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UNIVERSIDADE D COIMBRA

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FABRICATION OF SOFT MECHANISMS IN A SINGLE PROCESSING STEP

Dissertação no âmbito do Mestrado em Engenharia e Gestão Industrial orientada pelo Professor Doutor Pedro Mariano Simões Neto e apresentada ao Departamento de Engenharia Mecânica da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

Setembro de 2022

FCTUC FACULDADE DE CIÊNCIAS
E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

DEPARTAMENTO DE
ENGENHARIA MECÂNICA

Fabrication of soft mechanisms in a single processing step

Submitted in Partial Fulfilment of the Requirements for the Degree of Master in Industrial and Management Engineering

Fabrico de mecanismos soft num único processo

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Coimbra, September, 2022

Many young men started down a false path to their true destiny. Time and fortune usually set them aright.

Mario Puzo, in The Godfather, 1969.

ACKNOWLEDGEMENTS

Words cannot express my gratitude to my advisor, Professor Pedro Neto, for his never-ending support, providing tools and knowledge, imperative to the development process, pushing me to become the best version of myself. Also, I want to express my gratitude to Professor José Afonso for taking interest in my work and sharing his expertise.

I am also grateful to my peers and fellow researchers for their invaluable patience and thoughtful suggestions, assisting me to overcome the obstacles I have stumbled upon.

Additionally, I could not have undertaken this journey without the support of my family, especially my parents, who believed in me and helped emotionally and financially throughout this long endeavor.

Lastly, I cannot forget to acknowledge my girlfriend and friends, who allowed me to unwind and enjoy this journey even more.

Thank you,

Afonso Teixeira da Silva

ABSTRACT

In recent years, a specific set of materials gained visibility in the robotics field. Flexible polymers became attractive for various reasons, and researchers all around the world are trying to develop new technologies integrating soft matter in different applications. Soft robots are the closest we can get to mimic nature and they have plenty applications, including in the industrial field. Although soft robots are promising due to their compliant motion properties and soft touch, their development is limited by relatively slow and complex fabrication processes. It is demonstrated that this process can be improved with the help of a common fused deposition modeling 3D printer and off-the-shelf processes. Here it is shown a new method aiming at a faster fabrication, where the production is mostly unsupervised, and allows the creation of geometries more complex than the traditional method, by using sacrificial cores. Moulds and hidrossoluble cores are 3D printed and, in a single processing step, soft mechanisms are created using silicone casting. Finite element analysis (FEA) was used to simulate pre-fabricated designs to reduce the overall production time of new prototypes. A heated water circuit was created to optimize the dissolution process. A set of actuators was created and tested, using this new method, to display its strengths and exhibit its versatility among the know soft robots' techniques. These actuators were used to develop two robots that were able to move when pressurized, with controllable pressure and frequency.

Keywords: Soft robotics, Fabrication, Actuators, 3D printing, Robotics, Single-step.

RESUMO

Recentemente, um tipo de materiais ganhou visibilidade no campo da robótica. Polímeros flexíveis tornaram-se atrativos por variadas razões, e investigadores de todo o mundo estão a tentar desenvolver tecnologias integrando matéria soft em diferentes aplicações. A Robótica Soft é a tecnologia que está mais perto de conseguir imitar a natureza. Existem inúmeras aplicações, nomeadamente no domínio da indústria. Apesar dos soft robots serem promissores devido às suas capacidades ao nível do movimento e toque suave, o seu desenvolvimento está limitado por um lento e complexo processo de fabrico. É demonstrado que este processo pode ser melhorado com o auxílio de uma simples impressora 3D de deposição de material e materiais fáceis de adquirir. Aqui expõe-se um novo método, focado na agilização do fabrico, onde a produção é maioritariamente não supervisionada. Isto permite a criação de geometrias mais complexas que o método tradicional, através da utilização de machos sacrificiais. Os moldes e os machos hidrossolúveis são impressos em 3D e num único processo os mecanismos soft são criados através de moldação de silicone. A análise de elementos finitos foi usada para simular os designs dos atuadores, previamente ao fabrico, de modo a reduzir o tempo total de fabrico usado na otimização de novos protótipos. Um circuito de água aquecida foi criado para acelerar o processo de dissolução. Exemplos de atuadores feitos com este método foram desenvolvidos e testados para demonstrar as suas vantagens, e expor a sua versatilidade em relação às técnicas já existentes. Esses atuadores integram dois robots, capazes de se movimentar quando pressurizados através de um circuito pneumático com controlo de pressão e frequência.

Palavras chave Soft robotics, Fabrico, Atuadores, Impressão 3D, Robótica, Processo único.

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1. INTRODUCTION

One of the main goals for the roboticists all around the world is to develop robots that replicate natural life (animals). This is a challenging task, since animal flesh, muscles and tendons are quite flexible and move with unmatched degrees of freedom when compared to rigid structures. Soft robotics pursues to achieve the same kind of movement freedom and flexibility as animals' soft bodies, alongside the ability to make a delicate contact with the environment around it. In the 1980s, robots made of soft materials emerged, mainly polymers or gels, aiming to replicate skin properties – softness and elasticity. Since then, many advancements were made to improve their features, applicability, and fabrication feasibility.

Soft robots have internal chamber networks where the fluid flows (usually air but it can be another gas or liquid) and gets pressurized and unpressurized, making the body of the robot inflate and deflate. This creates the naturally looking motion of the robot. Depending on its geometry, and the geometry of the internal chamber networks, soft robots can move longitudinally, radially, bend, curl, and combine these movements simultaneously. This allows them to mimic the movement of a human hand grasping an object, an octopus' tentacle curling around something, or a fish tail waving left and right.

The applications of soft robots are multiple, but there are critical factors holding soft robotics back: its design, actuation principle, fabrication and control. The actuation can be fluidic, electrostatic or dielectric, by light, among other less popular actuation principles. The most common, fluidic (pneumatic), is characterized by a fast actuation, requiring valves and an electronic circuit, which means these robots are usually tethered to an external station. Eletrostatic soft actuators, like a phase-change actuator, are slower, but have the potential to be untethered. Dielectric actuators are relatively fast in what concerns the actuation but require higher currents and they are limited to produce small efforts (Acome et al., 2018).

The fabrication of the soft actuators is a challenging process, and this is the focal point of this thesis. Traditionally, soft robots are fabricated using elastomer casting, which is a time-consuming process requiring multiple steps, challenging to produce chambers and consequently not optimized to prototype development. Every feature change implies mould redesign, which becomes a challenge when there are several integrating parts of a mould. Looking at the literature, there are emerging alternatives within the 3D printing realm, which will be presented in the next sections. Those alternatives are not yet optimized and present significant challenges. The review in next section aims to provide a deep understanding of the 3D printing techniques and features, in order to develop a new and improved method, towards a single-step production of soft robotics.

2. STATE OF THE ART

2.1. Applications

The properties of soft robots are quite appealing for multiple reasons. The materials used are soft, which means they can operate in unstructured environments and safely interact with humans/animals.

Collaborative robots emerge to operate safely side-by-side with humans in all domains (industry, education, social context, etc.). Although they are still in an early stage of development, it is clear that these robots can enhance its characteristics when equipped with soft mechanisms so they could present no harm to the people around them. The application of soft mechanisms such as grippers (Howard et al., 2022), or soft wrapping increases humans' safety which is a key factor.

In industry, specifically in logistics, there are numerous soft robotic picking systems, which are especially interesting to solve the emerging problem of reverse logistics in e-commerce companies. The regular pick and place of items is enhanced by the flexible capabilities of soft grippers, becoming a better alternative in relation to traditional grippers, since they can grasp a wider variety of objects with different shapes and sizes.

In food industry, soft robotic grippers are very attractive due to their ability to safe grasping fragile products (Soft Robotics Inc., 2021) such as eggs, meat, or fruits. Although there are several concerns due to technological and sanitation challenges in the food industry, there is a requirement to shift this labour-dependent industry to a more automated one. Moreover, it can be more hygienic to have a robot performing the picking of food items than instead of humans.

Soft robots are increasingly used for exploration purposes, either in land, underwater or even space. When it comes to moving in solid terrain, soft robots have the ability to navigate through it. Wheels cannot overcome all obstacles, and rigid legs have problems to keep the robot stable in some conditions, like in a rocky soil. Soft legs on the other hand, can climb and navigate through different levels, and the soft body also brings the advantage that if anything goes wrong, the "core" parts are not damaged. These types of robots were being studied by NASA (Loyd, 2019) for space exploration. There is a number of tasks that are needed to be performed in space, such as exploring sites, correcting instruments, or creating temporary shelters to shield devices from dust or wind, which could be (at least partially) performed by soft robots.

Another exploration robot is the Vine Robot (Hawkes et al., 2017), a soft robot that navigates in the environment through growth, reaching hundreds of times its initial size, resistant to adhesives, spikes, or even fire. The tubular shaped robot can be used to explore post catastrophe scenarios (rescue), mines (archaeology), or in-wall spaces, but in the future, the same moving principle can be applied to make intubations for patients with breathing troubles during medical procedures.

Underwater soft robots became popular due to their increased flexibility and adaptability to the environment in contrast with rigid robots. The review by Youssef et al. (2022) thoroughly explains this ability to change the shape according to the surroundings, shrinking and bending.

In any type of soft robots there is always the need for an external control system and frequently a pneumatic circuit, composed by solenoid valves for example, which defeats the premise of “completely soft” robots. Also, such circuit needs to be connected to the actuators through long tubing that may inhibit some sort of movement freedom. Pushing the boundaries in the academic field, a team of Harvard researchers (Rothemund et al., 2018) developed a soft bistable valve to control all kinds of soft robots. This valve would replace the external rigid control valves in an attempt to create fully soft robots. With a simple functioning principle – one additional pressure input defines which way opens and which way closes (in a 4/2 way valve) – the prototype was demonstrated to work on a gripper and on a earthworm-like walker. Whilst this was a step forward in the development of completely soft robots, it still requires tethering.

2.2. Design

Designing geometrically complex soft robots featuring internal chambers requires a good knowledge of the fabrication techniques available and how the design and fabrication parameters affect each other. Frequently, soft robots are designed and fabricated following an iterative process based on trial-and-error considerations from the design to the fabrication, consuming time and resources. To avoid several fabrication steps, non-linear finite element analysis (FEA) of hyperelastic materials simulation was introduced in the design phase (Smith et al., 2021). This brings significant advantages to the process, allowing to evaluate how different parameters affect each other under different conditions, such as the geometry features itself, dimensions, materials and loads/pressures (Xavier et al., 2021). Frequently, the design of the soft actuator is influenced by the fabrication process as the internal chambers may have complex geometries difficult to fabricate. The proposed fabrication process aims to mitigate such issue.

2.2.1. Finite Element Modelling

In soft robotics, the materials used belong to the hyperelastic domain. There are five popular mathematical models that replicate the behavior of hyperleastic materials, while assuming they are isotropic and incompressible: polynomial, Mooney-Rivlin, Ogden, Yeoh and Neo-Hookean (Xavier et al., 2021). These models are used in FEA software such as Abaqus, Ansys, COMSOL and Nastran. Typically, elastomers with higher shore hardness and deformations (like the commercial SmoothSil) can be used in Mooney-Rivlin and Neo-Hookean models, while softer silicones that are able to undergo higher deformations (like the commercial Eco-Flex) should be modelled by Yeoh or Ogden. Each of these models require specific set of parameters, varying by material type. These parameters are one of the key inputs of FEA, and they can only be achieved based on experimental tests. Unfortunately, different research teams have different ways to achieve such parameters, which leads to incoherent model and parameter choosing for the same materials. This problem is increased when a soft robot is made using several different interacting materials (Subramanian et al., 2020), which amplifies the error, and might cause very inaccurate FEA simulations.

In order to standardize the experimental process, researchers worked on a way to create and uni-axially test soft material specimens in a controlled environment (Marechal et al., 2021). Additionally, they provided a database for different silicones with model parameters so that anyone could use them in FEA.

Another issue is the computational effort and time needed to achieve valuable results and, for that reason, researchers tried to optimize FEA through shell meshing (Smith et al., 2022) instead of solid meshing. In FEA, the mesh is made of elements that define the solid, and a simpler mesh means less time to compute.

2.3. Fabrication methods

The fabrication process of soft robots is challenging. Soft robots' fabrication tends to require lots of intermediate steps. The soft matter is usually a gel or an elastomer, and both require some cure time to reach its solid state and, sometimes even a reheating process and/or a step to remove air bubbles inside a vacuum chamber. These processes, alongside the inability to mass produce lead to long fabrication times.

Traditionally, a common cast-based fabrication process consists in 6 different steps: design of the robot, design of the moulds, 3D printing of the moulds, deposit of the soft matter in the moulds, heat or vacuum treatment to reduce the porosity and wait time until the cure is completed. As explained before, soft robots need internal chamber networks to move. These chambers must be created by using moulding cores. If the network is too complex, the cores get more and more difficult to create and remove after the cure of the material.

The fabrication process for these actuators traditionally requires either:

- Creating two separate halves of the actuator and gluing them together afterwards
- Having a mould for the "main" material that creates the general shape of the actuator, and a second mould for the softer material to create a more flexible membrane after the first part is cured.

Both of these processes are not ideal and require moulds with complex interacting designs.

To speed up the fabrication, including soft robots featuring complex internal chambers, researchers started to explore 3D printing in different ways. Instead of printing the moulds and casting the soft material, they tried to either directly print the soft matter, or the moulding cores (into the soft matter). This way, one could totally or partially eliminate the steps of mould fabrication.

2.3.1. 3D Printing fabrication methods

3D printing is the process of converting a digital design into a solid object, through a programmable printer via G-code. During that process, the patterns are laid out, one layer at a time, using laser optics or an ink-based printhead. Hence, there are two main categories of 3D printing: light-based and ink based. Each with its own properties and flaws, being more well suited for some specific applications than others (Truby & Lewis, 2016). Some of these processes produce the moulds to create soft robots, while others directly print the soft matter in the desired final shape. There are also noticeable differences in the technology when it comes to the printers, because some processes just require a print-ready purchasable printer, whereas others are custom made for a more tailored utilization and specific capabilities (Lei et al, 2022).

2.3.1.1.1. Light-based 3D printing

Popular and pioneering methods using light to fabricate objects were stereolithography (SLA) and selective laser sintering (SLS). SLA uses photocurable resins, while SLS uses polymeric powders. Newer methods, like digital projection lithography (DLP), continuous liquid interface production (CLIP) and two-photon polymerization (2PP) use the same principle as SLA, where the support plate is situated right above the resin bed, and lasers, placed below the bed and pointing to the support plate, sinter the object (solidify the resin locally) layer by layer, while the plate gets slowly elevated (Jia et al., 2022).

On the contraire, SLS uses a bed with a thin layer of powder, that gets locally heated (in the desired shape) by lasers. Each time the layer gets concluded, the bed descends, more powder is added to it, and the lasering process is repeated, until the print is finished. These methods provide the highest feature resolution in 3D printing, but the number of materials that can be printed is limited to either resins, or powders, which sometimes do not have the required mechanical properties to specific purposes, like not having enough flexibility to expand or bend for soft robotic actuation. (Truby & Lewis, 2016).

2.3.1.1.2. Ink-based 3D printing

This is a common category of 3D printing, well known among general population. Usually, there’s a polymer that gets heated and extruded through a heated nozzle into the build plate. The print head moves around, performing layer by layer, while depositing the material in the plate. This method is called fused deposition modelling (FDM). In this method, elastomers can be used instead of the classic and cheap polyalactic acid (PLA) rigid material.

Other printing method is the direct ink writing (DIW), very popular on the soft robotics community. DIW is the act of printing fugitive organic and epoxy filled inks (sometimes used as sacrificial materials, or, in moulding terms, as sacrificial cores) directly into or onto viscoelastic matrices. In some cases, an additional step of photopolymerization or thermal curing might be needed to harden the soft materials in between prints (Truby & Lewis, 2016).

2.3.1.1.3. Stereolithography

Extending the 3D printing concept, researchers started to work on materials that have abilities of shape memory and self-healing, while can respond to external stimulus such as electric, ionic strength, light, magnetic field, pH and temperature (Khoo et al., 2015). This extends the concept of 3D printing to 4D printing (with the additional dimension being the responsiveness too stimulus), and these materials are called “smart” due to their self-actuation properties. One of the most used smart materials are hydrogels, but they are not “smart” in their natural state. They possess 3D network structures with tunable physical and chemical properties (Taylor & Panhuis, 2016), which can be developed to turn them into smart materials while keeping them soft.

Using SLA, researchers were able to use hydrogels to print a bio-bot (Cvetkovic et al., 2014). The biological aspect of this robot it is the use of mouse myoblast cell line and extra cellular proteins integrated in the body. This robot was able to contract and generate sufficient force to power its locomotion. It was the first biological machine controlled by external signals. The thin beam of SLA printed hydrogel has self-healing properties to regain its shape after being bent by an electric signal. SLA allowed the rapid polymerization of biocompatible materials and potentiated scalability, promoting a faster and efficient fabrication of prototypes.

2.3.1.1.4. Digital Projection Lithography

A family of highly stretchable and UV curable (SUV) elastomers has been discovered (Patel et al., 2017). The elastic ability of this elastomer surpasses the one from EcoFlex – a commonly used silicone for the fabrication of soft robots – and reaches 1100% elongation, which is more than five times the elongation at break of the commercial UV curable elastomers. Then, with the simple use of DLP printing (elastomer used in the bed, instead of the usual "hard" resins), researchers (Patel et al., 2017) were able to print various prototypes, ranging from grippers, balloons, and even a Bucky Ball coated with silver nanoparticles that can conduct current and emit a signal when squished.

This presented a major turnaround in the use of DLP for soft robotics fabrication. The ability to produce soft materials with this method facilitates the fabrication and speeds up the entire process since there is no need for moulding/casting, and light-based 3D printing is much faster than ink-based printing. Also, it was proven that there are highly stretchable UV curable alternatives to the silicones traditionally used in the casting techniques. Since then, this process was used to create a soft thermoelectric actuator (Zadan et al., 2022). In the other hand, this method requires a complex chemical process to synthesize the elastomer.

2.3.1.1.5. Fused Deposition Modelling

FDM printing is highly used to produce rigid parts, for example the moulds to fabricate soft robots. For a long time, researchers have been trying to use soft materials as the filament for the printing process itself. One initial approach (Bakarich et al., 2013) was to extrude hydrogels, specifically ionic-covalent entanglement gels (ICE), through a modified 3D printer. A pressurized barrel held the ICE gel, and then loaded it into the extruder, which would print the desired design. Since the hydrogels require photopolymerization to solidify, an additional step of UV exposure was added after the printing was concluded. This process can create soft structures with high mechanical strength, but low elasticity and significant number of defects – since extruding hydrogels is not as precise as extruding the normal polymers.

Another approach (Yap et al., 2016) uses commercially available thermoplastic elastomer filaments, such as NinjaFlex, in a low-cost open-source 3D printer. This FDM-based technique can create soft actuators without the need of moulding cores, by printing them in a way that minimizes the area of overhangs. The soft actuators were later tested in terms of elongation and strength, showing decent results, but they were limited to higher forces. The material itself was not as versatile as desired considering soft robotics applications, but the fabrication process was proved to be valuable. These actuators were then incorporated in a soft robotic exoskeleton hand to assist finger flexion, wrist flexion and extension. Recent studies tried to directly print actuators in NinjaFlex and other TPU filaments with different actuation results (De Pascali et al., 2022).

2.3.1.1.6. Direct Ink Writing

Direct ink writing is a popular 3D printing method for soft robotics. Gallium-indium alloys are getting more sought-after for stretchable conductors (Haake et al., 2022) and sensors (Kwon et al., 2022), due to its low viscosity, low melting point (liquid at room temperature), high thermal and electrical conductivity (Dickey, 2017). Being a liquid metal, it is often associated with toxicity, due to mercury, however, gallium has really low toxicity. Hence, the idea of 3D printing a sensor that could be applied in soft robots (Boley et al., 2014), using eutectic gallium indium (EGaIn), was clearly demonstrated. Through a DIW approach, EGaIn was deposited into two different materials, a polydimethylsiloxane (PDMS) and a glass matrix, becoming encapsulated by the matrix. Post curing, the sensor resembles a RFID tag with high stretchability, and strain sensory ability.

Dickey's review from 2017 presents different implementations of the EGaIn and other liquid metals of the same family. They are used to create sensors and other electronic devices such as wires, interconnects, electrodes, antennas, memory devices, capacitors and diodes.

A complementary approach, called "Hybrid 3D printing" was developed to incorporate electronic components in EGaIn stretchable sensors/circuits (Valentine et al., 2017). This method consisted of the already presented DIW of liquid metals, but with the addition of a pick-and-place of integrated circuits, using a vacuum nozzle, into the designed EGaIn layout. This is a step further into the development of wearable electronics with endless applications.

Like EGaIn, other conductive inks can be used for the same purpose. Researchers synthesized a conductive self-healing (CSH) hydrogel and used DIW to incapsulate it in a PDMS matrix (Darabi et al., 2017). This allowed to create another wearable stretchable strain sensor.

A different DIW-based approach focusses on printing fugitive (sacrificial) inks inside soft matrices. The “Octobot” is a soft robot with microfluidic logic control that regulates fluid flow through its built-in tubing and actuators (Wehner et al., 2016). Embedded 3D printing (EMB3D, a variation of DIW, which includes the placement of soft control system in the matrix) is used to fabricate such networks within the moulded body, with the help of fugitive ink (for the network) and catalytic ink (for the reaction chambers). These fugitive inks “auto-evacuate” at high temperature, creating an open pneumatic network ready to operate. The actuation itself is made with a chemical reaction, using monopropellant fuels that rapidly decompose into gas, generating pressure, and therefore movement. This study revolutionized soft robotics, creating an autonomous (no outside control needed) robot in (almost) a single processing step. Although, it has its limitations: the pressure generated by the monopropellant fuels is very low, and the number of times the reaction happen is limited to the amount of fuel existent in the reserves (inside the Octobot’s head).

Following the previous work, (Truby et al., 2018) tried to use the same fabrication process (EMB3D printing) to produce integrated sensors (curvature, inflation, and contact) in the same fabrication process as the actuator itself. These sensors would allow proprioceptive and haptic recognition in a soft gripper. Conductive ionogel (EMIM-ES filled with fumed silica particles for the sensors) and fugitive ink (Pluronic F127 for the actuation network) are printed in uncured silicone, placed in a mould. Using three of these types of actuators, a gripper was created, and then used to test the sensory abilities of the integrated sensors. The results were promising and the EMB3D printing method was, once again, proven very efficient and accurate.

Other peculiar method is the use of ferromagnetic domains in DIW printing (Kim et al., 2018). An elastomer composite filled with ferromagnetic particles is magnetically polarized during the extrusion and mixed into an uncured elastomer matrix. This allows to print objects that can be controlled remotely using external magnetic fields. For this purpose, the custom print head is quite complex, but the final product has the ability to shrink and bend by just applying a magnetic field to it.

To fabricate objects with reversible shape changes, which might be interesting to soft robotics, there is other solutions than the magnetically induced ones. Liquid crystal elastomeric actuators (LCEs) fabricated using DIW, were able to change their shape through thermal stimulus (Kotikian et al., 2018). Heating above their "nematic-isotropic temperature" makes them bend and twist.

DIW can also be complemented with an UV photopolymerization step when using specific materials. Researchers developed a photocurable ink (Kuang et al., 2018) that can be used to fabricate self-healing and shape memory objects, with high stretchability. The process consists of applying the ink using a heating syringe working as a printing head. After every layer, a UV light is turned on until the material is fully cured, and the DIW proceeds. Although every layer is solidified separately, the material still presents good cohesion and even self-healing ability. When deformed, the object returns to its original form, proving its shape memory.

2.3.1.1.7. Multimaterial 3D printing

3D printed objects often require different materials with complex interlapping (in between materials) geometries. While challenging, this can be achieved through multimaterial printing, where light printing is not well suited to these ends, since it requires either a bed of resin, or a bed of powder, and those are the materials that solidify and create the object. Mixing them is not feasible and changing the resin/powder during the printing process is not advised either. On the other hand, both ink-based techniques mentioned before, FDM and DIW, are capable of doing so. There are already FDM printers on the market that can easily print with different types of polymers, using the same nozzle or not. Multimaterial DIW can be made using different nozzles, or printheads that allow switching, mixing or multicore shell printing - printing a filament inside another filament (Truby & Lewis, 2016). Other technique is liquid-solid co-printing (Hayes et al., 2022) where liquid droplets are added to create channels inside the solid injected matrix, and can remain inside of it permanently. This can be used to 3D print hydraulically actuated robots and actuators (MacCurdy et al., 2016).

One application of this method was the fabrication of a soft robot powered by combustion (Bartlett et al., 2015), where all the materials used, soft and rigid, were printed using a multimaterial printer. This robot is able to move by a chemical reaction that results in a contained explosion that occurs in two of its three supporting “feet” (at the same time), making the soft casings to expand drastically, acting as a propeller, lifting the robot from the ground.

A multimaterial multinozzle 3D (MM3D) printing method is used to fabricate voxalized soft components (i.e., one finite-volume element at a time, as in one cube of a 3D matrix). This method (Skylar-Scott et al., 2019) is able to produce complex architectures, such as complex networks of wax within an elastomer matrix using a voxel-by-voxel theory. Considering that wax was used to this type of prints, it can be used as a fugitive ink (low melting point), and possibly make that network of chambers available for soft actuation. A custom asymmetric nozzle was designed to allow this type of printing.

One of the key advantages of multimaterial printing is the versatility of applications that comes with the use of different materials. It can be applied to the fabrication of both actuators and sensors, and in some instances, both at the same time (Hainsworth et al., 2020).

2.3.1.2. Discussion

Both light-based and ink-based 3D printing methods have applications in soft robotics fabrication. Aside from the examples presented in this paper, more of them have been compiled in other reviews (Truby et al., 2016 & Zolfagharian et al., 2016). After a closer analysis, it can be said with relative certainty that the most common and important fabrication methods have been exposed. The SLA method has the advantage of high precision printing, but the materials available are a huge limitation due to the lack of stretchability. On another hand, there is a work with DLP (Patel et al., 2017) that showed a great advancement in this area, a material that can substitute the resin and that has a higher stretchability than the most used silicone for soft robots. The ink-based methods are naturally more suited to soft robotic purposes. FDM can directly fabricate (without moulds) some soft materials, but realistically, they are not as good, mechanically, as other solutions, and have reduced applicability. The NinjaFlex actuators (Yap et al., 2016) though, had direct applications and seemed to work as intended, during controlled experiments. Also, the fact that they can be directly printed, without cores, and without additional steps of photopolymerization must be considered an advantage because it reduces the already long fabrication time in a FDM printing process. DIW seems to have the widest variety of applications and probably the most appealing ones. The ability to create networks of either conductive/magnetic materials or empty space (to fluid flow) is key to speed up the fabrication process and even integrate sensory systems inside the soft matter (Truby et al., 2018). This is what could already be considered as fabrication in a single processing step, but it relies on complex processes to synthesize inks and combine compatible materials. Additionally, there are no commercially available printers to execute this method without modifications. The multimaterial process MM3D can, to an extent, be considered as a multinozzle DIW, and that might be just a faster way of fabricating soft robots. It would be interesting to see that multinozzle print head extruding both a conductive material and fugitive inks at the same time, and perhaps that might be the way to go. Lastly, a hackable 3D printer (Lei et al., 2022) has been developed to complement the different processes, using multiple printhead modules for DIW, multimaterial, FDM and UV curing in the same device.

2.3.2. Fused Deposition Modelling attributes

The existing literature shows that researchers have tried to refine the way FDM printing can be used in soft robotic fabrication. Although, the most successful FDM approach to soft robotics is still the moulding fabrication, even with all the inherent limitations. There are three very appealing reasons to justify the application of FDM, namely the reduced cost and availability, ease of use, and the versatility of materials/filaments that can be used (PLA, ABS, PETG, flexible, biodegradable, hydrosoluble, magnetic, conductive) to produce moulds.

Up until now, apart from being time costly, especially in the prototyping phase – any geometry adjustment results in the re-design and re-print of the various different moulding parts – FDM-based methods are seen as limited due to one the fact that it makes it difficult to create certain complex geometries (especially the chambers). The cores need to be extracted after the silicone is cured, which means the internal chambers must have a simple geometry and their cross section needs to fit through the exterior holes (usually with a small diameter to accommodate the tubing). Though, if we consider all the materials available, there might be another way to look at the FDM mould printing method.

2.3.2.1.1. Support structures

In additive manufacturing the objects are made layer by layer, generally through some kind of material deposit or syntherization. Usually, in the slicer (software that defines the point trajectories for the 3D printers), the position of the object is selected to reduce possible fabrication defects. This is achieved by taking advantage of the build table to create better quality flat surfaces, or by minimizing hanging features (areas of the object where there's no material below). But sometimes, it is impossible to position an object in a way that it does not have hanging features at all. If the curvature of the overhang is gradual, the printer might be able to reproduce it without issues, otherwise, it requires support.

Support structures have a simple geometry and thin walls for economic reasons, since they are going to be disposed after the print. There are three support possibilities for FDM printers:

- Build material as its own support – the only available choice for printers with a single extruder. Often cheaper, but the surfaces in contact with support structures have a poor finish;
- Breakaway supports – easy to remove, but requires compatibility with the build material, and there are not many options in the market;
- Soluble supports – offer the best surface quality. These filaments dissolve in water or specific chemicals, allowing for an easy removal. Although, they have issues with humidity absorption during storage, requiring some pre-emptive measures must be taken.

2.3.2.1.2. Soluble filaments

Traditionally, soluble filaments are used for support applications. Broadening the current view, one could find uses for this material outside the normal approaches, even for soft robotics fabrication.

In the literature, there are some studies (Dahlberg et al., 2018; Goh & Hashimoto, 2018) that explored other particularly interesting applications for soluble 3D printing materials. Researchers printed a simple planar network of polyvinyl alcohol (PVA) and later covered it with PDMS. After curing, the PVA was extracted in a supersonic water bath, creating hollow ramifications and small chambers. These experiments were used in an effort to create 3D bio-compatible lab-on-a-chip devices for the medical field. Other researchers used PVA as a support filament to fabricate soft pressure sensors (Alsharari et al., 2022).

2.3.3. Alternatives to classic 3D printing techniques

Recently, researchers developed a method for soft robot fabrication (Jones et al., 2021), similar to DIW. This method consists on injecting fast curing silicones “inks” into rigid moulds with a hollow channel. When the silicone reaches the end of the channel, pressurized air (the “bubble”) is injected into it, pushing the silicone to the way where it came from, leaving behind a thin membrane of silicone glued to the mould internal walls. After un-moulding, the cured silicone tubing can be actuated, and depending on the geometry and thickness, it will move in different ways. This process is remarkable, considering that the bubble speed, which basically means air pressure, controls the thickness of the final actuator and therefore, its actuated behavior.

Also based on the common inkbased 3D printing techniques, researchers developed a technology to print ultraflexible magnetic materials via screw extrusion (Cao et al., 2022). This method allowed to create soft actuators that change their shape depending on the magnetic field applied.

Other alternative is using micro-organogels (O’Bryan et al., 2017) that can be jammed, have increased density upon, to be used as a support medium for 3D printing. This technique could be applied to soft robot fabrication, using a 3D printing needle to inject silicone. Jamming and unjamming allows the creation of any desired shape but, the overall complexity of this method, makes it unfeasible to produce soft robots. Instead, it can be used for 3D bioprinting for tissue engineering.

3. PROPOSED APPROACH AND METHODOLOGY

In this thesis it is proposed a novel casting-based single-step fabrication method for soft robotics. While it is based on traditional elastomer casting supported by 3D printed moulds, the limitations in producing complex geometries in internal chamber networks are solved using cores made of 3D printed water-soluble materials. A heated water circuit is proposed to dissolve and extract the water-soluble material (core) from inside the actuator. The design and fabrication are linked and supported by non-linear finite element analysis (FEA) of hyperelastic soft materials to optimize its geometry. Different soft actuators were designed, featuring linear elongation/contraction and bending motion. The actuators were successfully applied in two different prototypes featuring robot locomotion, demonstrating the effectiveness of the proposed single-step fabrication.

3.1. Materials feasibility

Several experiments were conducted to test the feasibility of each material to create the internal actuators chamber networks by injecting them into an un-cured silicone matrix. The materials considered are water, salt water, water-based gel, paraffin wax and a water-soluble filament.

Aside from the filament, all materials were injected into an un-cured EcoFlex 00-30 matrix, at different stages of the cure, using a syringe. Pure water and variations are not known to react with platinum catalyzed or platinum silicones used in soft robotics. Salt water was an attempt to match the silicone’s density by adding a calculated amount of salt. The water-based gel was an experience to test if higher viscosity fluids would work better for such end goals. On another hand, a wax-based solution was already used in a DIW-based experiment studied before (Skylar-Scott et al., 2019), showing very attractive results, and having a low melting point which facilitates the removal of material. The soluble filament, PVA, was simply cut into two small pieces and inserted inside the silicone. Results of experiments are shown in the Table 3.1.

Table 3.1. Results of the material experiments

	Result	Reason
Water	Unsuccessful	The fluid ascends and forms a sphere
Salt water (matching density)	Unsuccessful	The fluid forms a sphere
Saturated salt water	Unsuccessful	The fluid descends and forms a sphere
Water-based gel	Unsuccessful	The fluid ascends and forms a sphere
Wax	Unsuccessful	The fluid ascends and spreads on the surface
PVA	Successful	—

Due to surface tension, all water-based fluids have the tendency to retract to a shape with the lowest surface-area possible, which is a sphere. For that reason, it is impossible to create specific geometries with such fluids. Wax, even when injected at more advanced stages of the silicone's cure, has a much lower density, and very low viscosity when melted, which makes it float. It would be necessary to create a wax-based solution, like other researchers did (Skylar-Scott et al., 2019).

After the silicone curing, the PVA needs to be removed. In order to do so, the experiment was placed inside a cup and hot water was added to it. Every few hours the hot water was replaced to maintain a high temperature inside the cup and speed up the dissolution process. Even with such care, the process took way more time than expected, due to the lack of water movement inside the cup, the constant deposition of dissolved PVA in contact with the undissolved filament, and the small contact area between water and PVA. Despite those facts, the filament was eventually completely dissolved, leaving behind two intact tubular holes in the silicone sample.

3.1.1. PVA feasibility

Considering the previous results, more testing was necessary. One PVA tube with 4mm exterior diameter and 2mm interior diameter was printed. It was placed in a PLA mould with two holes on opposing faces. After casting and applying vacuum to remove any air bubbles, the silicone was cured for 4 hours. The mould was then placed in a glass container, and the tubing was connected to it. Hot water (70º C) was added to the container and re-heated every 2 hours. In around 6 hours the PVA was removed, much faster than the first experience.

Although this process might be slower than the regular FDM printing with PLA cores, it is still competitive, and has the advantage of allowing any geometry possible for the core. With this process, any soft robot can potentially be created in silicone, which hadn't been possible until now.

To further experiment this new fabrication method of using sacrificial hollow cores, a test soft actuator was designed (Figure 3.1). This actuator resembles a PneuNet (Ilievski et al., 2011; Mosadegh et al., 2014), but it is made in SmoothSil 940, a silicone tougher than EcoFlex and more compliant than a flexible 3D printing filament. The process is the same as in the previous trial – 3D printing the PVA core and the PLA mould, casting the silicone, applying vacuum, curing, and dissolving the PVA with the water circuit. Additionally, after the PVA was dissolved, the actuator needed to be closed, i.e. the end-tip needed to be sealed using more silicone, which required another process of casting and curing but in a very simple mould. This preliminary experimental trial was successful: the PVA was completely dissolved, and the overall quality is much superior than any FDM (directly) printed actuator.

Without this technique, it would be impossible to create this actuator in silicone, unless it was made in two (or more) parts – which would greatly increase the complexity of mould design. Although it is time costly, both for curing and dissolution, those tasks shouldn't require any supervision (with a proper setup), facilitating and simplifying the overall fabrication process.

3.2. Simulation

The proposed fabrication method requires the mechanical simulation of soft robots to reduce the time-consuming process of prototype optimization.

In order to produce accurate simulations, one has to create a computational model that is able to predict the actuator's behavior under pressure. The model parameters, specifically the material-representing properties must be optimized, based on a real testing scenario. To do this, the actuator previously fabricated was submitted to a simple bending test under controlled conditions, to provide a term of comparation for the simulation.

The test was conducted by fixating the test actuator on the inlet side, and pressurizing it with 30kPa (relative), bending it parallel to a horizontal surface (to reduce gravity's impact on results). The test was recorded and later analyzed frame-by-frame to measure the deformation. At max pressure, the result was 53.5mm ± 0.5.

In the definition of the FEA model, using Inventor Nastran, one can directly use the actuator CAD drawings made in Inventor to make the simulation. The first step to construct the model is choosing a hyperelastic model that can represent the material deformation based on its strain percentage. As said previously, SmoothSil 940 is a silicone that doesn't bend as much as other silicones, with 300% deformation at break, which means much lower deformation (usually below 100%) with the commonly used pressures in soft robotic applications. Therefore, the Neo-Hookean model was selected because it's suitable for materials with high shore hardness and is simpler than the Mooney-Rivlin model. The model is defined by:

$$W = A_{10}(D_1 - 3),$$

(3.1)

where W is the strain energy, A10 is the material constant and D1 is the first invariant of the right Cauchy-Green deformation tensor, although simple, it can accurately represent its behavior. Using this model means that we only have to define the material-related parameter – A10 – since D1 is automatically calculated in Inventor Nastran. The parameter A10 is a representation of how much the material deforms (the higher it is, less flexible the material is). In the literature, there's only one use of this specific material in FEA (Subramanian et al., 2020), where A10 is defined at 0.12MPa. In another work, using SmoothSil 950 (Connolly et al., 2017), A10 is defined at 0.34MPa.

Thus, the generic FEA parameters must be defined: the mesh (the element structure to be analyzed), and the number of increments (the number of intervals in which the load will be divided, and later applied from 0 to 100% load). The mesh should have half of size of the thinnest geometric feature of the actuator, which in this case is 1mm. The number of increments should be high enough to get the most accurate results in a trade-off with computational time (more increments mean more time and can result in non-linearly). In FEA, the first step is converting the pressure in nodal forces, which takes into account the surface area of each element where the pressure is applied (F=p*A), and that area is always the one at the beginning, no matter how many increments are made. That means, when the pressure is higher and the element is more deformed (has a higher surface area), the calculated force will lower than the real one, which results in lower maximum deformations when using lower number of increments. For that reason, after several simulation runs, the number of increments was defined as 300.

Table 3.2. FEA model parameters

Mesh	Increments	Neo-Hookean model parameter (A10)
1 mm	300	0.48 MPa

To find the right material property, A10, the model was ran several times with the parameters previously defined, until the maximum deformation reached the result obtained in the real life test. After multiple tests with different parameters (updated incrementally), the result (Figure 3.1) of 53.9751mm was achieved to a A10 value of 0.48MPa (Table 3.2).

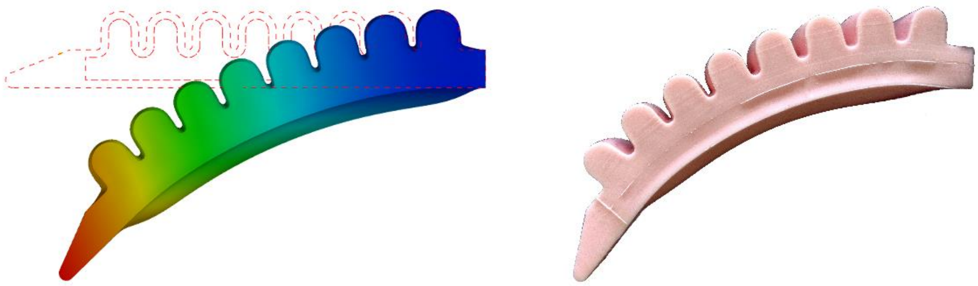

Figure 3.1. Simulation and test comparation

This value of A10 is very different than the one found in the literature (Subramanian et al., 2020) for the same material, and is also higher than the one (Xavier et al., 2021) for SmoothSil 950 (material with higher Shore A hardness, which should have higher A10 than SmoothSil 940). This discrepancy might have several possible reasons. First of all, the real-life test conducted isn't the most accurate, neither the most adequate for said purpose. Second, the article by Subramaniam et al. mentions that the simulation "was defined as a one-step static analysis", which means using only one increment with 100% of the pressure applied, and it was already explained that the number of increments greatly impacts the final result. Also, other researchers (Gorissen et al., 2017) found that the mechanical properties of silicones could vary from batch to batch, which would also impact the behavior of a specific material, making so that similar works could find different results, even without making any mistakes.

All in all, this method might not be the most accurate, but it provided good results in terms of magnitude and position of the expansion, and can provide a very decent prediction on how would a soft robot actuate, which is the whole purpose of the simulation.

3.3. Fabrication

After the first experiments, it was demonstrated that PVA is a promising material to make sacrificial cores. This creates a new perspective on FDM printing and moulding for soft robots, since complex chamber geometries are no longer an issue: using sacrificial cores means that the core does not need to fit through the holes made for tubing (for its removal after curing). Such concept elevates FDM printing to a new level, allowing the creation of high-quality soft mechanisms in a single step processing using just FDM printing. Moreover, FEA simulation supports the design and fabrication. Thus, the proposed framework (Figure 3.2) stands on four pillars: FEA, FDM 3D printing of both moulds and cores, casting and vacuum, core removal.

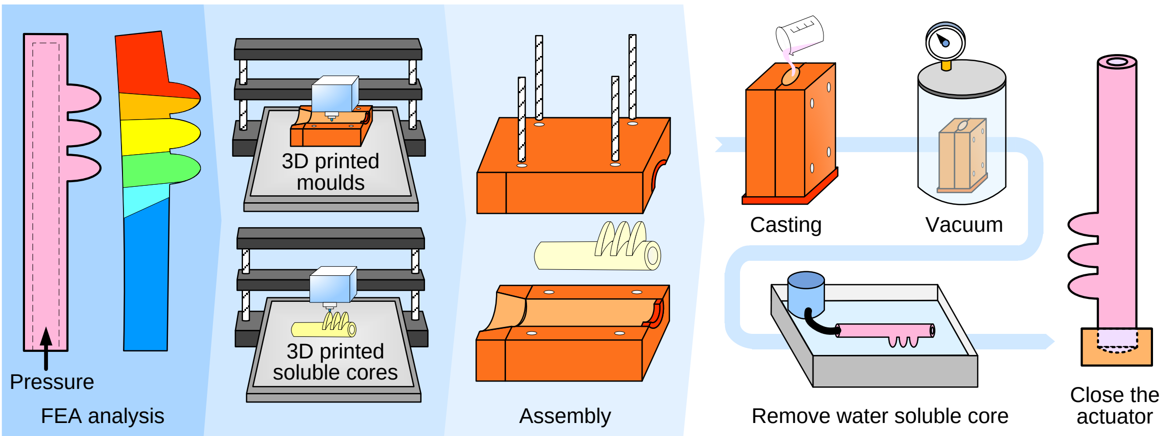

Figure 3.2. Fabrication framework showing the proposed cast-based single step fabrication process, from the FEA, to the mould and core fabrication using 3D printing, to the assembly of the mould, casting, vacuum treatment for porosity removal, to the bath in water to remove the water soluble core and finally the closing of one of the actuator end-tip.

3.3.1. Mould and core fabrication

Designing moulds is as important as designing the actuators, because any mould defects will create actuator defects. The generic mould design was optimized through an iterative process to make them as easy to draw and print as possible, while being completely functional and have the best internal surface quality. Therefore, moulds should be split in two parts, and if possible, by the exact middle of the actuator, to facilitate unmoulding, without causing any tears in the silicone. They need geometric features to hold the cores in place during casting and curing, and there’s also need for screw holes to secure both parts tightly together.

Moulds were 3D printed in an Ultimaker[3], using RS Pro PLA at 215º Celsius and 0.1mm layer height for the best quality possible for round surfaces. The sacrificial cores were printed in a Prusa MK3+ using SMARTFIL PVA at 205º Celsius, 0.1mm layer height, low speed, and very rigid support structures because the geometries are quite challenging to print and PVA has low inter-layer adhesion.

Additionally, if stringing occurred during printing, moulds could be cleaned using a small brush and acetone, while the cores were brushed with water. This simple process removes any superficial imperfections and doesn't change geometrical features.

The moulds produced (Figure 3.3) have high quality and can be used several times. While the hollow cores, although challenging to print, are very effective.

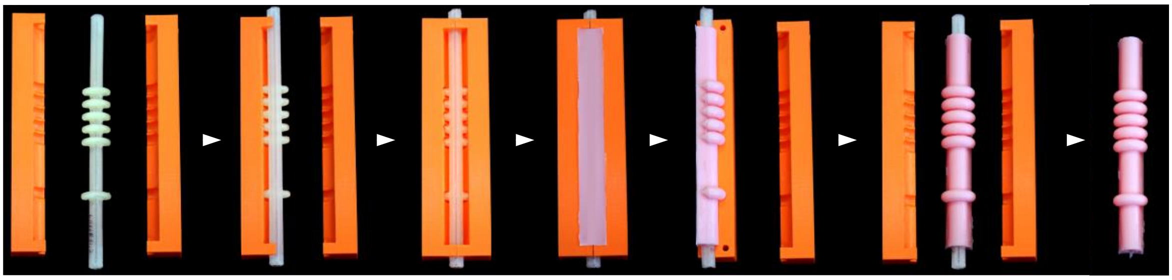

Figure 3.3. Casting sequence.

3.3.2. Casting and vacuum

Casting and vacuum are directly correlated. Vacuum is applied to the material before casting and to the mould after casting, to ensure the best material quality, removing any possible air bubbles. Depending on the geometry of the actuator, and how the air might become trapped inside the mould, casting can be done in two ways: pouring or injection. If the actuator has a large flat surface, pouring is fast and easier, but if the geometry is complex and the air might get stuck inside the mould, then injection is advised. Whenever injection is required, small holes on both sides of the mould need to be designed in order to accommodate the syringe tip. These holes should be placed specially on areas that would most likely create an air bubble. Additionally, the mould should be placed vertically during casting, and the silicone should be injected from bottom to top, to prevent air trapping.

3.3.3. Core dissolution

Although the whole process is relatively easy and without need for supervision, the core dissolution in water faces some challenges related to the time it takes and by slowing down the fabrication. The main issues are related to the small contact area (between core and water) and lack of flow. The water needs to be in constant motion to not let saturated suspensions of PVA stay on top of undissolved PVA, and the contact area must be as large as possible. For those reasons, the process needed to be optimized – instead of a compact core, the core should be hollow (Figure 3.4c, Figure 3.4d), to let water flow through it, maximizing the contact area, and continuously removing PVA. Additionally, the cores should have a tubular ending to connect them to a liquid pump, through tubing, that creates the flow. The water should remain at a constant temperature, around 65º, and this requires a heating element, a thermistor and a microcontroller to regulate the temperature (Figure 3.4a, Figure 3.4b).

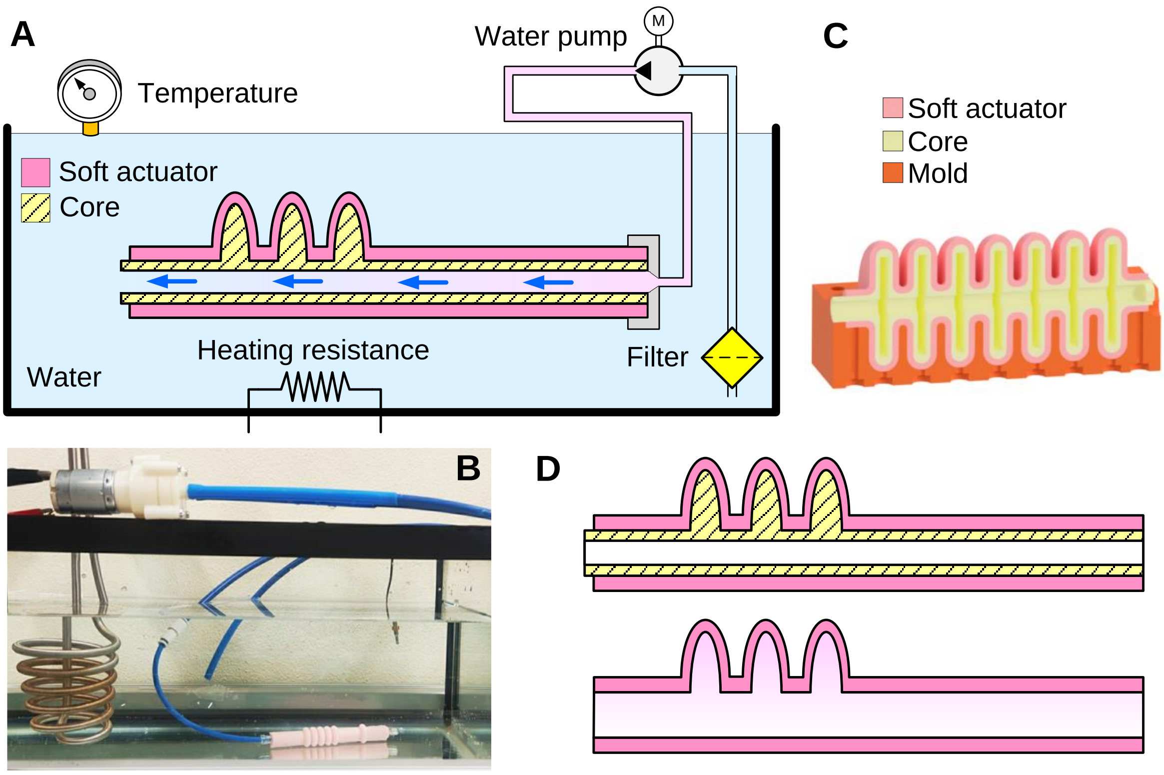

Figure 3.4. a) Schematic of the water dissolution circuit. b) Water dissolution circuit with the key components c) Cross-section of the mold, actuator and core. d) Cross-section of a soft actuator before and after dissolution.

4. EXPERIMENTS AND RESULTS

Here it is shown the applicability of the proposed process in the fabrication of soft actuators that can achieve bending and linear motion. Three one-chamber actuators (Figure 4.1) were fabricated, two of them are bending actuators, and the other is a linear actuator. All the prototypes were made using the simulation-aided design, and fabricated through casting SmoothSil 940 in 3D printed moulds. One chamber actuators are simple to control because they require only one pressure signal to actuate. Whenever they are pressurized, they expand creating bending or linear motion. When the air evacuates, the silicone's elastic properties make the actuator return to its stable position (after continuous work, the silicone is not able to return to its exact original shape due to elastic hysteresis).

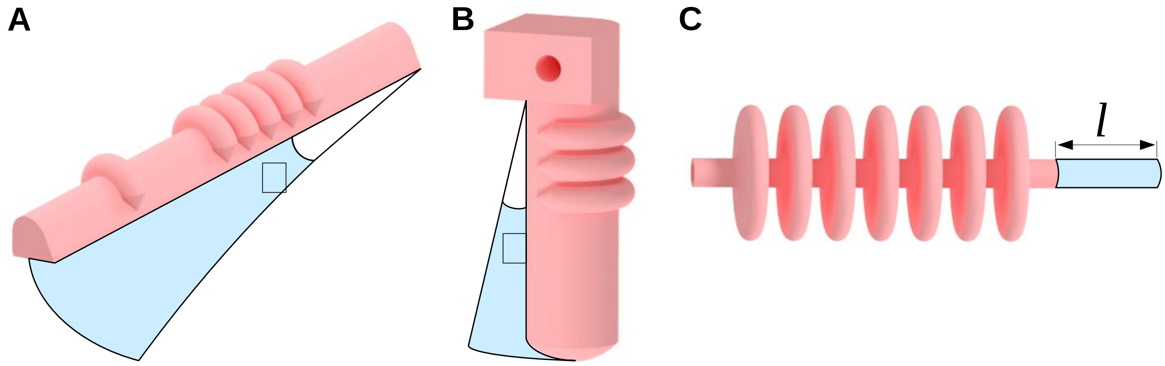

Figure 4.1. 3D render of the designed actuators: a) bending actuator 1, b) bending actuator 2, c) linear actuator

4.1. Bending actuator 1

As exposed before, soft robots are widely known for their gripping applications. Usually, grippers are composed of 2 or more bending actuators that are pressurized at the same time. These actuators can achieve the bending motion by having pneumatic chambers or a more flexible material on one side, and a flat surface on the other.

The goal was to create an actuator capable of bending up to 90º, using a single mould. It should resemble a finger, long and skinny, that bends mainly in the proximal interphalangeal (PIP) joint but also in the distal interphalangeal (DIP) joint.

After an iterative process of drawing and simulation, the final design was achieved. The actuator has five pneumatic chambers to mimic the PIP and another one to mimic the DIP. Each chamber has conic-shaped endings, to promote the inflation on the top rather than on the sides.

4.2. Bending actuator 2

One-chamber bending actuators like the bending actuator 1 can be used as soft legs for a walking robot. Although, some changes should be made to the design to provide more support and hold higher loads. In order to do so, both diameter and wall thickness should be larger.

This soft robotic leg should also have a “hip” for tubing and connection to the body. Movement will be achieved by expanding the pneumatic chambers that will replicate a “knee”.

4.3. Linear actuator

Soft actuators like the McKibben muscles use fiber reinforcement to create linear expansion. The alternative is having a design that has chambers all around the main channel, which, using non-sacrificial cores, meant fabrication through a two-step moulding process and bonding.

The simplest linear actuator is a tube with concentric disk-shaped chambers along its length. The same process of drawing, simulating, and creating the moulds was followed.

4.4. Results

During the design phase all the actuators were tested using FEA simulation at different pressures to antecipate its behavious (bending angle and linear displacement) when pressurized. Upon fabrication, they were submitted to the same pressures in order to compare the real motion against the value obtained in simulation.

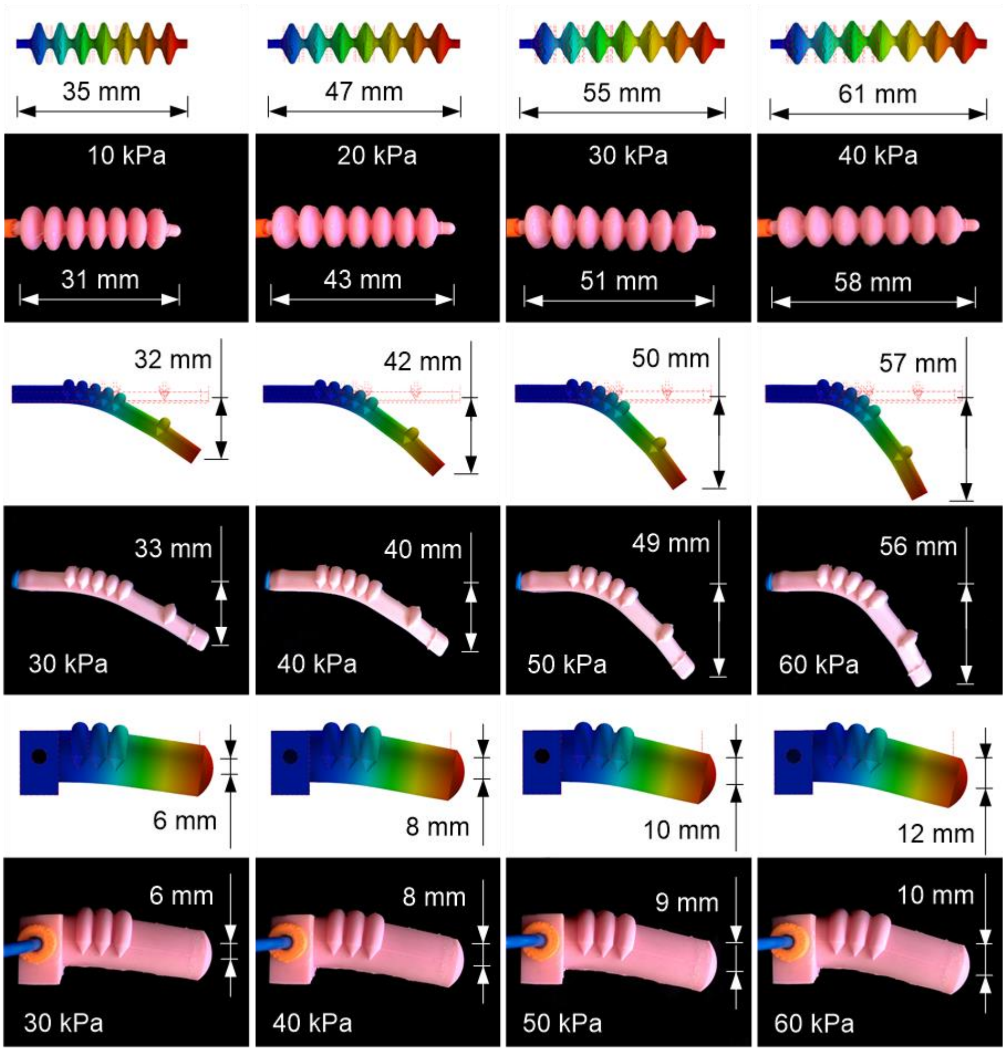

Figure 4.2. Actuation comparison at different pressures, real and simulated

The FEA simulations display the maximum displacement in a specific axis when the actuator is submitted to a given pressure. For the geometries studied the simulation is accurate and is able to give a clear representation of how an actuator will respond purely based on design and actuating pressures (Figure 4.2).

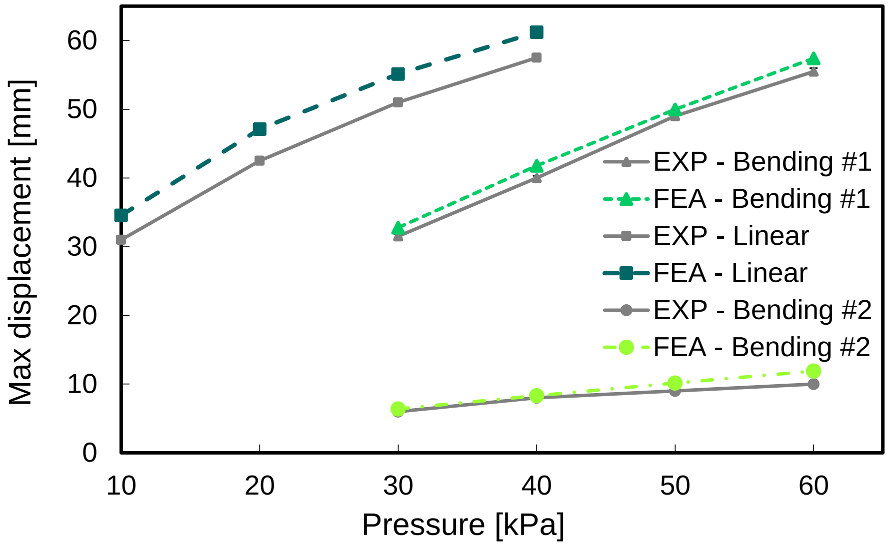

Figure 4.3. Displacement comparison at different pressures, real and simulated

The exact actuation pattern of the proposed linear actuator is harder to simulate (Figure 4.3) due to the fact that the wall thickness is relatively small so that the radial expansion is very noticeable. Radial expansion limits linear expansion, and for some reason the model does not reproduce this factor accurately. Although, even with a faulty representation of how much does an actuator expand, it is possible to understand how an actuator expands, and that in itself is already a decent breakthrough for simulation aided design of soft mechanisms.

As long as the simulation parameters are refined, through intensive testing even without specialized tools such as uni or biaxial tensile test machines, it is demonstrated that fabrication of soft robots should not be a lengthy process of trial and error when aided by FEA simulation. Spending computational time is faster and cheaper than spending materials to print moulds and cure silicone. Alongside experienced mould creation, there is no reason for a fabrication process to take more than one try and a single step.

In terms of elasticity, there is a direct correlation between wall thickness and bending capability. The bending actuator 2 has specific design characteristics to provide strength and stability. As expected, those characteristics prevent the radial expansion (on the chambers) that curve the actuator. In contrast, the thinner and lighter bending actuator 1 is able to bend up to 60º at 60kPa pressure (Figure 4.4).

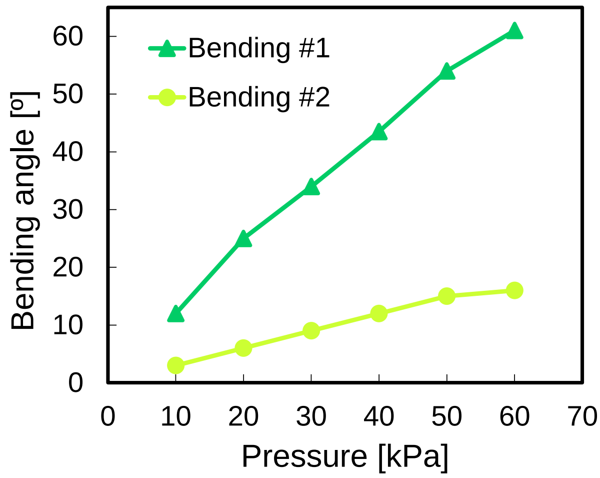

Figure 4.4. Correlation between pressure and bending angle

5. ROBOT PROTOTYPES

The actuators produced with the single step fabrication method can be used in many different applications. Soft bending actuators are very popular among gripping solutions as shown before but, to take this technology one step further, two walking demonstrators were created.

The goal is to build simple pneumatic powered robots, with one-chamber actuators and tethered control. This category of robotics has been a focal point of research in the last few years, due to the growing desire of exploring new types of locomotion.

A completely soft robotic millipede walker was developed by Skylar-Scott et al. (2019), using MM3D printing. The robot has 4 columns of 4 legs each, and the outer columns are facing in the opposite way of the inner columns. This disposition alongside a synchronized actuation pattern makes it possible to walk at 10mm/s while carrying 209g of additional weight.

Other approach is combining a rigid body with soft actuators that will promote locomotion. Researchers (Tang et al., 2020) created a robot, using bistable soft actuators and a preloaded spring to increase the potential energy, that resembles active spine mechanism of a cheetah. The small 3D printed feet covered with silicone to increase friction are able to walk in horizontal or diagonal planes.

5.1. Tetrapod walker

Many terrestrial mammals, beside humans, actively use four limbs for some type of locomotion. Inspired by nature, a pneumatically controlled tetrapod was developed using both soft and hard materials.

5.1.1. Assembled robot

The robot is comprised by four soft legs, the bending actuator 2 presented before, and a 3D printed body in rigid material. Each leg is fixated in the rigid structure. Additional tube-management structures were added.

The actuation is antisymmetric, i.e. the legs are connected through tubing in pairs – front left (FL) and back right (BR), front right (FR) and back left (BL). After testing, the most efficient actuation pattern, that is able to promote a continuous walking movement without any stops, i.e. without having all legs unpressurized at once, was chosen (Figure 5.1). The control system consists in an assortment of 2 way, 2 positions solenoid valves that are connected to an Arduino, that shifts the flow between legs.

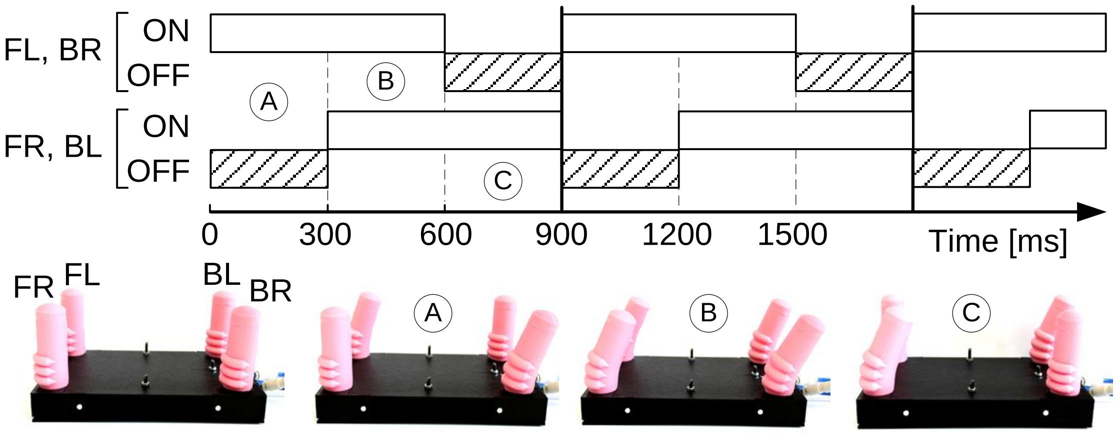

Figure 5.1. Pressure signal diagram and respective leg actuation

5.1.2. Results

As expected, the input pressure has a direct impact on the tetrapod’s movement speed (Figure 5.2a). Following the the current design, the tetrapod can carry small loads, which also correlate to the movement speed (Figure 5.2b). Not only the weight, but also the configuration of the loaded object has a direct impact on speed – objects with a low center of mass that don’t change the overall center of mass of the tetrapod too much are easily carried, but if they’re tall with a center of mass farther from the tetrapod’s own center of mass, the tetrapod would most likely lose balance in between steps. Nonetheless, if more legs were added – turning it into a hexapod or octopod - it could easily hold more weight.

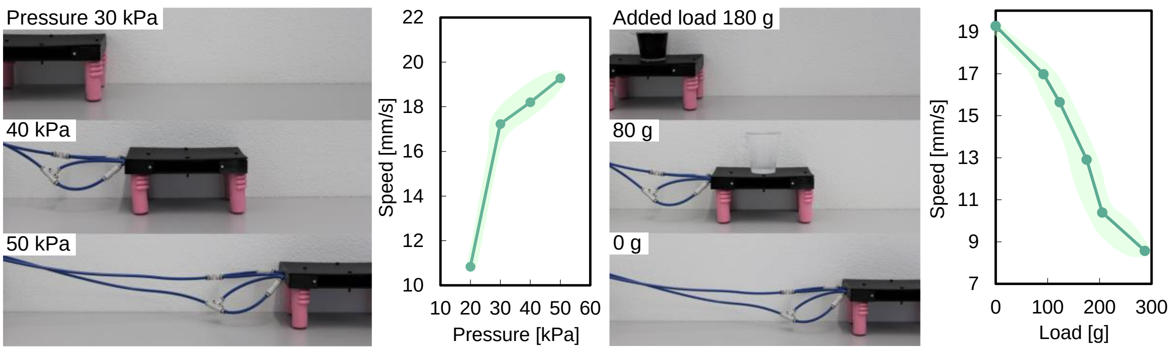

Figure 5.2. Speed's variation with: a) Pressure; b) Load at a constant pressure of 50kPa

5.2. Linear-expansion walker

Converting the actuator expansion in linear movement is a design challenge. In order to achieve movement in one direction, the actuator needs to have backwards movement constrained, i.e. it cannot expand or contract in the opposite direction. To achieve this, the concept of unidirectional friction was explored.

5.2.1. Assembled robot

The robot consists in a singular linear actuator, placed horizontally supported by two simple 3D printed structures (Figure 5.3). The actuator will push the front and pull its back. Additionally, to connect both ends and ensure that they remain parallel to each other, two metallic cylindric shafts were placed in one end through tight fitting.

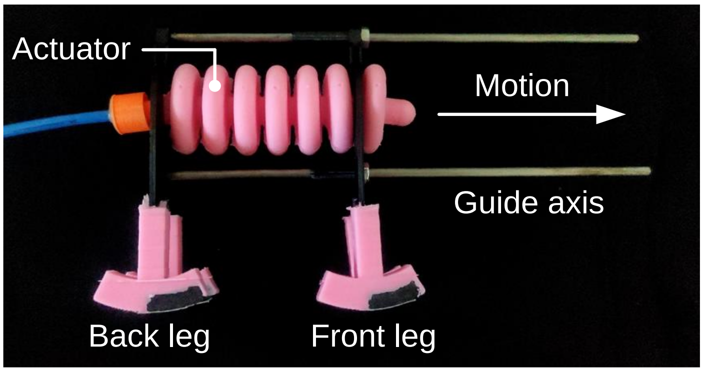

Figure 5.3. Assembled robot

Unidirectional friction was achieved by creating a flexible leg that shifts the point of contact with the ground depending on the force applied (pull vs push). The leg was fabricated in SmoothSil 940 and has a 3D printed tip in PLA. This design allows the forward movement and constraints any backward movement, which promotes linear locomotion.

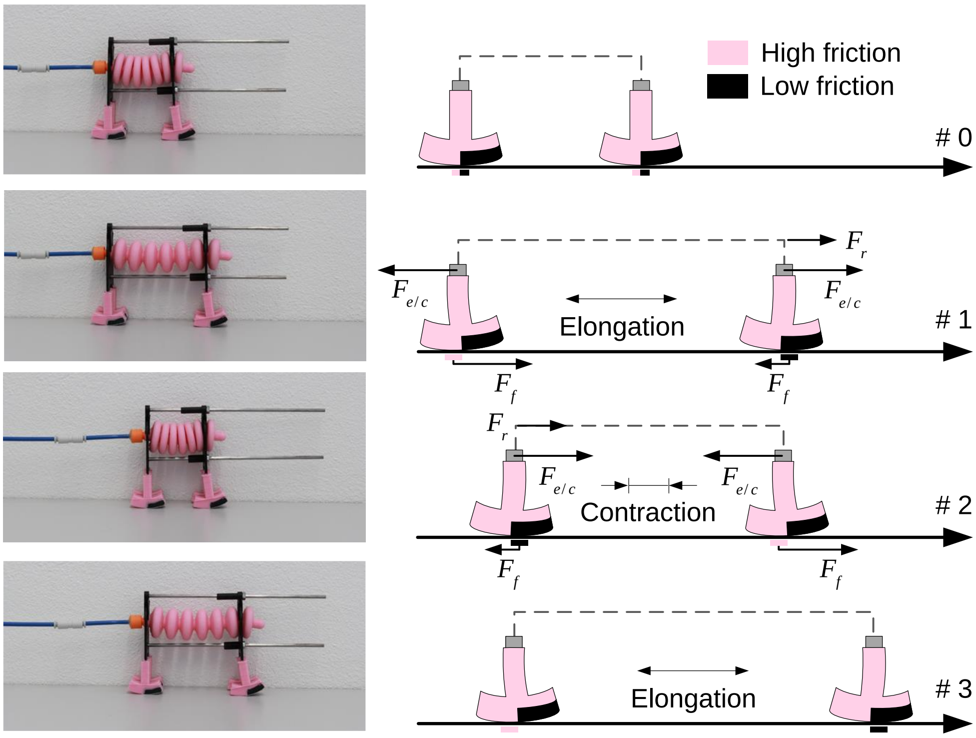

Figure 5.4. Walking behavior

During elongation (Figure 5.4) the point of contact with the ground on the back is silicone, while in the front is PLA, which results in a higher friction force (F_f) on the back. Since the elongation force ($F_{e/c}$) is the same on both directions, the resultant force (F_r) is the difference between both friction forces, which is positive, therefore the robot moves forward. Furthermore, during contraction the point of contact with the ground on the back is PLA, while in the front is silicone. Although, the higher friction still faces forward due to the fact that contraction force ($F_{e/c}$) is facing inward, which also promotes the forward movement of the robot.

5.2.2. Results

A simple on/off cycle is enough to achieve locomotion depending on the frequency. The actuator needs to have time to deflate, so there is a limit for how high can the frequency be set to. Higher frequencies mean smaller and faster steps, and on the contrary lower frequencies mean longer and slower steps. To analyze the impact of frequency in its movement speed, several tests were conducted (Figure 5.5). Up to 4Hz, the speed increases with the frequency, but at 10Hz the robot cannot move, because there's not enough time for the robot to contract and expel the air inside it. Therefore, the elastic force that the actuator is able to apply to the air during the contraction (i.e. deflation) is what constraints speed.

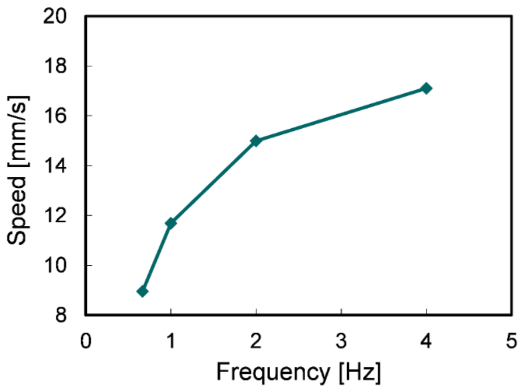

Figure 5.5. Frequency's impact on movement speed

6. CONCLUSION

Soft robots are evolving, and so does the technology around them. From design and fabrication to control, there are a number of scientific challenges to make soft mechanisms suitable for innovative applications in all domains. The work presented in this thesis was an effort to simplify the fabrication and improving the overall output quality of soft actuators. It is as simple as the traditional FDM printing and casting method but requires only one moulding process. Furthermore, it is not technologically expensive, because any FDM printer can perform the tasks needed, neither requires any major tuning or additional devices, other than a simple water circuit to dissolve the cores. The benefits are clear, and it was demonstrated that is capable of producing silicone actuators in a single step which would not be possible with other methods with such level of simplicity. Mould design and treatment are considered fundamental tasks to ensure prime output quality. Additionally, the simulation aided design, although time consuming in an earlier stage of the process, especially if the material properties are not correctly defined, efficiently provides a very decent perspective of how will the finished product react to pressure, with an average predicting error of 7.2%. Thus, in the end, FEA can actually be considered time saving, if we take into account all the failed iterations that didn't reach the fabrication stage, which includes 3D printing of both moulds and cores, casting, curing and dissolution.

In an attempt to demonstrate the actuators' performance, two walking robots were created. With the premise of simplistic design and with the less tethering possible, both robots were fully functional, reaching satisfying speeds of over 16mm/s. Moving forward, there is plenty of space for improvement: the concept of unidirectional friction, or variable friction depending on the direction, should be closely analyzed, specifically in the materials stand point at a microscopic level. There might be an advantage turning the tetrapod in an hexapod or octopod, because that would most likely improve the ability to carry weight and overall stability, and also allow climbing or at least walking in rougher terrains.

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