this was chosen for modelling. Using this, 7 ideas were developed in the scope of the chosen design.

2.4.4.1 "Sock-like" approach

The sock-like valve was designed to utilize the symmetrical cross-section of the system and block the channels connecting to ambient environment from the cells. The valve was attached to the base of the cylinder and when necessary, the sock could be pulled over the channels to block cells from ambient environment as in Figure 16.

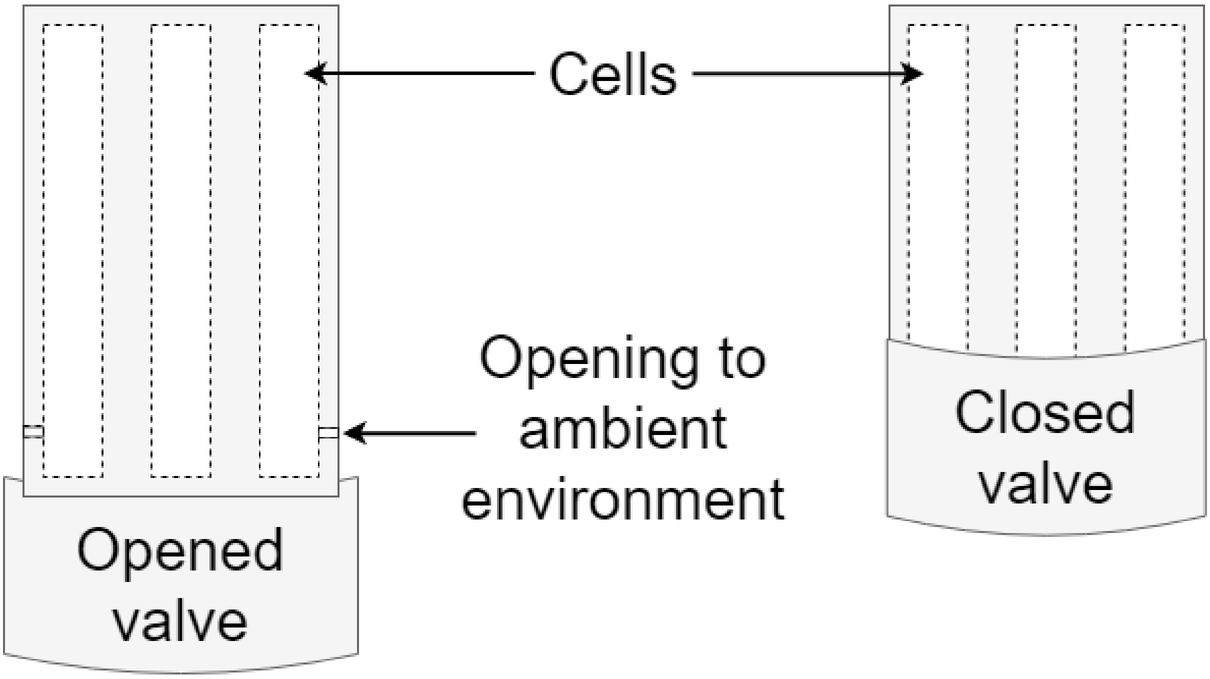

Figure 15: The sock-like valve can be pulled over the openings connecting cells to ambient environment. Opened cells and closed cells on right and left respectively.

2.4.4.2 "Strangulation" valve

Using a soft silicone matrix for the system allows elastic deformations. When threads are integrated into the system in a knot-like configuration as in Figure 17, it should be possible to induce temporary decrease in the radius, as when the threads are pulled, the radius of the "knot" decreases along with the radius of the valve, therefore, shutting the ports. To allow better dynamic properties, silicone oil was introduced to the system.

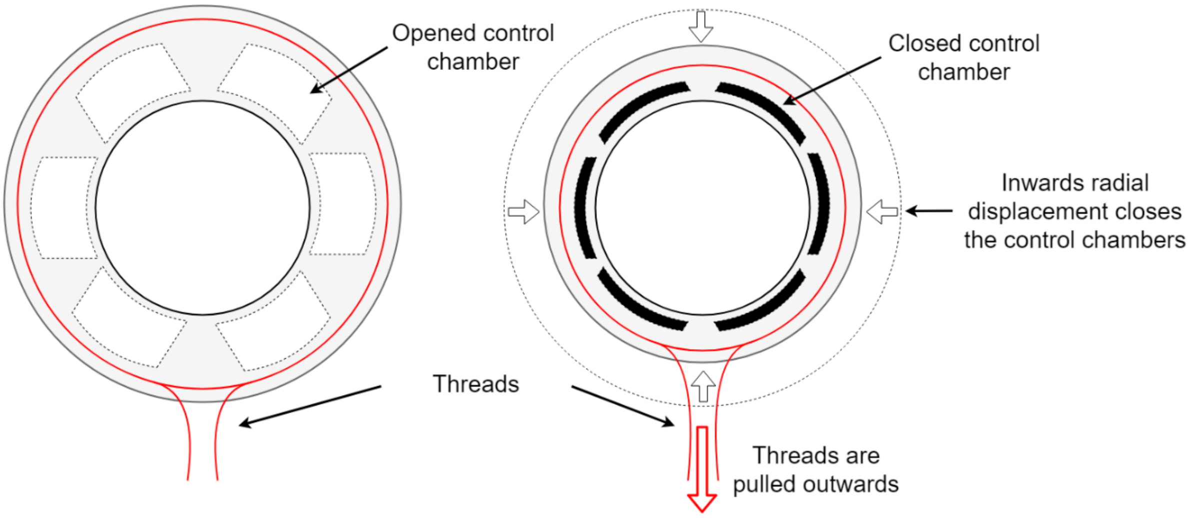

Figure 16: Opened and closed state of the threaded valve in right and left, respectively. The threads are denoted with red and closed valves with black.

2.4.4.3 Control chambers

A control chamber is a hollow structure inside the soft matrix, which will expand as pressure inside increases. Paired with a thin membrane between the control chamber and valve ports it enables to shut the fluidic movement between the cells and ambient environment through the valve ports. This is facilitated by design, as the membrane is to have thickness of 0.2 mm, while other parts will be thicker, therefore, the membrane will start expanding due to concentration of mechanical stresses. Due to cylindrical shape of the system, the intended expansion will also be radial, with four different designs created with control chambers.

2.4.4.3.1 Custom silicone tube

The most straightforward method for a control chamber would be the integration of a radially placed silicon tube to the system. Per design the thin tube was casted, as the commercial counterparts had too high thickness for their outer surfaces. The tube (d=2 mm, thickness≈0.1 mm) was positioned by the inner surface of valve ports as in Figure 18a, to achieve the membrane thickness of 0.2 mm between the tube and valve ports. When a control signal is inserted to the tube, e.g. pressure increases by Δp, then the tube is expected to expand radially outward to fill the valve ports, closing the bidirectional movement of fluids between the ambient environment and the cells (Fig. 18b). To allow better hermetic seal, the shapes of valve ports was designed as half-circles to remove possible leakages in the corners.

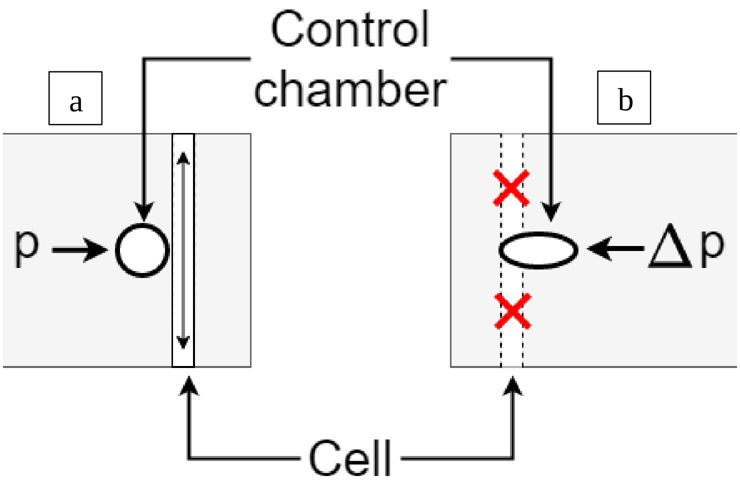

Figure 17: Partial cross-section of a) opened and b) closed valve on left and right respectively. The valves' control chamber is made using a custom-casted tube.

2.4.4.3.2 Thin film

A thin film (<0.2 mm) was designed to be casted into the soft matrix in a similar manner as the previously mentioned tube. After aging the film is to be removed, creating a small radial chamber as in Figure 19a, allowing bidirectional fluid movement between the cells and the ambient environment. When the thin control chamber is pressurized by Δp (Fig. 19b), it will expand due to same mechanism as described in the last section, swelling the valve ports shut and disabling fluidic movement.

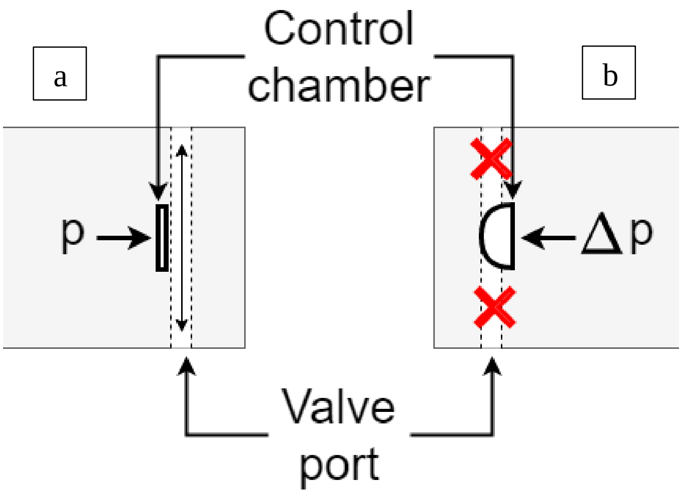

Figure 18: Partial cross-sections of a) opened and b) closed valves on left and right respectively. The valves' control chamber is made using a temporary thin film.

2.4.4.3.3 Longitudinal control chambers parallel to valve ports

Longitudinal control chambers were integrated to the linear side of the ports, placed to 0.2 mm from the ports' surface (Fig. 20). To connect the longitudinal chambers a perpendicular radial chamber (Fig. 20 red dotted line) was designed beneath the longitudinal chambers, as a separate bottom piece, to allow simultaneous control over all ports.

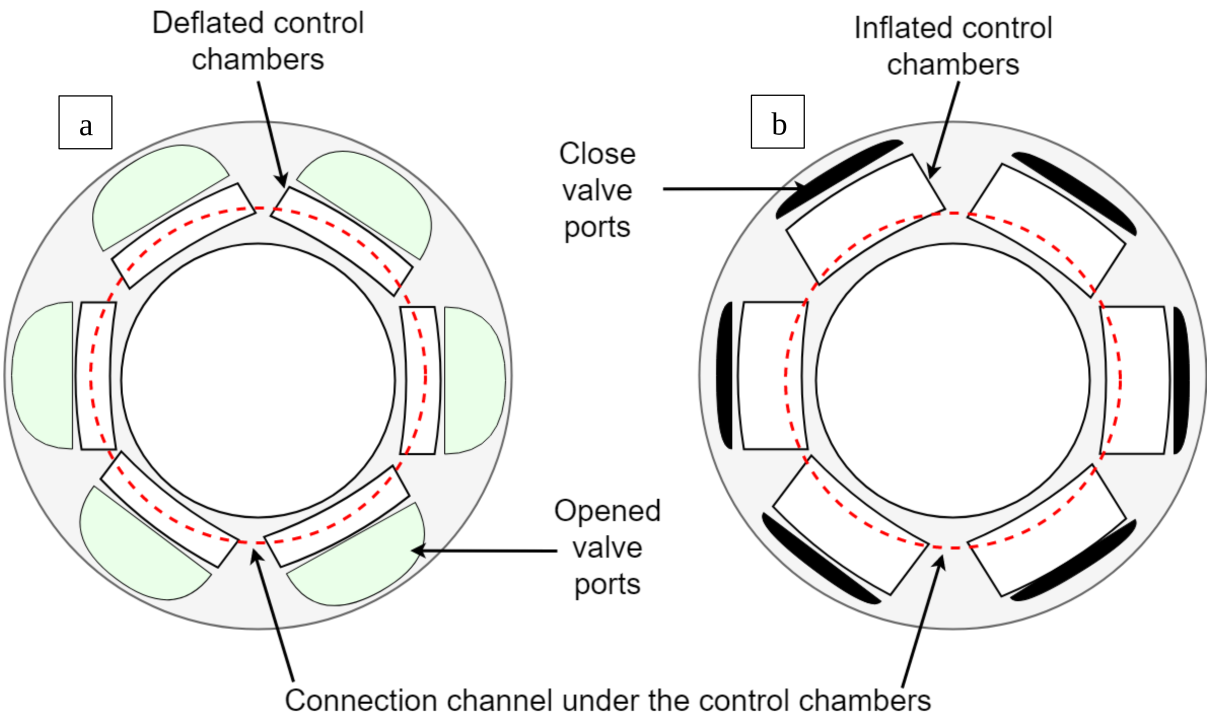

Figure 19: a) Opened and b) closed cells on right and left respectively, where control chambers are situated behind cells.

2.4.4.3.4 Central control chamber

The valve was designed as an assembly of 3 parts – bottom piece as control chamber, thin membrane and tube for control. The bottom piece featured a ring-shaped control chamber along with the control tube to enable forwarding of a control signal to the chamber. The chamber is covered with a thin membrane, which grants a single convenient expansion direction for the membrane, due to its low thickness relative to rest of the valve. This way, when a control signal is given, the expansion causes displacement on the edges, opening the cells to ambient environment.

3 Methods

The general research flow started with implementing the initial plan through 3D-modelling after which moulds were created using 3D-printing. The moulds were assembled and silicone was casted inside it, after which it was left to cure overnight in room temperature. After demoulding, defects were removed from the casted piece, e.g. burrs and when necessary, additional pieces were connected with an adhesive to finalize the assembly. Later on visual checks were implemented to ensure correct working principles which was followed by pressure measurements on the casted piece's body.

3.1 Modelling

In the scope of this work, 8 iterations of models were created, using SOLIDWORKS 3D-modelling software, which were denoted as letters starting from "A" to letter "H". Each modelling iteration started with set implementation focus which acted as guidelines by which the new model was created. Focus for the iterations were derived from the design requirements, previous limitations or from feedback of previous iterations.

3.1.1 Body

To allow later assembly of the soft valve, an anchoring system with angled surfaces was designed to allow the fixation of the valve and enable reliable positioning during usage cycle. For testing and manufacturing simplicity, the main shape used for the system is abstracted as a cylinder and the body itself has openings on both sides and the created system is shown on Figure 21.

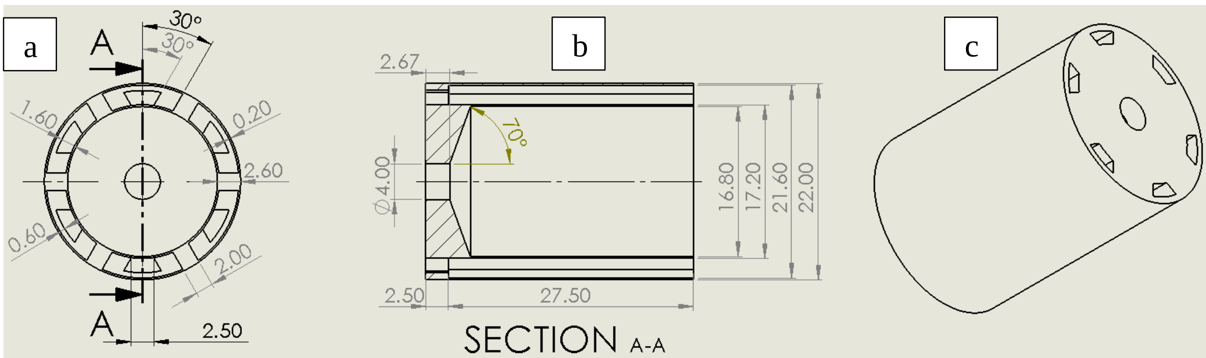

Figure 20: Views of vascular cellular system, from left to right: a) top view b) cross-sectional view c) isometric view, respectively.

A total of 6 cells were placed uniformly around the radii to provide a supporting structure while permitting palpation of the system. This build enables to change the stiffness due to repulsion forces inside the cell. For better tactile feedback, the outer wall thickness of 0.2 mm was chosen, while thickness of walls between the cells was chosen as 2 mm to understand the effects to adjacent cells and to increase structural stiffness.

3.1.2 Valve

All the valves described in the design section consisted of casted silicone parts, while most being single- or double-part systems. As for most valves, external added parts, e.g. tube and film, needed fixation during casting, therefore, different supporting structures were designed for the moulds used in the casting process.

3.1.2.1 Strangulation loop

Support structures were designed to the moulds to fixate the threads with the correct radius at the specified height using assisting structures. As the positioning of the threads was done using assisting poles on the mould (Fig. 22), additional openings were created in the structure, from where the threads were visible, connecting them to the ambient environment, which did not have any negative effects to the system. Through the same openings silicone oil can be introduced to enhance the dynamic properties of the valve.

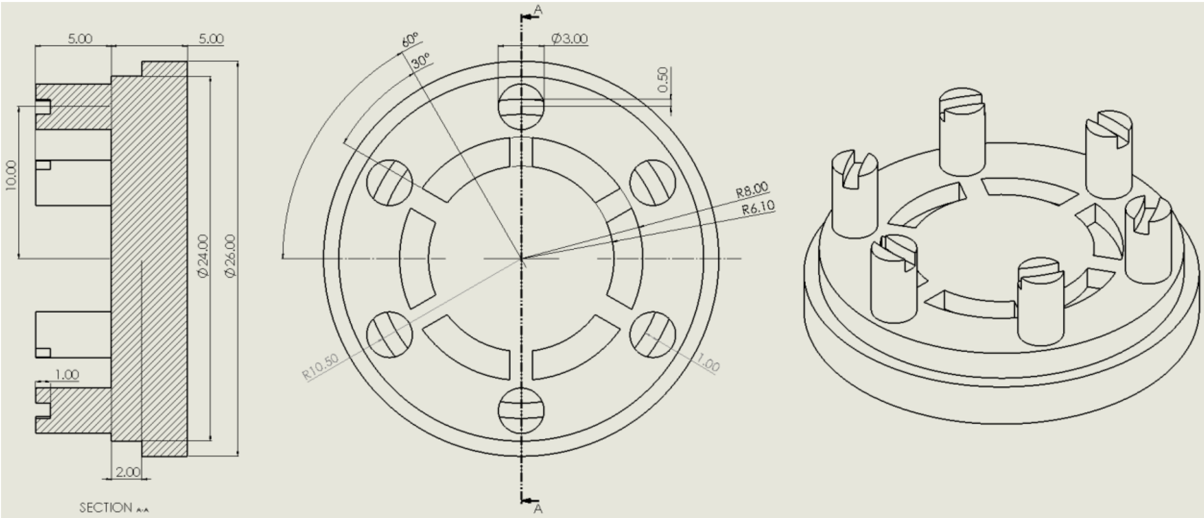

Figure 21: Assisting structures used for fixating threads. From left to right: a) cross-section b) top view c) isometric view.

3.1.2.2 Tubular and thin control chamber

For longitudinal and central control chambers, additional structures were not needed as external elements were not used inside the matrix. For the creation of chambers with a custom tube and a thin film, assisting structures, similar to the one in previous section, was needed. Two implementations were created for this, seen on Figures 23 and 24.

For the custom tube a knitting needle (d=2 mm) was used. The needle was covered with a layer of wax on to which silicone was poured. The needle was turned until skin had cured to allow a more uniform and thin walls for the tube and then left overnight to cure. Then the needle was warmed to melt the wax and enable dismounting of the created tube. For casting the tube as a chamber to the matrix, a V-shaped pole was placed by the inner surface of valve ports. The tube would then be inserted onto the pole and an opening would be created after removing the mould, which will not have negative effects on the control mechanism.

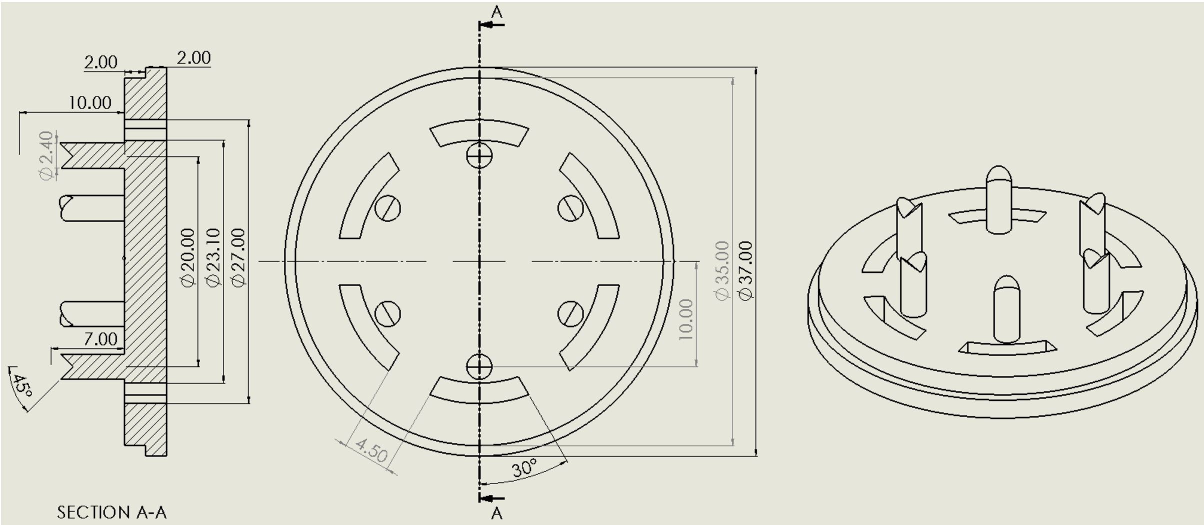

Figure 22: Support structures on the mould for valve with thin tube control chamber. From left to right: a) cross-section b) top view c) isometric view. Support structures are placed behind the valve ports.

To fix the position of a thin film, similar structures were used, however, to hold the film, thin slits were created to the top of the structures. Relative to the previous structure, on Figure 23 the structures are placed between the valve ports to enable closer positioning relative to the ports. After casting the moulds and the film was removed, leaving openings to the channels and not holding pressure, due to which, all but one opening was filled. The single opening was then used to control the pressure inside the chamber.

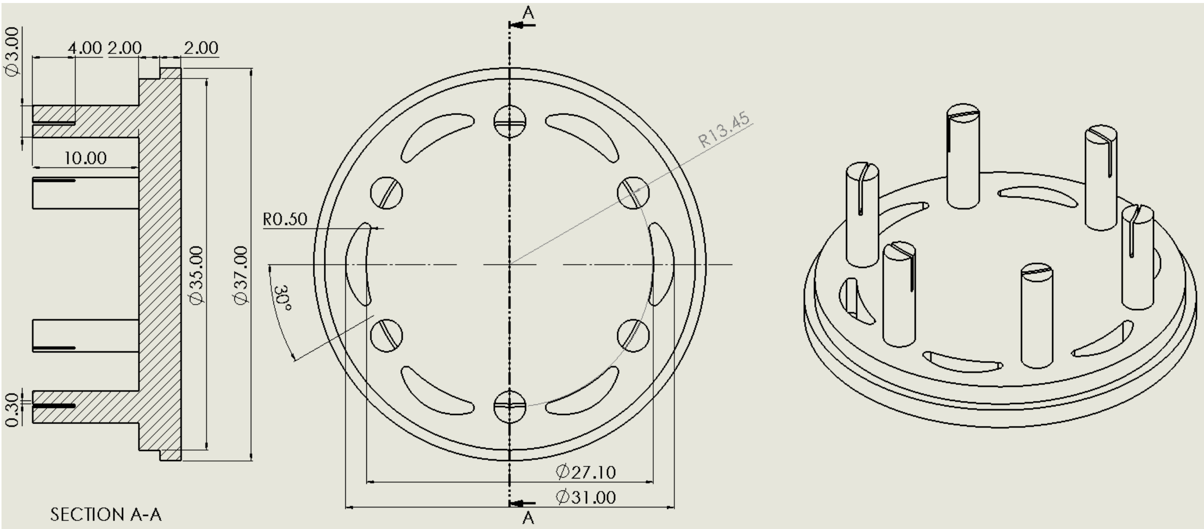

Figure 23: Support structures on the mould for valve with temporary thin film. From left to right: a) cross-section b) top view c) isometric view. Support structures are placed between the valve ports.

3.1.2.3 Ring-shaped control chamber

The design features a 3-piece assembly due to ease of manufacturability as the complexity of a single-piece part increases rapidly. The bottom piece of the valve is presented on Figure 24 and shows a ring-shaped control chamber, which will be covered by the thin, 0.2 mm membrane. The part features a concentric hole (Fig. 24b) for anchoring to the cellular system.

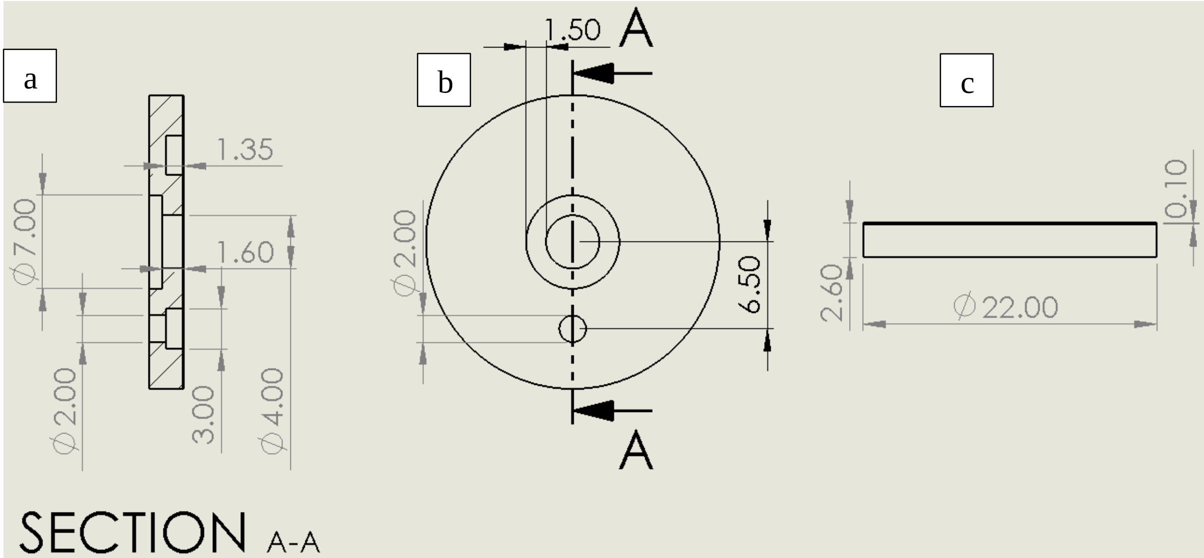

Figure 24: From left to right: a) cross-sectional b) bottom c) side view of the soft valves' bottom piece, respectively.

3.1.3 Revisions overview of valves

In the scope of this thesis, 8 revisions were designed and Table 1 affiliates the design ideas with revisions.

Table 1: Valve designs corresponding to revisions.

Rev.	Valve design
A	"Sock" valve
B	"Sock" valve
C	"Strangulation" valve
D	Tube valve
E	Thin film valve
F	Thin film valve
G	Longitudinal chambers valve
H	Ring-shaped central valve

3.2 Manufacturing

The manufacturing process can be divided into 3 separate subtasks – 3D-printing of moulds, casting, and assembly. Apart from printing moulds, the casted details and assemblies were aged overnight to ensure sufficient strength for the parts.

3.2.1 3D-printing of moulds

As some inner wall thicknesses of the structure are relatively low, capable manufacturing methods were needed, therefore, 3D-printing was used for creating moulds. After creating the part models using 3D-modelling software, the moulds were created according to the parts models and were then converted to *stl* format, which corresponds to ***S****tandard* ***T****riangle* ***L****anguage*. For printing, *Original Prusa i3 MK3* printer was used along with *PrusaSlicer* which was used to auto-generate the G-code for the printer, which will move the printing stage and printing head, while also controlling printing parameters during operation. Whenever possible, the printing direction was addressed during G-code generation so that it would match with the direction of decoupling of the mould and the casted part. This was done to ensure lower friction force between the mould and the casted part as it is possible to create defects during this process and ensure bigger strength and less sway for the longitudinal mould elements. However, for some moulds this was prevented due to overall design of the part which prohibited printing in the desired direction. Due to this the longitudinal elements, with single point of fixation on a single end, had the possibility to sway in from side-to-side, which can cause deviations from the set thicknesses, which can be highly problematic for thicknesses around 0.2 mm. This was solved by implementing fixation points on both ends of the mould, either by through-holes or a hollow hole, which also only allows correct assembly methods to be used.

3.2.2 Casting

Before casting, the moulds were sprayed with release agent (*Mann Ease Release ™ 205 Release Agent*[41]) to ease decoupling as defects could be introduced to parts due to high adhesive force between the part and the mould wall.

The two-component silicone was mixed in the ratio of 1:1 and properly stirred to obtain uniform mixture. During stirring, a few drops of *Silc Pig™ Blood* dye[42] was introduced to lower transparency of the silicone in order to have better visual oversight. The mixture was placed into a vacuum oven and pressure of < 10 mmbar was reached at ambient temperature to eliminate most of the air bubbles formed inside the mixture during stirring. After vacuuming, the mixture was poured inside the mould after which it was left to cure overnight. The decoupling was done carefully to decrease the probability of different surface defects and burrs and other casting defects were eliminated.

The valves' membrane is the only part in the system that is not casted into a mould. As the membrane for the valve has a thickness of 0.2 mm, a Casting Knife Film Applicator Elcometer 3580/1 was used, for which the thickness of the film can be modified using turn knobs, with a lowest increment of 0.01 mm. A plastic film was coated with the release agent mentioned earlier and a volume of silicone mixture was poured onto it. Then the Casting Knife Film Applicator was pulled over the silicone to obtain the desired thickness of membrane and left to cure overnight before assembly.

3.2.3 Assembly

Two distinct phases can be seen during the assembly – pre-assembly and main assembly. During pre-assembly, the lid was connected to one end of the soft systems' body and the valve membrane was connected to the valve base. During main assembly, the assembled valve was placed concentric to the anchoring slot in the bottom of the soft systems' body. For both assemblies, the connections were done using the same casted silicone as used before, as an adhesive and the assemblies were kept overnight to cure.

The plastic film used for casting the membrane was kept on during the pre-assembly of the valve to decrease the probability of two silicone surfaces sticking to each other which will result in defective membrane due to its low thickness. The plastic film was removed after overnight curing.

3.3 Measuring system

Two measurement systems were used in the scope of this thesis – a) a pressure sensor connected to a probing system to measure the repulsion forces inside the cell b) laser distance measurement device with a pressure sensor to measure the relationship of pressure *vs* vertical displacement due to inflated control chamber. The measurements were done on separate systems.

3.3.1 Stiffness characterization of a synthetic vascular tissue

The stiffness of the soft system was measured in two states – closed cells and opened cells. For measurement, a custom built probe system with an force sensor was integrated to a moving stage, used as described by Johannes Muru in his work "*Design of Dynamic Anisotropy for Soft Robotic Simulation Trainers*"[43]. The measurement was conducted on a single position in the middle of the cells' outer surface (Fig. 25), by configuring the probes' stage movement using G-code.

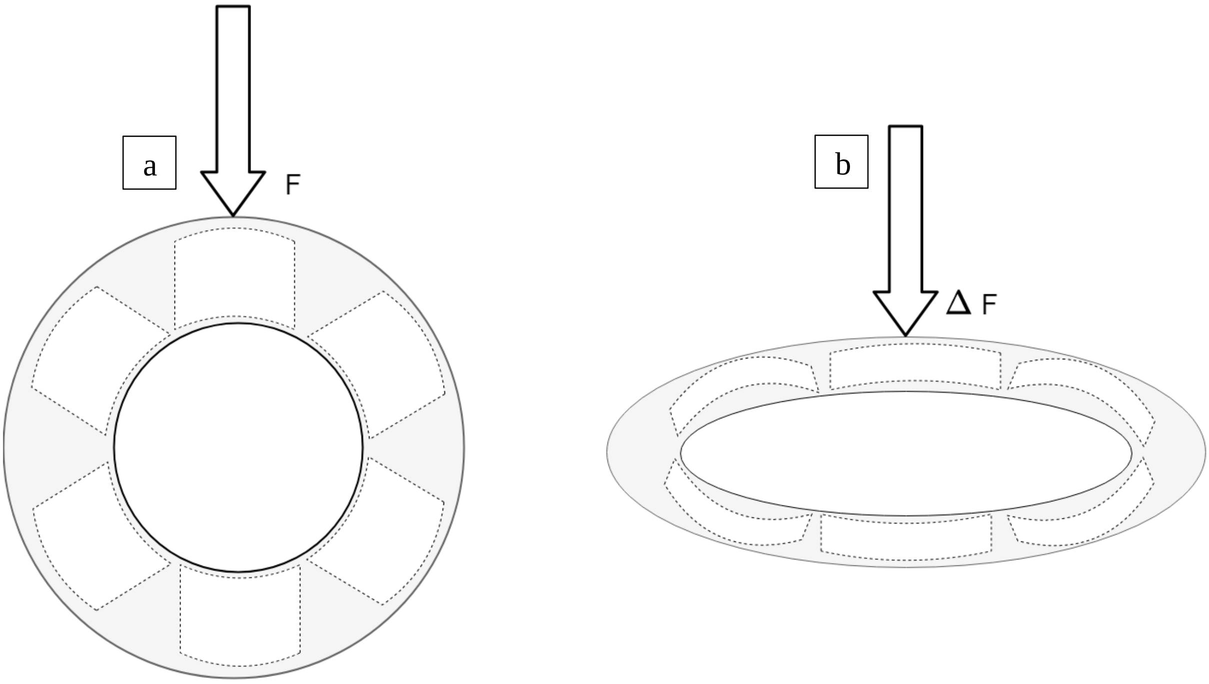

Figure 25: Measurement scheme for Method A. a) pretension F is applied, no significant displacement b) force ΔF is applied from up-to-down direction and causes displacement in the system.

The probe was moved into contact with the surface of the systems' body, creating slight pretension. From that stage the probe was lowered by 2-10 mm depending on the measurement configuration, reversible deformation in the system. Voltage on the force sensor was read using National Instruments USB-6211 data acquisition device (DAQ). The scheme used for the measurement is shown on Figure 26. The force sensor was in a Wheatstone bridge configuration, meaning that to observe small changes in voltage an instrumental amplifier INA 128P was used with G=501, which all was powered by 2x3 V batteries in series. Four measurement configurations were used with this setup:

a) 10 mm displacement induced on the cells' surface
b) 2, 5, 8 and 10 mm displacements induced on the cells' surface
c) Method B as a 3-point pressure test
d) Method B on the wall between the cells

Method A configuration produces displacement similar to the system radius, therefore, deforming all the cells in the system. Method B measures the stiffness profile of the system as a range of displacements is induced. Method C was set up to observe the stiffness change during operational use, which is similar to the 3-point test used in mechanical testing. Method D is used to understand if the stiffness profile is present when structural parts of the system are displaced instead of the cells. All measurements were conducted on a flat surface, if not specified otherwise and two-point calibration was performed using known weights for the force sensor in the system.

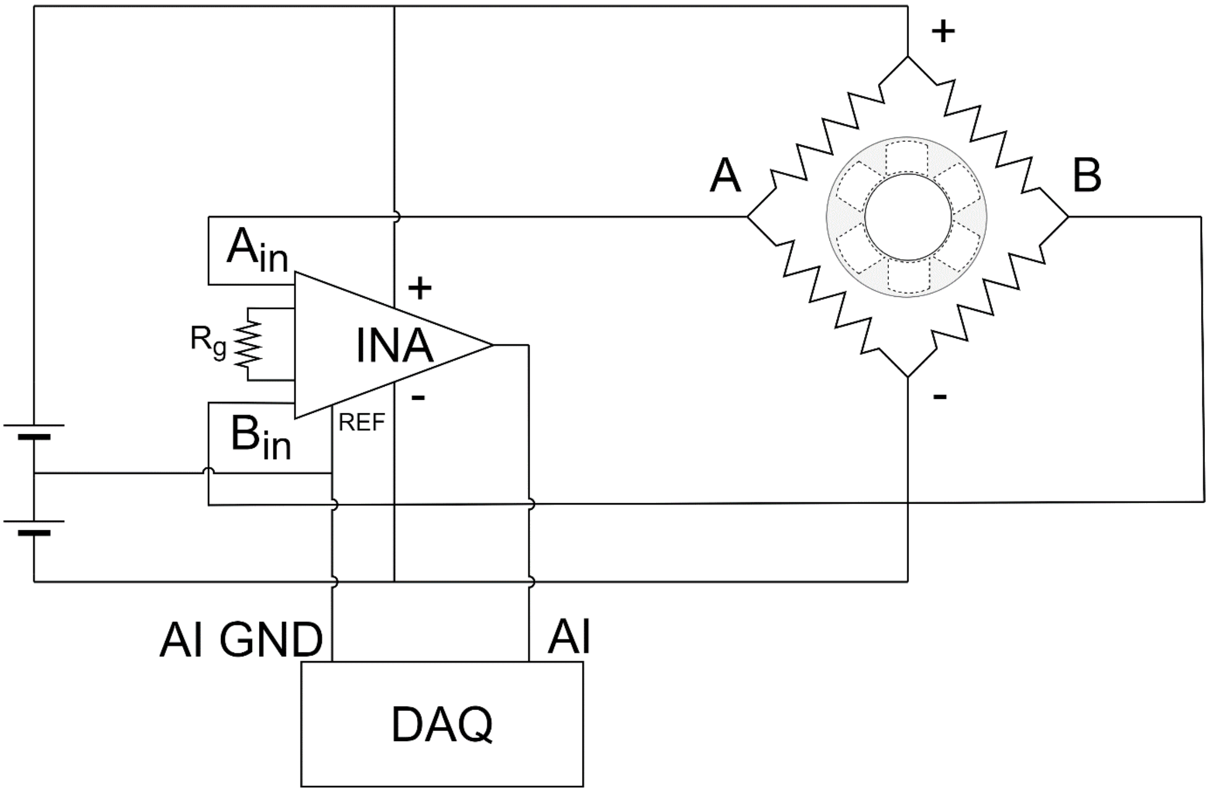

Figure 26: The stiffness measurement scheme. It was conducted using INA 128p, G=501, Wheatstone bridge force sensor and 2x3 V batteries for power. The amplified voltage difference in the Wheatstone bridge was read to an analogue input (AI) of a DAQ device connected to a PC.

3.3.2 Displacement of soft valve during increased control chamber pressure

When the pressure in valves' control chamber increases, it starts to expand, lifting the edges of the valve and opening all the cells in one operation. For characterization the vertical displacement caused by the swelling of the valve was measured along with the change in valves inner pressure, independent from the rest of the system. The displacement of the valve was measured according to Figure 27, where a reflecting laser beam is measured using Keyence LK-G10 laser distance meter and LK-GD500 controller and voltage on the controller was read from NI SC-2345 device to a PC.

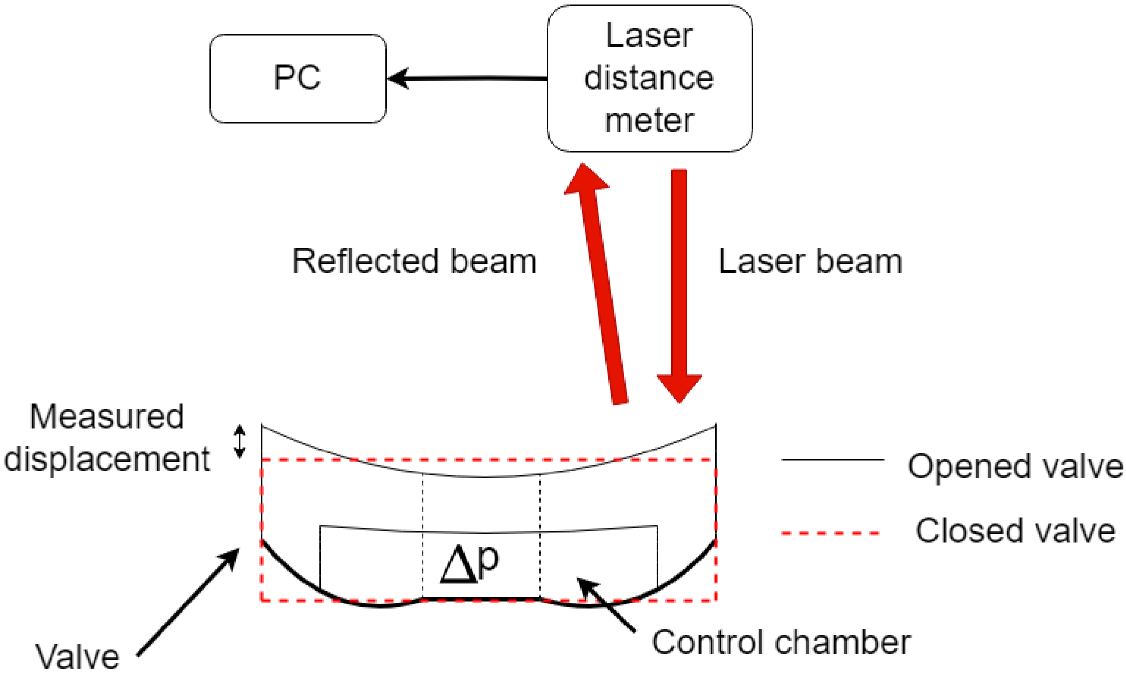

Figure 27: Schema of soft valve measurement. Here the vertical displacement was observed.

Control signal to the valve was given using a manually controlled syringe. Approximately 0.1 mL of air was pumped into the control chamber via a tube to increase pressure. The pressure of the control chamber was measured using a Honeywell 24PC Series 4CF6D pressure sensor, that was connected to a NI USB-6211 data acquisition device. The full measurement scheme can be found on Figure 28 for pressure and displacement measurement loops in orange and green respectively. Two-point calibration for the pressure sensor was done using a commercial blood pressure meter as the reference.

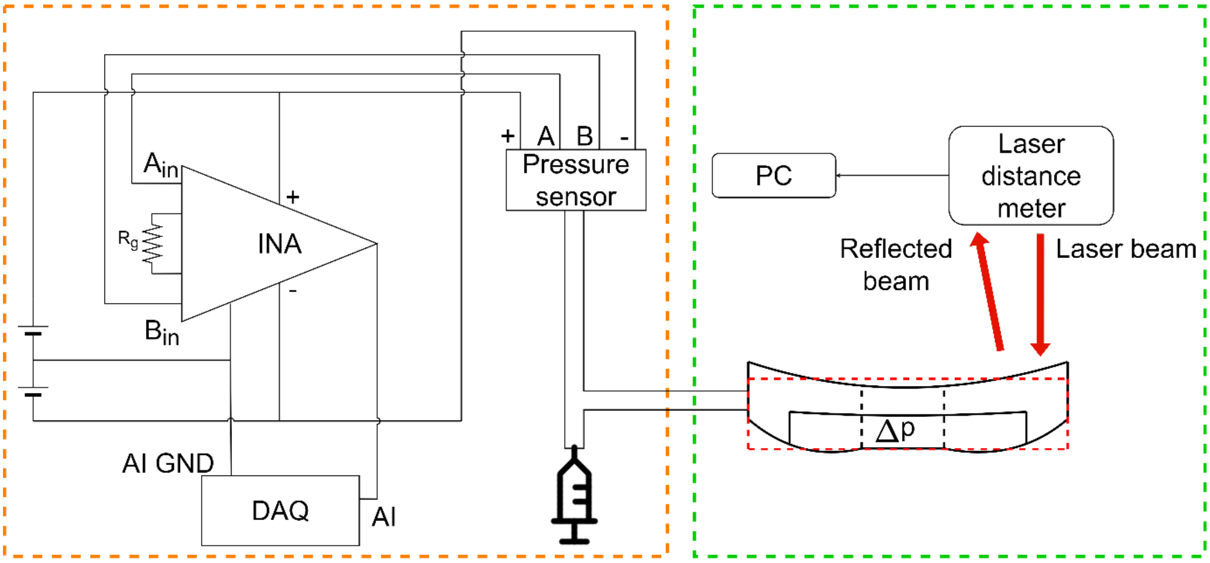

Figure 28: The displacement (green loop) and control chamber pressure change measurement (orange loop) setup. The pressure measurement loop featured INA 128P amplifier with G=501 and a DAQ device for measuring the amplified voltage from the pressure sensor. The displacement loop featured Keyence LK-G10 laser meter and LK-GD500 controller, the output was measured using NI SC-2345 DAQ device connected to a PC.

4 Results and discussion

4.1 Design feasibility

Throughout the iterations, the design of the body was changed the least. Most experiments conducted focused on casting and moulding capabilities with different wall thicknesses tested below 1 mm range.

The main hardship of this work was to construct a soft valve capable of shutting of valve ports. Some of the designs created include a loop valve, thin film created control chamber valve, longitudinal control chamber valve and a central ring-shaped control chamber and the positive and negative aspects of the designs are discussed.

4.1.1 Strangulation valve

By casting thread loops inside a soft matrix, a soft valve was created that was able to demonstrate reversible closing of valve ports. To position the thread in the matrix, support poles were used to elevate and hold it in the correct position. During manufacturing there were issues with holding the threads in place as the structures needed to be open from the top to enable dismounting after aging. This also meant that hollow openings were created in the structure, however, as strings are not using pressure to expand or contract, this did not cause any issues, on contrary, the holes were utilized for lubricating the thread with silicone oil for better dynamic properties.

The lubrication was needed as the threads did not slip that well in the matrix independently. Overall, even though the closing of valve was demonstrated, the forces needed were unreasonably high, which also caused deformation in the whole matrix not just the thin areas near threads and valve ports. The ports opened up after force was forfeited, however, the original shape of the valve did not fully recover, resulting in slightly smaller dimensions until pulled to the original position manually. Even though the system was lubricated, which increases the maintenance need, irreversibility of the system is believed to be caused by slipping issues of the thread, which do not allow the knot to return to its original position.

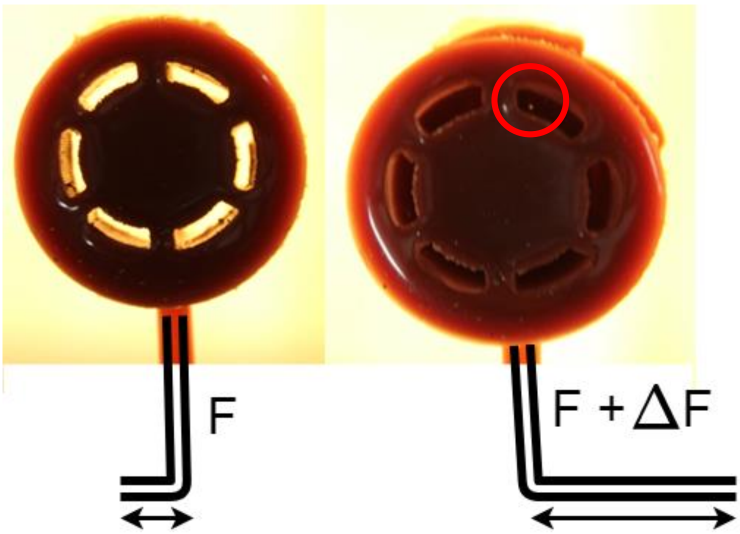

Figure 29: Opened and closed state of the loop valve with initial valve ports. On the picture there is the open and closed valve on left and right, respectively. The red circle points to the pathway that was not closed during action.

During pull tests it was discovered that the threads might not be able to close the ports fully due to the cross-sectional shape of ports, which was originally ring-shaped sections as seen on Figure 29, where a small dot of light can be seen in the top middle of the valve. This also increases the possibilities of having more such pathways, albeit less direct, in the system. It is believed to be caused by the sharp corners of the ports' cross-section, which are not adequately closed and therefore allow fluidic movements. For this reason, the cross-section of cells was changed to half-circles (Figure 30) to eliminate most of the sharp corners and allow more uniform connection between the ports surfaces. Even though the ports seemingly have closed more uniform, light is still visible from two ports. On both figures the remarkably decreased central radius can be seen, caused by high pulling forces.

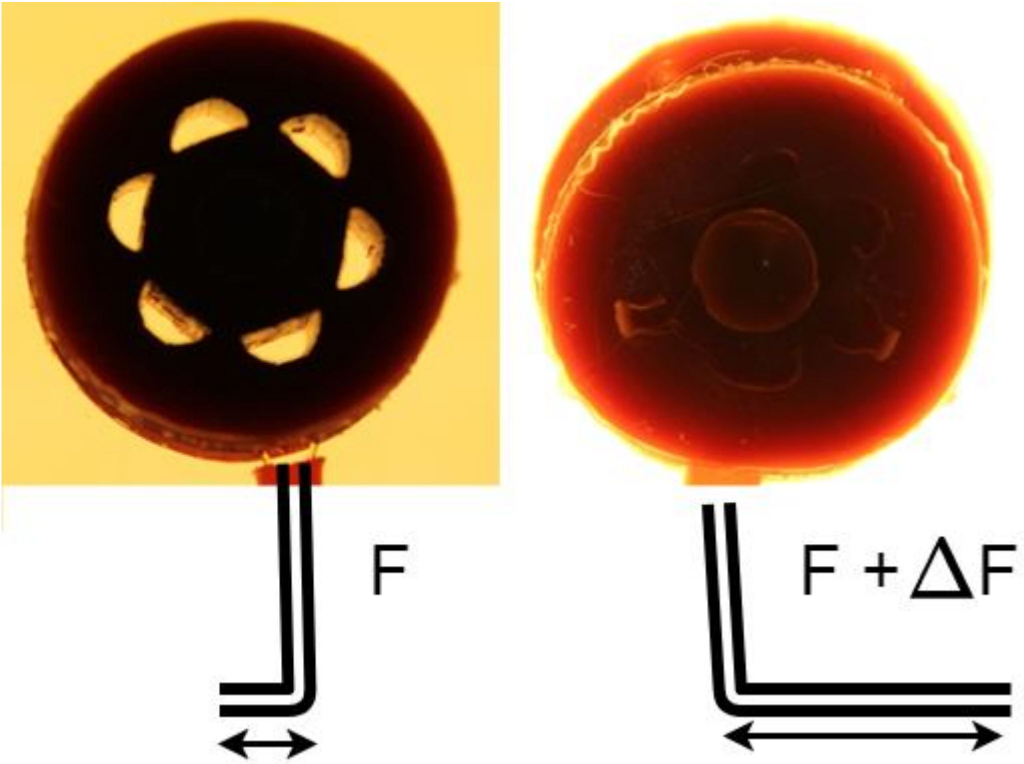

Figure 30: Opened and closed state of the loop valve with new, half-circle ports. On the picture there is the open and closed valve on left and right, respectively.

As the design was not fully able to close down the ports and needed excessive force to close them, the design was rendered unfeasible for the system and the valves' port closing abilities were not quantified.

4.1.2 Thin control chamber

Due to production methods, assistance poles are used and after removing the mould, it leaves hollow openings to the structure. As the film is also pulled from the structure, the openings will prevent holding the pressure inside the control chamber. Filling of the openings has to be conducted carefully, to not fill the control chambers themselves, therefore, unnecessarily increasing the control structures volume.

During pressurization of the system the expansion of the channel was non-uniform and not able to close off the ports. Two possible reasons were found. Even though the chamber was carefully placed to be 0.2 mm from the ports, the assistance structure was not able to provide the needed level of positioning. As we can see on Figure 29a, the design was made to create a circular chamber, however, after further analyses, it was discovered, that when the temporary film was tightly positioned on the assisting poles, the chambers' shape could be more hexagonal as in Figure 31b. As adding more fixation points or decreasing the size of the poles were not feasible due to more holes in the system and mould fractures, respectively, the redesign was not considered. The second issue could be caused by the low thickness of the chamber, as silicone is prone to stick against other silicone surfaces, the air pressure provided by a syringe might not be enough to facilitate the expansion of the chamber. For these reasons this design was discarded.

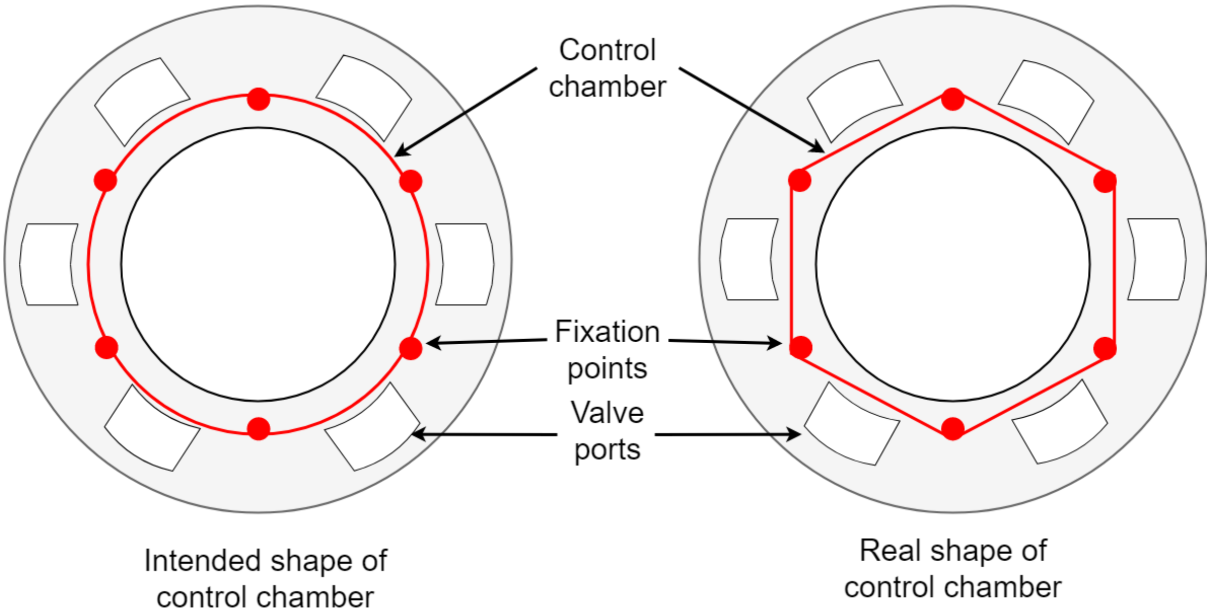

Figure 31: Intended and achieved thin film control chamber shapes. a) Design versus b) reality of the thin film made control chamber on right and left respectively. Red denotes the control chamber inside the cross-section.

4.1.3 Longitudinal control chamber

This design offered the most effective expansion area for the ports, however, there were issues with connecting the control chambers to each other. By design the control chamber featured a small connecting chamber beneath them, however, during assembly it was seen that while creating a uniform connection between the valve parts, it was not possible to repeatably prevent the silicones' movement to the connecting chamber, rendering the valve quickly unusable. During dismounting from the mould it was also evident that the 0.2 mm membrane was too thin to pull out mould elements from both sides of the membrane without causing any damage, rendering the process unstable. Due to these instabilities, the design was not developed any further.

4.1.4 Central ring-shaped control chamber

Sticking of silicone to other same-material surfaces became quickly very evident with the central control channel, where a thin membrane was separately attached to the valves' base. Due to this adhesion, some defects were already visible before usage cycle, making the assembly slightly more challenging during that part, however, keeping the plastic film on the membrane until end of assembly was a good technique to bypass this issue.

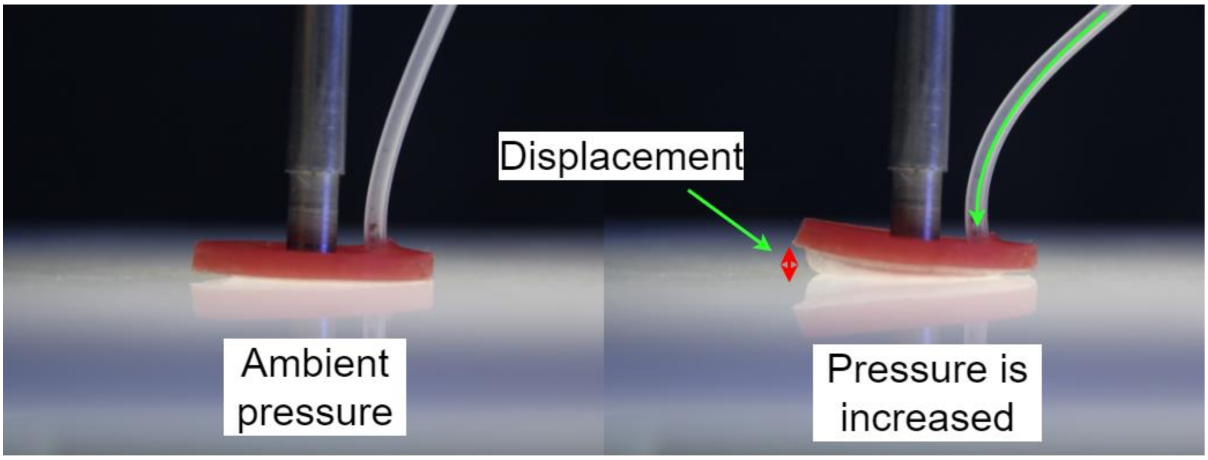

Figure 32: Operating concept of the central control chamber valve.

This method allowed the highest control over dimensions out of all design concepts due to assembly parts being of lower complexity rather than one complex part. This was also visible during pressurizing tests, which showed good repeatability and noticeable expansion (Figure 32) in the membrane, which will be more thoroughly discussed in the measurement section of the results. Design wise, the built system was an easy to assemble soft valve, that showed noticeable radial displacement around the valve, therefore, following distributed functionality principles. For these reasons the design was chosen for further characterization for showing great potential for blocking the cells, when the shape of the valve is enhanced.

4.2 Effect of chamber state on stiffness of the synthetic vascular tissue system

During characterization of the system the aim was to find out if the stiffness profile of the system can be modified using binary control and possible usage feasibility as a simulation system. For this, four measurement setups were created and the results of the measurements will be discussed in this section. Out of made iterations only revision H was measured as it was made as a golden sample, featuring the most optimal solution found and due to its compatibility with the measured valve.

4.2.1 Method A – 10 mm displacement

The 10 mm displacement approximately corresponds to the cylindrical systems' radius, therefore, significant deformation is induced in the system, which should be able to influence all the cells in the system. This way, the measured stiffness can be viewed as descriptive for the whole system not just a single cell. The results for the measurement are shown in Figure 33, where the displacement of the system is visible.

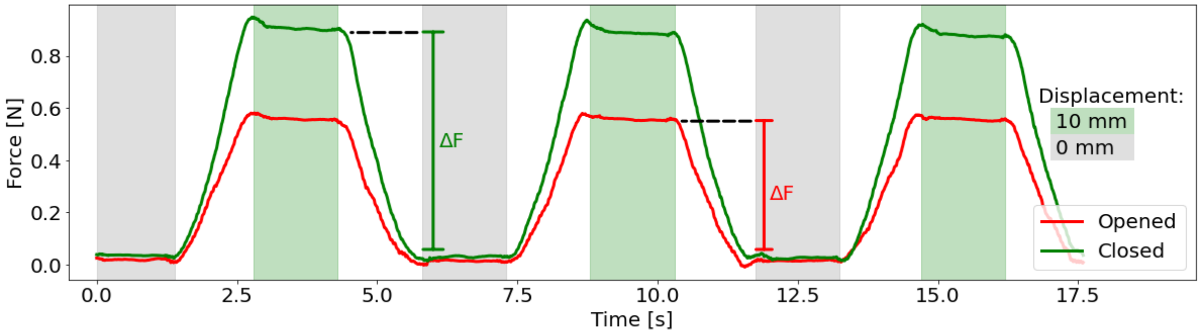

Figure 33: Force applied on the surface of a cell with 10 mm displacement.

The first grey plateau on the graph shows the amount of pretensions applied to the system for creating starting point, which corresponds to approximately 0.02 N. Following the rest of the measurement it can be seen that starting point of measurement does not significantly differ from the beginning, suggesting that the measurement method has no drift.

At the beginning and end of each slope connecting the pretension plateau and displacement peak there is a visible arc, which corresponds to the stage mounted probe movement of the measurement system, which will be eliminated during interpretation of the results. Interestingly it can be seen that the stage will initially move slightly in the opposite direction before starting moving according to the written G-code, which is attributed to the stages' nature.

From the displacement peaks it can be seen that the force applied on the surface is significantly different between the opened and closed states of the system. For this 10 mm induced displacement the force applied to the surface increased approximately 44%, rising from 0.55 N to 0.88 N, averaged over the 3 peaks visible on the graph. As the three peaks have no significant drift, it can be said that the system was made airtight for the measurement, as it was conducted without the presented valve.

4.2.2 Method B – stiffness profile

The obtain a better overview of the systems properties a stiffness profile is to be constructed. As mentioned in the previous section, displacement of 10 mm was chosen to ensure the contribution of most cells to the force measured. Therefore, it would be expected to see from the figure, that the force for closed cells is growing non-linearly with displacement relative to the opened cells. For that the measurement setup of Method B was implemented, where force on different displacement levels was measured: 2 mm, 5 mm, 8 mm and 10 mm. The stiffness profile of the system can be found on Figure 34.

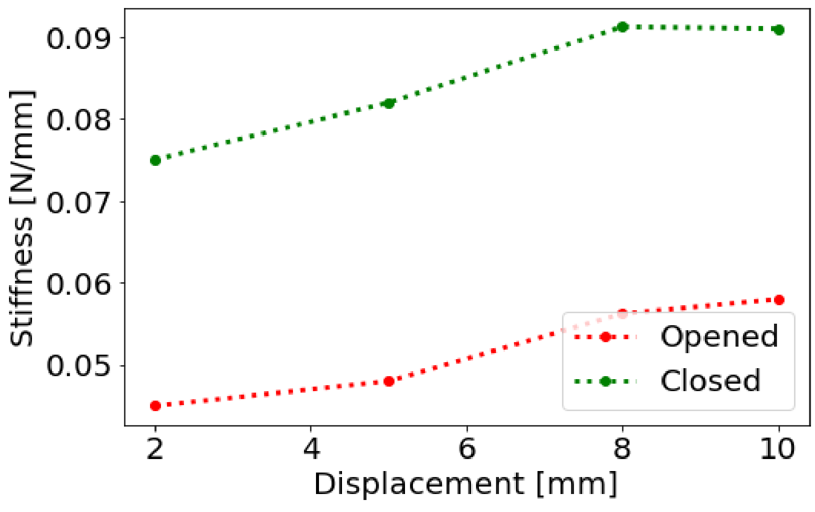

Figure 34: Stiffness profile of the system with method A measurement.

From the figure we can see non-linear growth for both situations, which indicates that with increased displacement more and more cells are contributing to the measured strain, which was to be expected. As the profiles are identical in their shape, it indicates that no significant changes happened in the system, therefore the difference in stiffness can be attributed to the differentiating state of the cells.

The growth of stiffness for closed state relative to opened one was approximately 55%, 64%, 59% and 55% for 2 mm, 5 mm, 8 mm and 10 mm displacement respectively, giving the average growth per step to be 58%.

4.2.3 Method C- 3-point test

Similar measurement method is also used in palpating the stiffness of the cervix by midwives, making it a good benchmark to understand if dynamic stiffness can be palpated from the system. The results for 3-point testing of the built system are visible from Figures 35.

From Figure 35 we can see that the stiffness profiles for different cell states are mostly resembling each other. The average growth recorded for the 3-point test is 34%, however, when we drop the first point at 2 mm displacement, the growth drops to 21%, which is approximately a 2-fold drop from the method A. Even though the difference in stiffness is smaller, it raises the possibility of being able to feel the difference during palpation, however, this was not in the scope of this work.

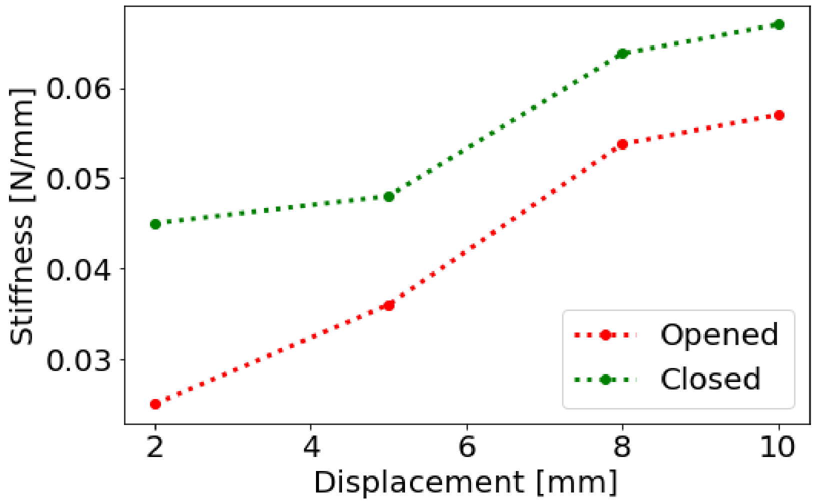

Figure 35: Stiffness profile of the system with method B measurement.

4.2.4 Method D – force applied to adjacent cells wall

The stiffness profile for method D is visible on Figure 35. It can be seen that the stiffness actually decreases for this method with every step, which indicates that there is no growth in stiffness. This means that the cells states give insignificant contribution to the stiffness change in this case, making most of the change in stiffness structural. However, as the stiffness plateaus in the later stages of the measurement, it can be assumed that the marginal contribution of cells states starts to show around that area, when most of the system is under large deformation.

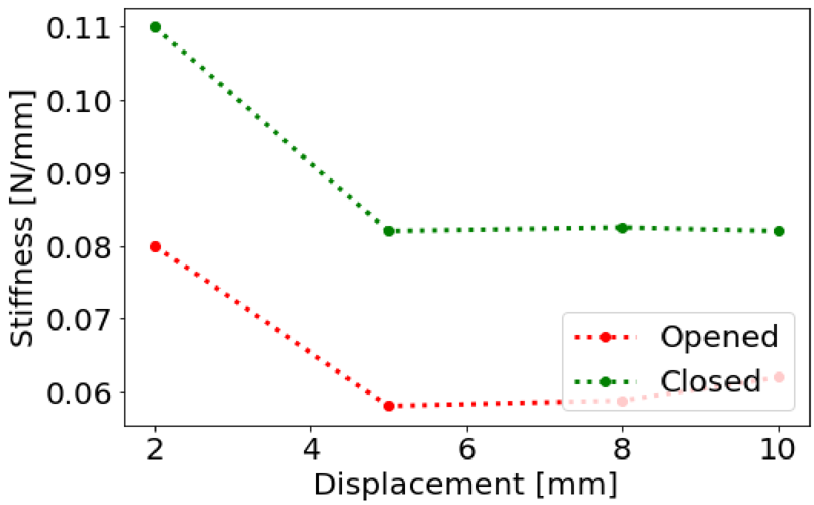

Figure 36: Stiffness profile of the system with method D measurement.

4.3 Displacement and pressure for the soft distributed valve

For measuring the displacement and pressure of the soft valve, system described in Section 3.6.2 was used. The version of the measured valve was H, due to unsatisfactory performance of other revisions, that have been discussed in the Section 4.1.

On Figure 37 are shown pressure and displacement changes over time. The measured displacement values exhibit very similar peaks relative to pressure, which indicates to a hermetic seal for the assembled valve. The maximum displacement observed was 0.55 mm, which should be more than sufficient to open the cells to ambient environment as even the slightest change in displacement, e.g. 0.1 mm should be enough to enable fluid movements from the cells. However, this was not confirmed in full setup in the scope of this work.

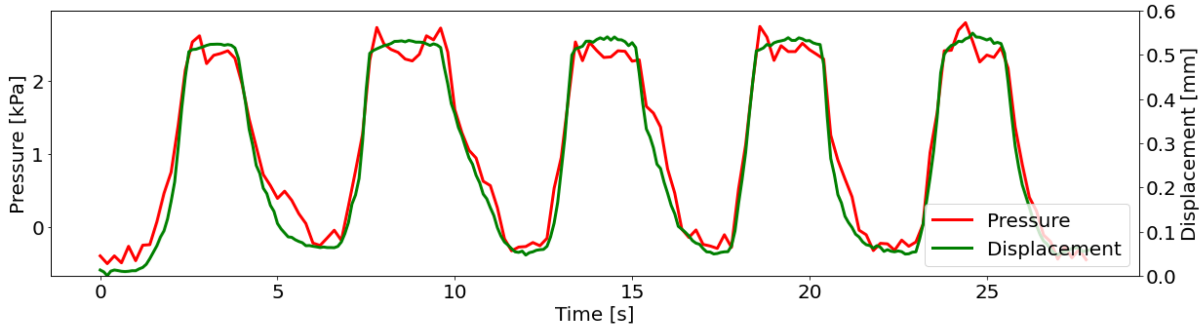

Figure 37: Pressure change inside the control chamber relative to displacement.

The average pressure difference measured over 5 peaks was 2.55 kPa, while the average change in displacement per peak is 0.4 mm. From this it can be calculated that the average change in displacement per pressure unit is 0.157 mm/kPa. These results indicate that low pressure changes are needed to manipulate the valve, which lowers the complexity of the system, as less sophisticated control systems can be used, e.g. syringes.

4.4 Future ideas

Along with the change of stiffness, midwives also have to observe the dilation of the cervix. One of the future development directions is to introduce fibres into the soft matrix to enable dilation simulation for the system. Initial work on this topic has been done in the scope of Johannes Muru's work mentioned earlier under the measurements section. This integration of fibres does not only enable the change in dilation, but also allows some stiffness profiles to be presented. Therefore, future research would find if the different mechanisms for producing stiffness profiles would be able to complement each other, making a multiple stiffness profile system, also able to change its dilation. As both methods have proved to be reversible, it would make new steps towards biomimetic simulation systems and enable more seamless learning experiences.

Secondly, there is room for enhancement in the design of the valve, which currently is at the proof-of-concept state, however working principle of the measured valve showed great potential due being able to reversibly cause displacement at low pressure. In the authors opinion a more lid-like radial solution would have better hermetic abilities to close of the cells.

5 Conclusion

The focus of this work was to create a synthetic vascular tissue for dynamic stiffness using a binary control system. For this two objectives were set – 1) design of a vascular cellular system to enable dynamic stiffness in the system 2) design of soft distributed valve – with the hypothesis that by changing the state of a soft valve it is possible to induce stiffness change in a vascular cellular system.

For the characterization of a cellular system the force applied to the surface during induced displacement was measured from which a stiffness profile was created. The soft distributed valve was characterized by measuring the pressure of the control chamber and displacement induced by the control chamber pressure.

As a result, both objectives were accomplished in the scope of this work. A cellular system was designed that showed change in stiffness for opened and closed cells, where the difference of force applied was approximately 60% for different displacement levels while the difference for force applied for a 3-point-like-test was around 30% Additionally, a soft distributed valve was designed that showed great potential for binary control as it was able to induce displacement on low pressure differences (0.157 mm/kPa) and produce displacement that should be sufficient for changing the state of the system.

Future developments for this work would be to introduce fibres into the soft matrix to enable dilation control for the system and enhancement of the valve for system implementation.

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