MASTER

Encoding Mechanical Functions Into Pulps of Soft Pneumatic Fingers for Simple Control of Dexterous Behavior

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Award date:
2021

Awarding institution:
Technische Universität Berlin

Technische Universität Berlin

School IV - Electrical Engineering and Computer Science

Department of Computer Engineering and Microelectronics

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Master Thesis

Encoding Mechanical Functions Into Pulps of Soft Pneumatic Fingers for Simple Control of Dexterous Behavior.

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ICT Innovation

Date of submission: **27.08.2021**

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Abstract

Soft robotics is a sub-field of robotics where the parts of the robot are made up of soft materials. These soft materials bend and deform when they are interacting with the objects in the external environment. During this process, the soft robot adapts and complies with the objects. Due to this compliance in the soft robots, they have increasingly become popular in the field of manipulation. As more research is done on manipulation by soft robots, contact-rich manipulation tasks (like sliding soft fingers across an object) are still difficult to perform by soft robots. Because precise actuation information of the soft robot for a contact-rich manipulation task is needed which then can be modeled and designed on the software side of the soft robotic control. Here, in this thesis, an idea is presented using the properties of friction and contact area, where even low accuracy of software control can provide high accuracy in sliding-based contact-rich manipulation tasks. This is done by creating a soft finger morphology where the friction profile of the pulp is controlled passively using only the applied force. A low application force gives very low friction on the finger pulp, and a high application force gives high friction on the finger pulp surface. This gives a higher range for applied forces for low friction, which makes the sliding of soft finger pulp easier on a surface by simplifying the control on the software side.

Zusammenfassung

Titel:
Kodierung mechanischer Funktionen in Kuppen weicher pneumatischer Finger für eine vereinfachte Ansteuerung geschickten Verhaltens.

Ein Bereich der Robotik ist die Softrobotik, bei der Teile des Roboters aus weichen Material bestehen. Dieses weiche Material kann durch äußere Einflüsse verformt werden, was beispielsweise beim Greifen eines Objektes passieren kann. Dabei passt sich der Roboter dem Objekt besser an, weswegen die Soft Robotik im Bereich der Manipulation immer mehr an Beliebtheit erlangt. Eine Herausforderung in dem Bereich sind die kontaktreichen Manipulationsaufgaben, wie z.B. das Gleiten der weichen Finger über ein Objekt. Um eine präzise Robotersteuerung zu entwerfen, werden genaue Informationen benötigt über den Zustand zwischen Roboter und Umgebung. Dies bringt jedoch einen hohen Rechenaufwand mit sich und sollte entsprechend an die Morphologie des weichen Roboters ausgelagert werden. In dieser Arbeit wird eine Idee vorgestellt, in der die Eigenschaften der Reibung und der Kontaktflächen zwischen Finger und Objekt zu Gunsten genutzt werden, um so die fehlenden softwareseitigen Berechnungen auszugleichen und eine hohe Genauigkeit bei kontaktreichen Manipulationsaufgaben zu erreichen. Dies wird durch eine veränderte Fingermorphologie erbracht, bei der das Reibungsprofil der Fingerkuppe passiv durch die angebrachte Kraft gesteuert wird. Bei einer kleinen Kraft, ist die Reibung gering und mit entsprechend zunehmender Kraft, nimmt auch die Reibung an der Oberfläche der Fingerkuppe zu.

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1 Introduction

Soft robotics is a relatively new research field, where research is usually inspired by soft bodies like animals in nature and incorporates soft materials in the robots [1]. The soft materials are compliant, and they bend or deform to their surroundings. During the deformations, the soft robot adapts and complies with the object being grasp or manipulated. Due to the compliance in soft robotics, they are becoming popular in the field of robotic manipulation. Another reason is the low complexity of control design, these soft robots do not need to know about the precise location and shape beforehand of a grasping or manipulation task. When the soft materials in the robots comply, they make small adjustments in grasping and automatically balance the forces exerted on the object being manipulated. This process can be referred to as morphological computation. When actuation is done on a soft robot, some part of control computation is done by the physical morphology of the robot, and the computation is offloaded from the software control to the physical body of the robot.

This compliance of soft robots gives them better grasping and manipulation abilities, but it also makes their dynamics complex. Soft robots work passively and have nonlinear dynamics which makes them difficult to model [2] for contact-rich manipulation tasks like sliding and griping with a soft robotic hand. But soft robots also leverage morphological computation by offloading computation from software to hardware. Using this approach a functionality in hardware can be designed which reduces complexity in software control and makes the contact-rich manipulation tasks easier to perform. Therefore a mechanical function can be created which represent the hardware functionality and the behavior of the soft robot.

An example of such encoding of mechanical function in a soft finger pulp can be illustrated by creating a mechanical function where the contact area does not increase significantly for a range of applied force but after a certain force threshold, the contact area increases in a high amount. See Figure 1.1

If the relationship between applied force and contact area has been characterized such as there is a quick transition between small and large contact area, we are able to design a controller that can robustly switch between these two modes of contact area. If these two modes now exhibit also significant differences in contact dynamics, the controller can be used to easily induce predictable and versatile manipulation behavior.

In this thesis, I present a soft finger pulp morphology which implements a me-

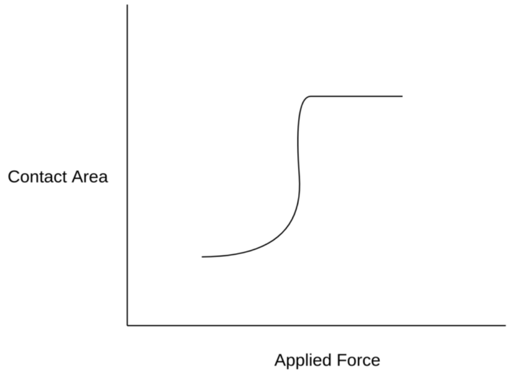


Figure 1.1: Example of a mechanical function where the behavior of contact area is characterized based on the applied force.

chanical function on the passive soft layer of a soft actuator, which can offload the control computation from the software side to the hardware side of the soft actuator. The finger pulp morphology was created based on the mechanical function, where the contact area and friction force are modulated by the applied force. The contact area and friction do not change much for a range of applied forces but these values change in a huge amount after a threshold of applied force. The soft finger pulp is the layer of softer silicone on RBO Hand 3 soft finger actuators. The soft finger actuator are a double compartment soft actuator of soft robotic anthropomorphic hand "RBO Hand 3" which is in the development phase at Robotics and Biology Laboratory [34] of the Technische Universität Berlin. The soft finger pulps improves and facilitates grasping by deforming and adapting to the contact surface under the influence of actuation forces. Changing the morphology of these finger pulps can change the overall behavior of the soft finger and therefore these are best suitable for implementing a mechanical function based on contact area and friction.

Before converging on the new design of finger pulp morphology, different morphologies for finger pulp were created using contact area and friction as the design properties for morphologies. All the morphologies were compared with the base morphology of the RBO Hand 3 finger pulp, because the base morphology is currently being used for different grasping and manipulations tasks. An evaluation task was created for the new morphology, where an object was tested for sliding manipulation. The object could slip on the new modified pulp morphology on a large range of applied force whereas on the default finger pulp morphology the object could not slip for those same ranges of forces. This shows that the manipulation task of switching between slipping and grasping on an object becomes much easier on a modified pulp morphology than on a normal pulp morphology and therefore more robust control behavior can be designed by changing the morphology of soft finger actuator pulp.

In the next chapter, I will talk about the background regarding soft actuators, contact area and friction. In Chapter 3, I will describe the related work on controlling friction in robots, which is related to this thesis.

Chapter 4 will explain the overall design process. Here I will describe how different silicone materials were tested based on the contact area. I will show how different morphologies for soft finger pulp were created and how they were evaluated based on contact area and friction properties. I will give a brief overview of the setup for taking data of contact area and friction. In Chapter 5, I will explain the manipulation experiment done on the modified finger pulp and discuss the required setup. Finally I will discuss about the results of the manipulation and evaluation experiments and validate the idea of encoding mechanical functions in the soft finger pulps. Chapter 6 will be about conclusion and future work.

2 Background

2.1 Soft Actuators and Soft Robots

This thesis focuses mainly on soft actuators and soft robots, therefore it is important to understand the background behind the soft actuators and robots and to discuss the challenges with the soft robots in general. As discussed previously in Chapter 1 that soft robots are inspired from nature. Here we see that, there are several soft actuators which are inspired from different organisms in nature [3] [4] [5] [6]. Trivedi et al. describe some of these soft robots as inspired with the muscular hydrostats [7] which are biological structure with mainly muscles and no jointed skeletal support but these soft bodied animals relies on a 'hydostatic skeleton'. These hydostatic skeleton are made up of fluid filled cavities contained inside muscular walls. The fluid is usually liquid and due to incompressibility, volume under influence of pressure does not change. Therefore a diverse range of movements and shape changes are possible due to contraction and retraction of muscular walls and movement of fluid around the body. Soft pneumatic robots like [3] [4] [8]are based on this kind of fluid mechanism but air is used instead of liquid. It's easier to work with gas fluids than with liquid fluids, but gas fluids are susceptible to volume change. Another issue in these fluid controlling soft robots is the controllability, it is difficult to control the flow of fluids precisely and this affects the actuation and control of the soft actuator in the soft robot.

Coming to soft robots, they are usually made up completely flexible parts, or mixture of flexible and rigid parts. But due to the soft and flexible nature of the soft robots they can be difficult to model. Trivedi et al. describes in [7] that soft robots have infinite number of degrees of freedom due to distributed deformations in the body. It is stated here that soft robots are underactuated because there is not an soft actuator available in soft robots for every degree of freedom, other than hard robots where an actuator is present of every available degree of freedom. Hauser puts similar argument [2], that due to non linearity in soft robots they are difficult to model and hard robots utilize rigid body parts and fully actuated systems to overcome these problems. Because it's easier to control the dynamics of rigid robot where the contact information between the environment and the robot is known, but it is difficult to model the rigid robot where little or no information is provided about the external unknown environment. So in case of both soft and rigid robots it is difficult to sense and model the physics that carry out the interaction with the world. Therefore, explicitly controlling them becomes an extremely difficult task, if no information about the unknown world are given. For example the problem of contact-rich manipulation tasks like sliding and grasping of unknown objects is difficult for both soft and hard robots. Therefore to solve the problem of control, there is need to look at the problem solving from nature and look for better approaches to control soft robots. Zambrano et al. gives a methodology for designing robots. It is proposed that [9] morphological computation can create a new paradigm for designing robots, where design is done based on control. In designing soft robots control should be given the highest priority and based on it, different mechanisms, sensors, proper morphology and mechanical characteristics are designed to have least control complexity.

2.2 Contact Area in Soft Robotics

Contact area in soft gripping is a useful property, because high contact area means better grasp and better shape adaption [10]. There are different methods for calculating the contact area from soft robotic actuators and hands. A pressure-sensitive cylinder is used in [11] to measure the pressure points from soft hand like Pisa/IIT soft hand [12]. The cylinder uses pressure sensitive film to measure the pressure points from the soft hand. A similar experiment where paint was used to measure the contact area made by a soft hand is shown in [13]. Here the Pisa/IIT soft hand and RBO Hand 2 [3] is used to measure the contact area and pressure measurements and it was compared with the human hand measurements. Recording paper and fine toner dust was used for verifying contact area while modeling the contact mechanics for soft robotic fingers in [14] and [15]. Based on these studies it was decided to use paint for measuring contact area in this thesis work. Using paint is more reliable because we needed to know the exact contact made by the silicone actuator pulp and single finger pulp has small morphology so using a toner paper or pressure sensitive paper would have give erroneous readings as the contact areas made by the finger pulps were very small.

2.3 Friction in Soft Robotics

Data about friction from contact points is highly relevant when doing grasping and manipulation experiments with silicone based soft robots. Because silicone is a non-linear material due to influence of adhesion [16], for which the friction profile changes in high amount based on force applied. Therefore the data about friction profile of a given morphology can help in understand the behavior of that morphology and later design or create a new type of morphology. Friction calculation in non-linear elastic material like rubber and silicones is difficult because of complex behavior of these materials, Gabriel explained about one of these behavior, which is waves of detachment in Ph.D [17]. A high speed camera and 3-dimensional force data were used to show effect of frictional shear stresses causing detachment effect in rubber [18]. Fujihira et al. has shown a new type of force called maximum resistible force [19] for soft robotic fingers, which is the maximum force before the fingertips starts slipping. For soft locomotive robots like inchworm, de Payrebrune describes a method with easy setup to calculate the friction [20]. For creating precise control of a fingertip, ho et al. has created a micro sensor which is embedded in a soft finger grip [21] for acquiring accurate data about force and moment acting on the fingertip. The sensor was capable of producing data about normal force and dynamic friction based on the signals from the sensor.

3 Related Work

Manipulation tasks like sliding with griping on the objects has been a challenging task for the robots, whereas human finger pulp can perform these manipulations easily [22]. The ability of human fingers to perform these complex manipulation tasks could be credited to the variable friction and contact area properties of human finger pulp [23]. Warman and Ennos did test on human fingers for contact area and friction on a acrylic sheet and discovered that friction increases with contact area [23]. Many efforts has been made to replicate the behavior of human finger pulp [24], [25] and [26].

Recent efforts has been made which focus on varying the friction in the robots [4],[27], [28] and [29]. The inchworm robot [4] which is inspired from nature is designed based on the behavior of inchworm. The inchworm can change the friction profile of its body in particular places to achieve locomotion. The inchworm robot works on the principle of friction hysteresis and it's capable to achieve continuous linear motion. The robot is designed in such a way that there is a deformation in one of the legs, which causes difference in friction between two legs and hence possibility of producing linear motion. The friction hysteresis can be controlled and the robot can be moved in forward and backward direction. Based on human finger skin, Spiers et al. has created a actuator with variable friction which incorporates two surfaces with different friction profiles [29]. The actuator has one variable friction surface and one constant friction surface. The actuator is capable of doing hand rolling and sliding of objects without any need for tactile sensing or other complex control methods. Tincani et al. has created smart gripper with "velvet fingers" which is able to emulate different level of friction. The gripper has active conveyors belts surfaces which comes in contact with the object being manipulated. By controlling the conveyor belts intelligently the gripper can provide a variable friction to the object being grasped or manipulated [28]. Umedachi et al. presents a 3-D printed continuum style soft robot which change it's friction profile by using a shape memory alloy actuator [27]. This soft robot utilizes two soft materials for changing the coefficient of friction and provide locomotion by inching and crawling motions [27]. Another interesting research paper shows the design of soft gripper which uses incompressible liquid to change the properties of the gripper [30]. Maruyama et al. has created an soft robotics gripper which has fingertips constructed from incompressible liquid [30]. The gripper has rubber bags which are filled with a incompressible fluid, a gel. The gel pressure can be controlled and the fingertip can grasp fragile objects, changing the pressure on the fingertip more stiffer object can be grasped as well. This soft gel gripper paper does not show data on friction properties, but still this gives a interesting design method which can be utilized to change the friction of the soft actuator.

4 Contact Area and Friction for Designing Morphologies

As discussed previously in 1 about RBO Hand 3 actuators and finger pulps. These soft finger actuator have finger pulps which deform and bend to the surface they come in contact with, thus they help in better grasping and manipulation. As the finger pulps first come in contact with a object which is grasped or manipulated with the soft robotic hand, therefore they could be used for creating a mechanical function. For creating a mechanical function in these silicone finger pulps, it is crucial to understand the different properties of materials used in the pulps. A understandable scenario is, when a force is applied by soft actuators, these softer silicone finger pulp will increase its surface area on a contact surface. Other scenario is that when a object is grasped by the actuators, the grasped object can slip or held firmly in the place depending on the friction profile of the pulp surface. Therefore contact area and friction forces are the two properties that can be used to create a mechanical function in the soft robot morphologies.

To investigate the mechanical function which includes contact area and friction the following hypothesis are proposed:

Hypothesis 1: This hypothesis is based on the force and contact area relationship of different silicone types. It states that, under the influence of a given applied force, the contact area made by that force increases from stiffer silicone to a softer silicone. In simpler words, softer silicone will have more contact area than a stiffer silicone for a given amount of force. This hypothesis can help in modulating a mechanical function based on the soft material used.

Hypothesis 2: This hypothesis is based on the direct relationship of force and contact area of a particular type of silicone. It states that for a given silicone type the contact area will increase when the applied force is increased. Simply said, more force will result in more contact area for a particular silicone. This hypothesis will be used to understand and investigate the relationship between applied force and the contact area for a mechanical function.

Hypothesis 3: This hypothesis is based on the effect of force and contact area in different shapes/morphologies of silicones. It states that for different morphologies the effect of force and contact area explained in **Hypothesis 1** and **Hypothesis 2** holds. Or the effect of **Hypothesis 1** and **Hypothesis 2** will remain true irrespective of the morphologies/shapes of the silicone. This hypothesis will be used to base the mechanical functions if they can be generalized across different pulp morphologies.

Hypothesis 4: This hypothesis is for testing effect of applied force and friction properties in different shapes/morphologies of silicones. It states that higher contact area results in higher frictional pulling force. Proving this hypothesis will make correlating the contact area and friction possible for the morphologies, which gives a relative idea about friction properties from only the contact area data.

4.1 Contact Area

4.1.1 Different Silicones for Contact Area

Different silicone materials will behave differently under the influence of comparable forces. Therefore, for understanding and designing new pulps with a mechanical function, it is important to understand the behavior of different silicone materials under the influence of comparable forces exerted by the soft actuators. The silicone materials are used from brand Smooth-On and the experiments will be done on the silicone in the range from hardness extra soft to soft, as shown in the Figure 4.1.

Silicone from shore hardness scale A will be DragnSkin-10 with shore hardness of 10A, with EcoFlex-30 and EcoFlex-50 from shore 00 scale with hardness from 00-30 to 00-50, respectively. Tests on Ecoflex-Gel will also be done which is very soft silicone with shore hardness of 000-35 which is below 00 shore hardness scale. As defined above the three hypothesis for contact area defined above (**Hypothesis 1**, **Hypothesis 2** and **Hypothesis 3**) will be tested here. So for the different silicone materials we can test the behavior of different silicones by these hypothesis. According to **Hypothesis 1** if 0.5N of force is applied on a silicone sample of DragnSkin-10 and EcoFlex-50, the contact area made by EcoFlex-50 must be greater than DragnSkin-10. Likewise **Hypothesis 2** says that, 0.5N force will result in more contact area for EcoFlex-30 than for force 0.3N.

4.1.2 Experimental Setup for Contact Area

For testing these hypotheses and calculating contact area an experimental setup is needed. The setup for calculating contact area can be imagined where a sample of silicone morphology can be fixed which is coated with paint. The coated paint will imprint the contact area when it comes in contact with the paper. The silicone sample should be able to move freely in the vertical direction so that the force of gravity can be utilized to exert pressure on the silicone sample. For creating such a setup, linear rails with ball bearing can be used which has minimal friction and

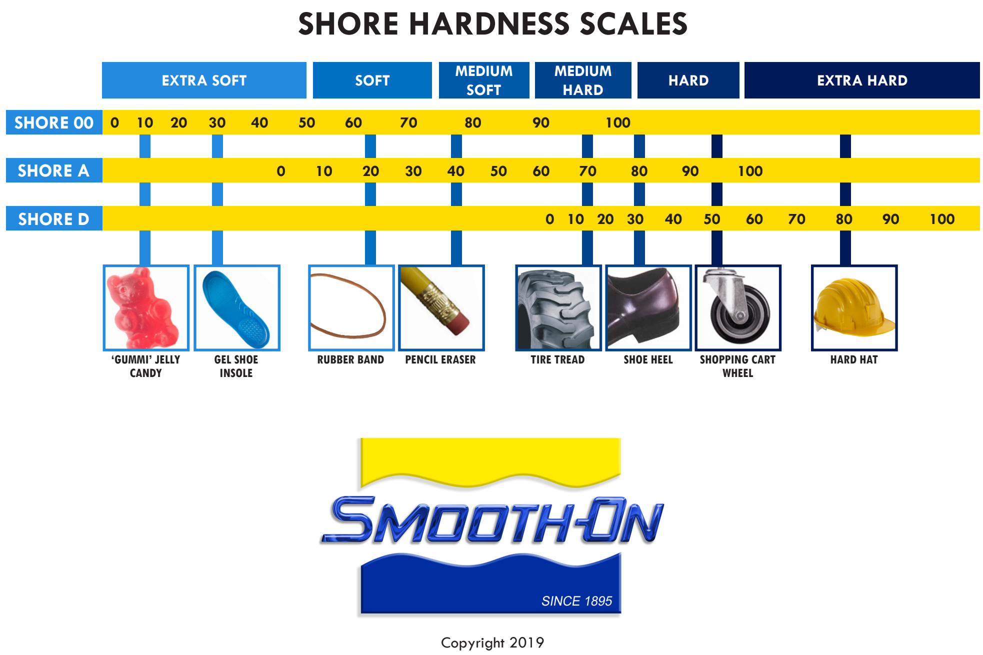


Figure 4.1: Shore hardness scale from Smooth-On [35].

can hold the silicone sample in place. The linear rail can be fixed vertically along the rail axis on a rigid support. Thus, when a given weight is put on the silicone, a force will be exerted on the silicone which will imprint the contact area on a paper. A schematic of such a setup is shown in Figure 4.2.

The setup helps in achieving constant force vectors across the experiments. Some precautions must be taken while taking the reading from the experiments. The setup must be fixed in one place so that it does not create errors while taking prints from the silicone sample. It should be leveled before use to make sure the platform with silicone sample that is lowered on the paper is horizontal, otherwise, it can result in errors in prints. While the platform is lowered on the paper, it should be lowered slowly, because due to high momentum the impact will make more contact than it should and will result in the wrong contact area. The setup is shown in Figure 4.3, where a silicone sample with coated ink is put in the moving platform. This setup was made by a fellow RBO Thesis student named Tessa Johanna Pannen, which was later modified for inserting a silicone sample in a tray.

For proving **Hypothesis 1**, **Hypothesis 2** and **Hypothesis 3**, two types of

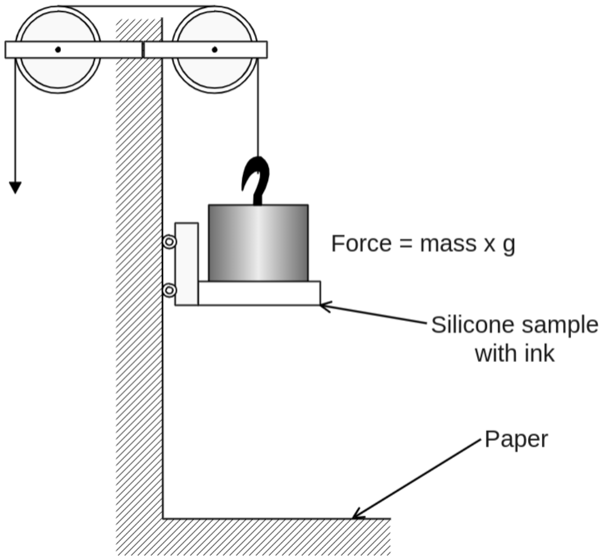


Figure 4.2: Schematic showing setup for taking area. Here the weight will apply force of $mass \times 9.8m/s^2$, which has silicone sample attached. The silicone sample is inked and a paper is placed on the bottom for taking the print of the force applied.

morphologies are chosen. Morphology 1 was created by pouring the desired silicone in a cup up to the height of 10mm. Morphology 2 was created by Vincent Wall which is the finger pulp for the RBO Hand 2 [3], the mold for morphology 2 was 3D printed. Morphology 1 and 2 can be seen in Figure 4.4a and Figure 4.4b, respectively.

Taking the idea from the contact area experiment from [13], different paints were tested. Using water-based paints like fingerpaint and acrylic paint, does not give a very coherent contact print on paper. The reason is that water-based paints do not stick well on smooth surfaces and the morphologies that were tested, were very smooth. Testing with the oil paint, gives a coherent and full print of the contact of the silicone sample on the paper. This helped in creating accurate prints for the different forces and morphologies.

4.1.3 Stickiness in Silicone

In softer silicone types like Ecoflex-gel the silicone has some adhesion properties. The effect of adhesion is highly pronounced in Ecoflex-gel and this effect makes it unusable, because it sticks to every surface it comes in contact with. For the current thesis topic where the focus is on sliding and grasping tasks a highly sticking surface is undesirable. To overcome this issue a layer of stiffer silicone can be applied on the surface of the soft Ecoflex-gel.

A comparatively soft silicone in shore hardness scale like Ecoflex-30 or Ecoflex-50

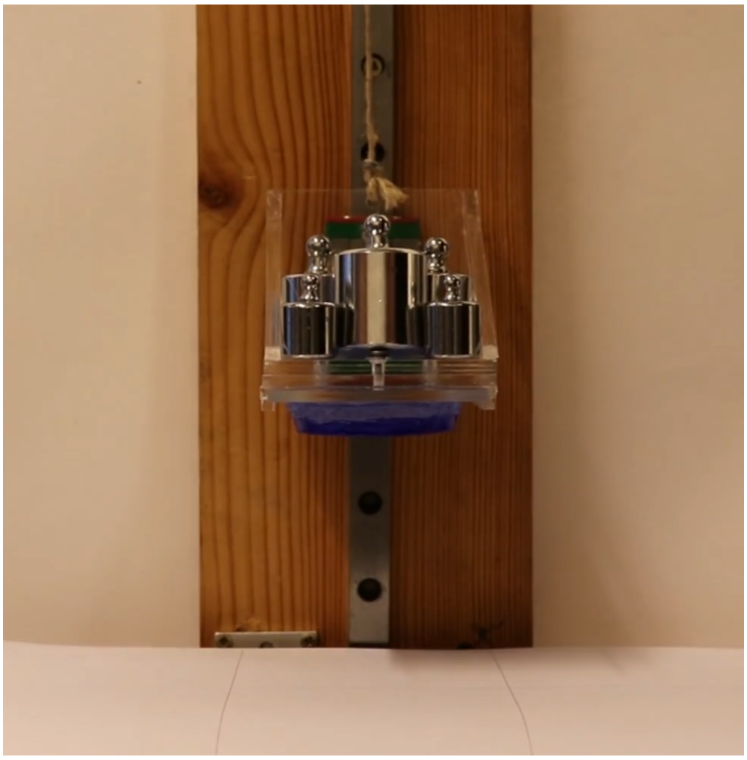
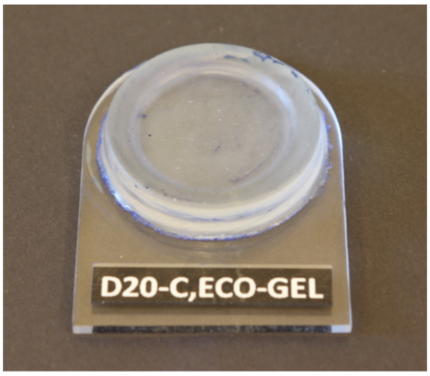


Figure 4.3: Setup for taking contact area.

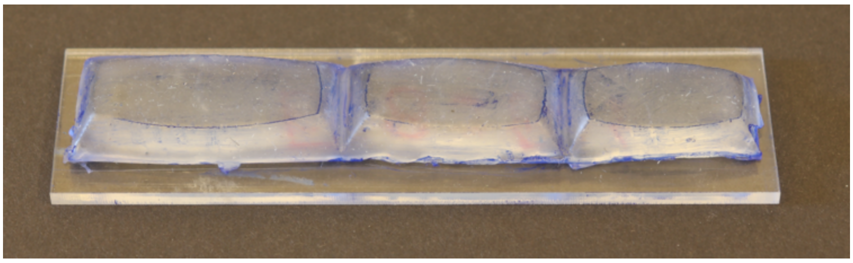
should be applied as a layer on the Ecoflex-gel because that will have least impact on the softness properties of Ecoflex-gel. But it was realized in the experiments that a layer of soft silicone like Ecoflex-30 or Ecoflex-50 on Ecoflex-gel is not very durable and wears off easily, this makes them not suitable for manipulation experiments. After experimental analysis of different silicone coatings, Dragonskin-20 was chosen as a silicone for coating on the Ecoflex-gel. Because all the silicone samples should have similar surface profile, all the silicone samples were coated with Dragonskin-20 for the experiments.

4.1.4 Contact Area Results

Contact area was taken by using the setup explained in the Section 4.1.2. Here the prints are made by silicone sample on a piece of paper, the physical prints are converted into digital images using a camera setup. Contact area from the print image are calculated using computer vision. Color segmentation and thresholding calculations were done using OpenCV [31]. A blue paint was used for print and thresholding is done on that blue color to have white pixels and background is converted to black. Counting the number of white pixels gives the contact area of



(a) Morphology 1 on a sample plate.

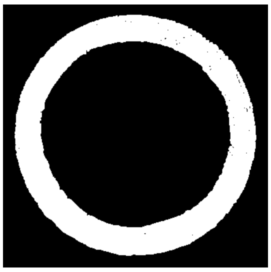


(b) Morphology 2 on a sample plate.

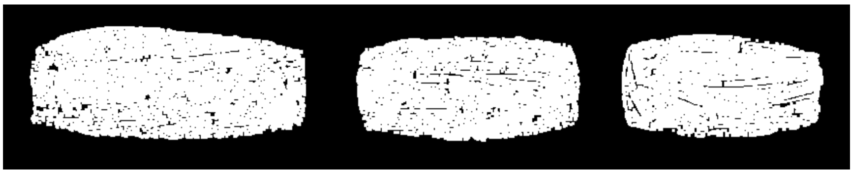
Figure 4.4: The two morphologies tested.

the print. A sample for area calculation is presented in Figure 4.5.

In Figure 4.6, the results from the contact area experiments of different silicones are comprised. Here it can be seen that the earlier proposed **Hypothesis 1**, **Hypothesis 2** and **Hypothesis 3** holds truth. We can see that Ecoflex-50(which is softer than Dragonskin-10) creates more contact area for any given applied force, this proves **Hypothesis 1**. Also if we look at Ecoflex-30 for all the applied forces, the higher forces creates larger contact areas, this proves **Hypothesis 2**. And the plots for morphology 1 and 2 shows same behavior, which proves the **Hypothesis 3**, that effect of **Hypothesis 1** and **Hypothesis 2** holds true in different morphologies. But from the plot it is also evident that the behavior for Ecoflex-Gel under the influence of 380*grams* of force seems a bit different, the contact area for this force is way above the predicted contact area. The reason for this behavior is the shape of the morphology 1. If we look at the morphology 1 again in Figure. 4.4a, there is small circular valley inside the morphology and a thick wall covering the edges of the morphology. This structure creates the unexpected behavior in the contact area. When the force is until 200 *grams*, only the wall of the morphology is touching, see Figure 4.7a, but when the force is 380 *grams* the small valley inside of the morphology 1 also starts touching see Figure 4.7b.



(a) Print for morphology 1 with EcoFlex-Gel and 100 *grams* applied force.



(b) Print for morphology 2 with EcoFlex-Gel and 100 *grams* applied force.

Figure 4.5: Contact area calculation from prints

This unexpected behavior of morphology is an example, where it shows that it can be possible to encode mechanical function in a morphology. Here at 380 *grams*, the contact area is increased to a greater extent. Therefore if there is some knowledge about this force beforehand for a morphology then this data can be used to create a morphological function, which is activated on a certain range of force.

4.1.5 Ecoflex Gel With Shell

As from the previous experiments, it is noticeable that Ecoflex-Gel provides high contact area for a given force. But the high contact area comes with the cost of very low strength and rigidity in the morphology. The coating of a comparative stiffer silicone is good for overcoming the effect of adhesion but it is still very fragile. A solution to this problem is to use a thick shell of outer silicone with low shore hardness. So a design is proposed where a thick shell of stiffer silicone like Ecoflex-50 or Ecoflex-30 is made which encapsulates the Ecoflex-Gel. The design can be visualized in Figure 4.8.

In the Figure 4.9, the result of contact area for shell type morphology is compared with the normal morphologies. From the plot it can be incurred that the Ecoflex gel with Ecoflex 30 as the shell has the high contact area for almost all forces. Because the coating of DragonSkin 20 on the Ecoflex gel makes the normal Ecoflex gel less compressible and the shell of Ecoflex 30 let the enclosed Ecoflex gel expand more than the stiffer coating of DragonSkin 20. For morphology 2, the 380 *grams* force

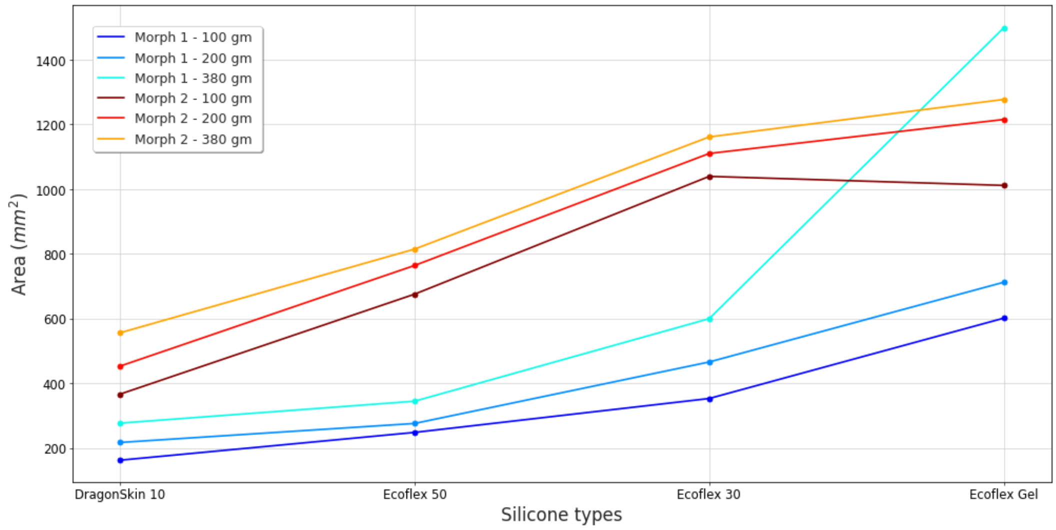
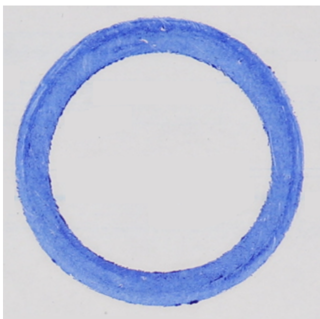
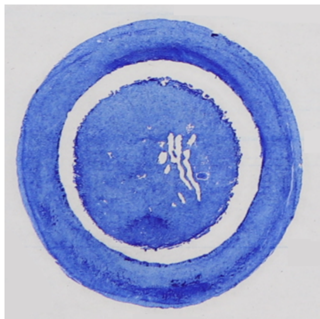


Figure 4.6: Contact area for morphology 1 and 2 in effect of weight force of 100, 200 and 380 *grams*

puts the contact area for Ecoflex gel with the DragonSkin 20 coating at highest because the coating hold the Ecoflex gel until a force limit, after the force limit the expandable Ecoflex gel expands fully and as the coating is thinner it expands more in case of normal Ecoflex gel than compared to the Ecoflex gel with the Ecoflex 30 shell.

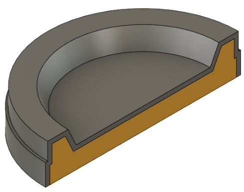


(a) Morphology 1 for Ecoflex-gel under 200 *grams* force.

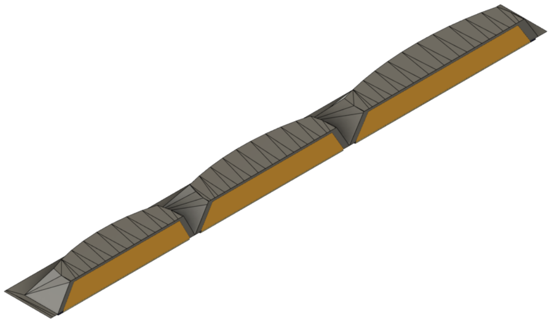


(b) Morphology 1 for Ecoflex-gel under 380 *grams* force.

Figure 4.7: Prints of Ecoflex Gel under different forces explaining the unexpected increase in contact area



(a) Morphology 1 with outer shell.



(b) Morphology 2 with outer shell.

Figure 4.8: 3D cutout of morphology 1 and 2, explaining the shell structure. Here the inside is Ecoflex Gel and outside shell is Ecoflex 30 or Ecoflex 50

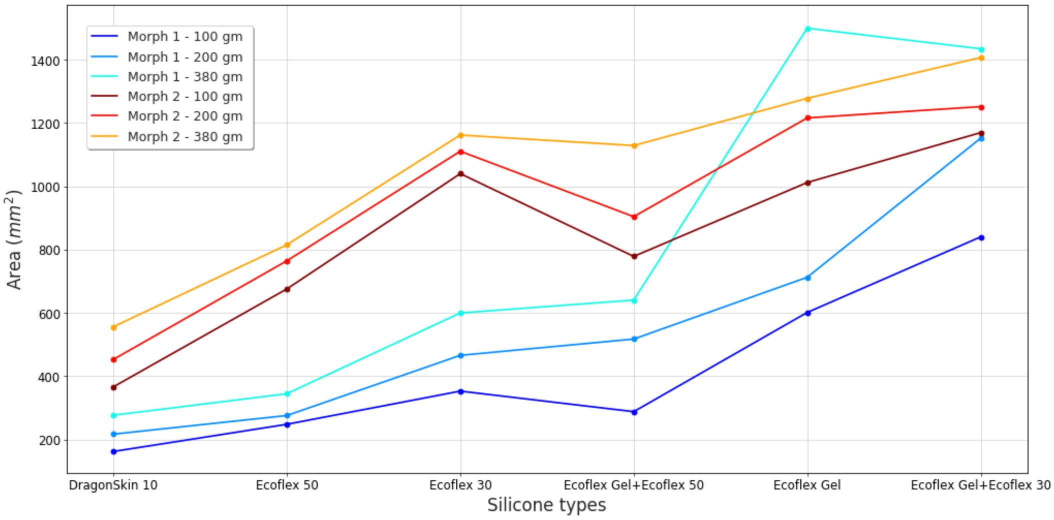


Figure 4.9: Contact area for morphology 1 and 2 in effect of weight force of 100, 200 and 380 *gms* with the shell type morphology with Ecoflex 30 and Ecoflex 50 as the outer shell

4.2 Friction Analysis

In Section 4.1, we talked about contact area in different silicone materials and demonstrated the evidence of **Hypothesis 1**, **Hypothesis 2** and **Hypothesis 3**. In this section we will discuss about the friction properties in soft robots and prove the **Hypothesis 4**.

Friction is one of the key aspect in robotics which is being researched on for dexterous grasping and manipulation. There are robots inspired by worms in nature, which are designed primarily based on the friction profile of the robots. Ge et al. has created an earthworm inspired soft robot [5] which works by changing the friction forces acting on its body. Already mentioned in Chapter 3 about [4] and [29], which utilizes the frictional properties to do linear locomotion and try to mimic complex human finger behavior. These examples shows that friction is an important aspect in terms of contact-rich manipulation and it is possible to create a mechanical function in a robot which can modulate the friction based on the applied force. Therefore it is necessary to understand the friction in various material surfaces which can assist in creating a mechanical function in the soft robot actuators.

Understanding friction in non-linear materials like rubber and silicone is a complex process as it is shown by Gabriel in the thesis [17]. Gabriel has explained about the stick and slip motion which is caused by waves of attachment and detachment in rubber [32]. This stick and slip motion alters the friction force periodically. In another method Persson has used the Leonardo da Vinci experimental setup to calculate the low-speed sliding friction [16]. As the friction is difficult to calculate for soft material like silicone, therefore here max pulling force will be used as the friction property identifier. The pulling force will be the maximum force needed to make the object move in a Leonardo da Vinci experimental setup, which will be equivalent to the static friction force.

4.2.1 Setup for Friction Calculation

For friction calculation a setup was created which was inspired from the Leonardo da Vinci friction setup [33]. In the setup a small prototype of RBO Hand 3 finger was taken where the test finger pulp was glued, see Figure 4.10. The prototype finger can move in the vertical direction, where weights can be put, this provides the possibility to add desirable weight on the finger and hence a desirable force. The bottom platform can move in horizontal direction and it can also be fixed. This gives the possibility to do experiments for friction analysis, when the horizontal platform can move and when it is fixed it can be used for contact area experiments. Both the platforms have Force-Torque sensor which gives accurate data on the normal force and the pulling force. The schematic for the friction setup is shown in Figure 4.11. The setup can be seen in the Figure 4.12.

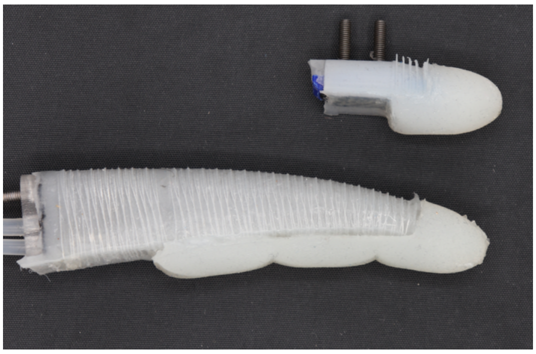


Figure 4.10: The smaller finger design(top), compared to a normal RBO Hand 3 finger(P.24 short)

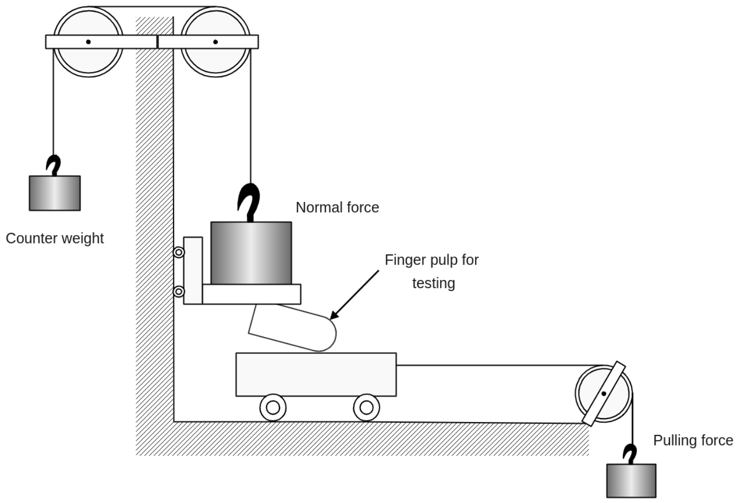
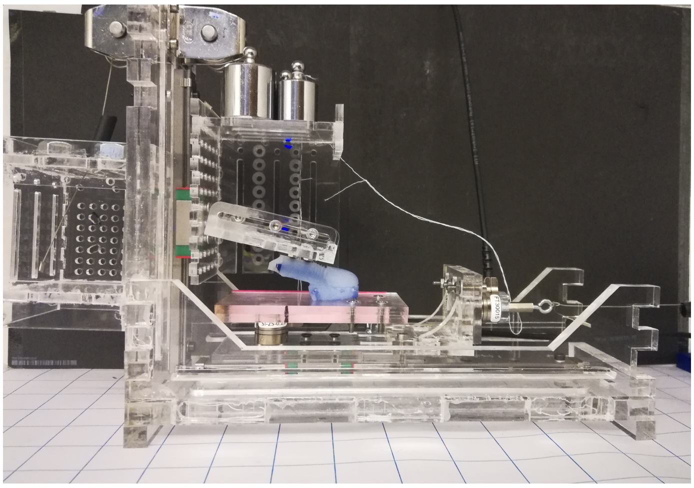


Figure 4.11: Schematic showing setup for friction. Inspired from the Leonardo da Vinci's friction setup

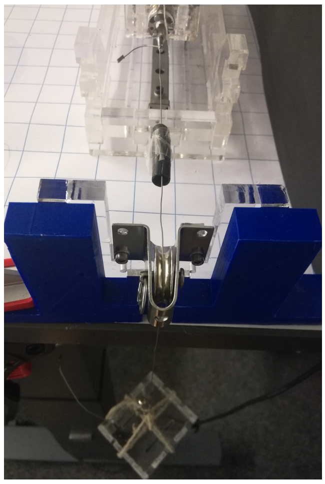
For calculating the static friction, reading of forces were taken when the object just starts to move. The motion was captured using a camera. The force data and video data was recorded in a ros bag and played using `rqt_plot`. Later the data was checked manually when the object starts to move and force readings were noted.

4.2.2 Different Morphologies

The contact area results of silicone analysis in Section 4.1.4 shows that it is possible to create an mechanical function in silicone morphology. To recreate the effect of



(a) From side.



(b) From front.

Figure 4.12: Friction setup

Morphology 1 of Section 4.1.2, a finger pulp morphology was created with a ring structure on the fingertip. The ring morphology 3D model can be viewed in Figure 4.13a.

An expected contact area and force plot for Ring morphology is presented in Figure 4.13b. Which gives an idea based on the previous contact area experiments about the behavior of ring morphology on a finger pulp under applied forces.

A block morphology was created, as shown in Figure 4.14 which should have high contact area and must be effective in grasping and manipulating heavy objects.

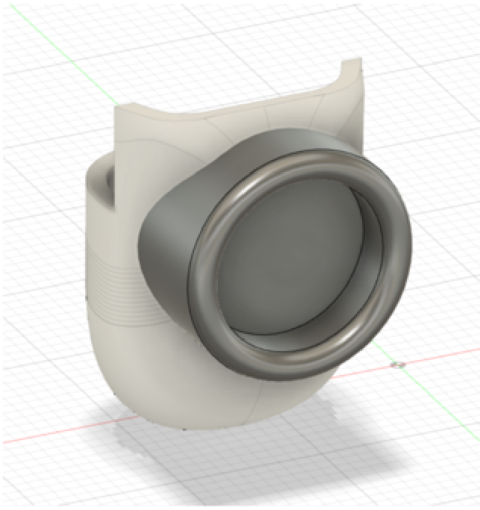
In similar manner three more morphologies were created. As shown in Figure 4.15 and Figure 4.16.

The contact area experiments were done on these morphologies using setup from Figure 4.12. The contact area results are shown in Figure 4.17

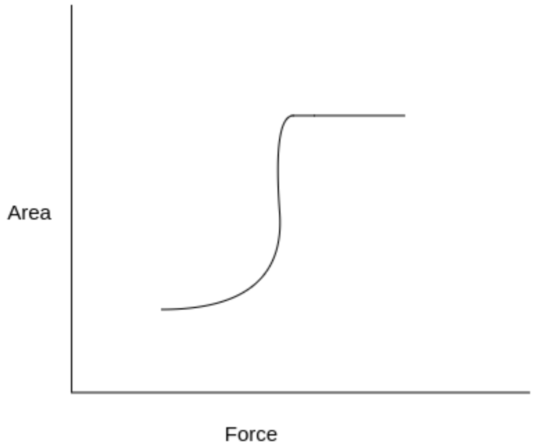
As from the results from Figure 4.17 it is visible that the contact area and force relationship between these morphologies are not, what was previously expected. But an observation to be noted is that the contact area for Block morphology, is highest of all other morphologies and also contact area and force behavior is somewhat similar to what was expected.

Meanwhile the friction results for the different morphologies can be seen in the Figure 4.18. Here the pull force is the maximum force, which is required by an object after which it starts to move.

As from the contact area results of morphologies in Figure 4.17, the behavior was unexpected and to make the behavior as in subsection 4.1.4 in Figure 4.6 for Morphology 1, a new type of morphology design was proposed. This new morphology

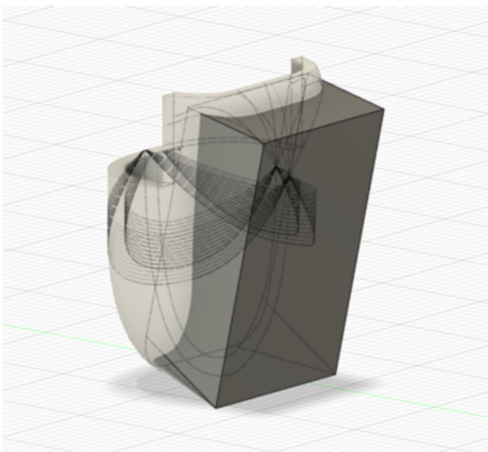


(a) Ring Morphology 3D model for fingertip.

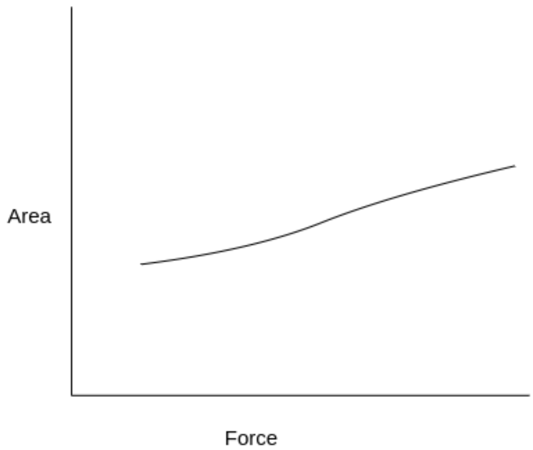


(b) Ring Morphology expected force area curve.

Figure 4.13: Ring Morphology for fingertip.

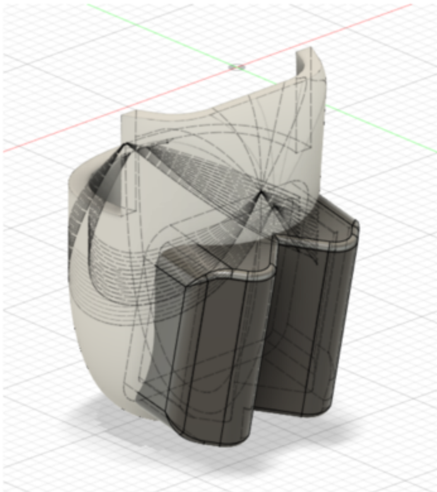


(a) Block Morphology 3D model for fingertip.

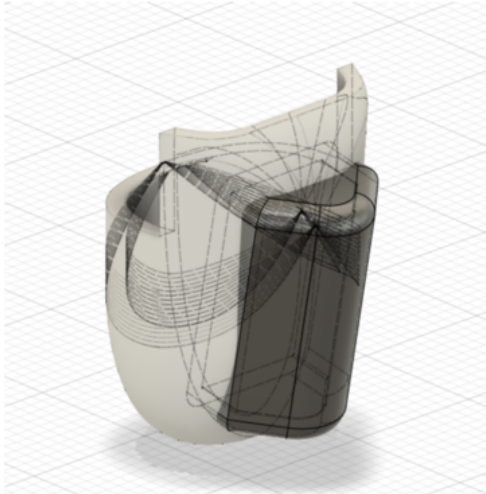


(b) Block Morphology expected force area curve.

Figure 4.14: Block Morphology for fingertip.



(a) Concave Linear Morphology 3D model for fingertip.



(b) Convex Linear Morphology 3D model for fingertip.

Figure 4.15: Concave and convex linear morphology for fingertip.

will have high contact area therefore it will have a base of block morphology (see Figure 4.14a). Also for low force values it should have a very low contact area therefore it will have small hill in the center. The proposed 3D diagram can be seen in Figure 4.19.

The contact area force data for Hill Block morphology with other previous morphologies is shown in Figure 4.20, which is closer to what was expected.

Also the pulling force data can be seen in Figure 4.21

Here, we can notice the behavior of the pulling friction force for all the morphologies in Figure 4.21. It can be seen here that with applied force, pulling force increases in general for all morphologies. But for ring morphology the pulling force has increased to a great extent but from the contact area plots the contact area is similar to the other convex and concave and pin head morphologies. Whereas the contact area and pulling force for normal finger does not increase too much with the increase in the applied force. This behavior can be explained by the process of taking contact area and pulling force readings. While taking contact area readings the morphology remains in place and give the static contact area, but during the pulling force experiment the morphology is deformed which changes the contact area of the morphology, this behavior is only experienced in the morphologies whose shape has extra bending silicone material in it. Therefore in the ring convex and concave linear and pin head this behavior was noticed and this can be seen in the screenshots from the pulling force experiments in Figure 4.22 and Figure 4.23. It

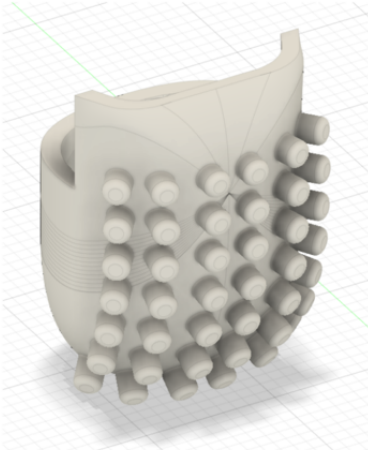


Figure 4.16: Pin head morphology for the fingertip

can be seen in Figure 4.23b the bottom part of ring morphology in scenario 1 when the morphology just touches the acrylic plate. Here the black vertical line shows the starting point of the motion in morphology. In Figure 4.23b, it can be noticed by looking at the other black vertical bar that even the pulp morphology has moved significantly the edge of the ring morphology has only traveled a small distance and in the Figure 4.23a from the side view it is evident that back part of the finger pulp start touching the acrylic plate, which shows increase in the area. This explains the higher pulling force for some morphologies even they have less contact area, as the contact area readings will give only the static contact area, whereas during the pulling experiment the contact area changes significantly and changes the max. pulling force. Video for this experiment is provied in the supplimentary material.

But if we consider the 200 *grams* force from the Figure 4.21, where the pulling force compares to the contact area force, it can be noticed that 200 *grams* of force has not caused very high deformations in the pulp morphologies and this data point can be used for comparing contact area and pulling force. Therefore if we look at the Figure 4.24, it can be seen that higher contact area results in higher pulling force. This behavior of contact area and pulling force satisfies the **Hypothesis 4**

Therefore from the above results pulling force can be taken as one of the criteria for designing the morphology. So for designing the morphology we will use contact area and pulling force as the design criteria. We take pulling force from the static friction which is $\mu = F_s/N$, where F_s is the maximum friction force and we call it pulling force in our case, because it is easy to find out experimentally and it gives better comparison about the grasp abilities of the different morphologies.

After doing the manipulation experiments as shown in Section 5 on Hill and block

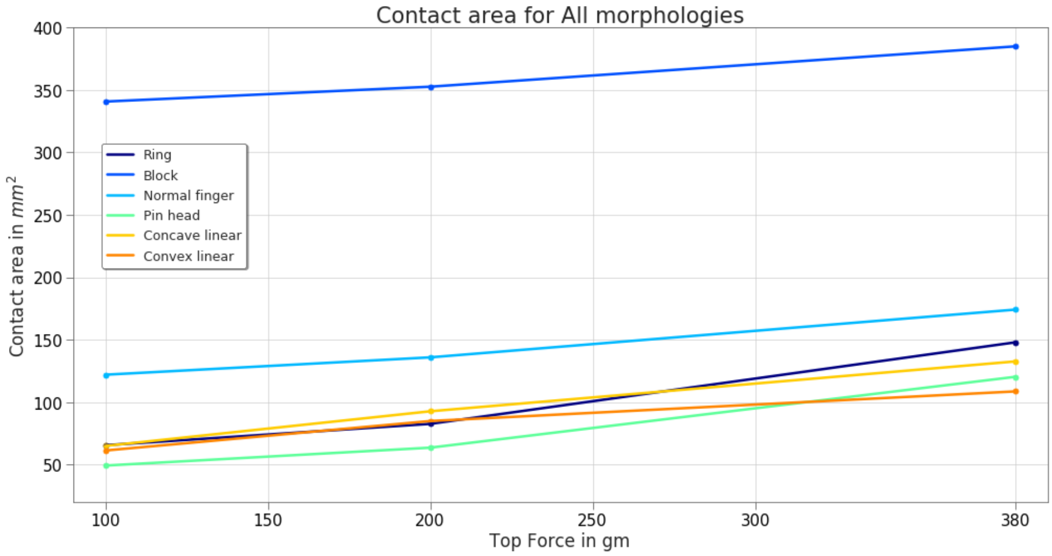


Figure 4.17: Contact area and force results for the five morphologies and normal finger morphology discussed in effect of weight force of 100, 200 and 380 *gms*

morphology, it came to the realization that Hill and Block morphology fails in the low force zone, because even if low force gives low contact area for Hill and Block morphology the friction force is still high for low forces zone and it gives high pulling force for small applied normal forces.

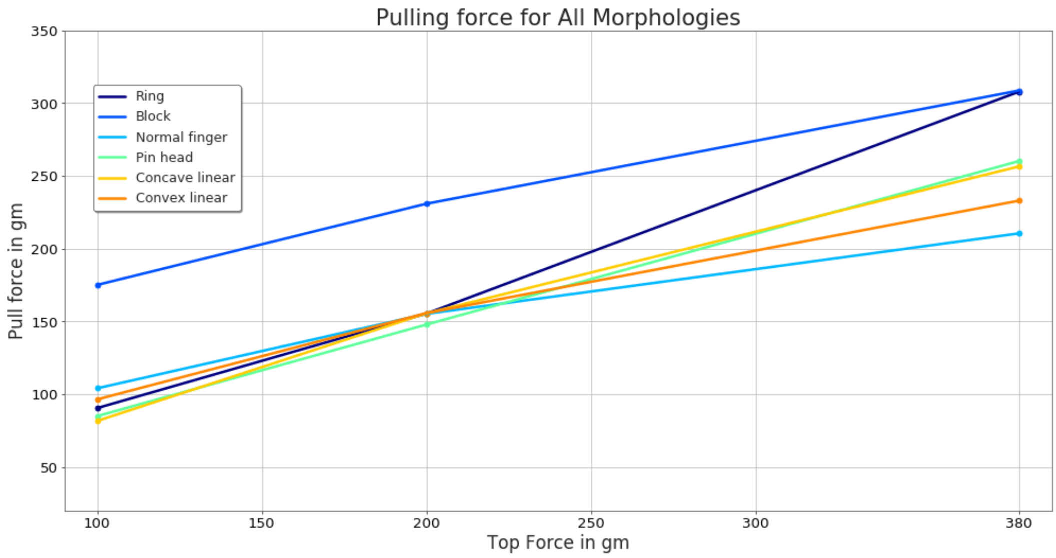


Figure 4.18: Friction plots for five morphologies and the normal morphology against weight force of 100, 200 and 380 *grams*

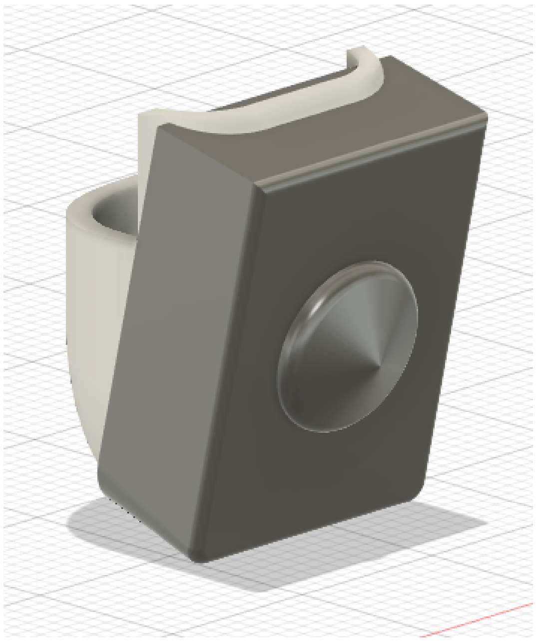


Figure 4.19: Hill Block morphology 3D model

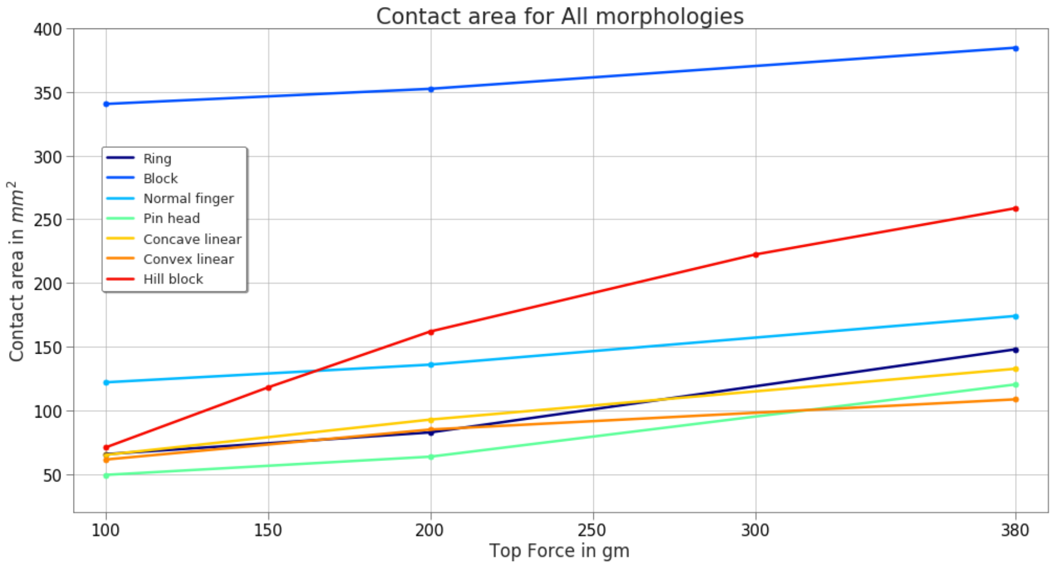


Figure 4.20: Hill Block morphology contact area plot compared with the previous morphologies

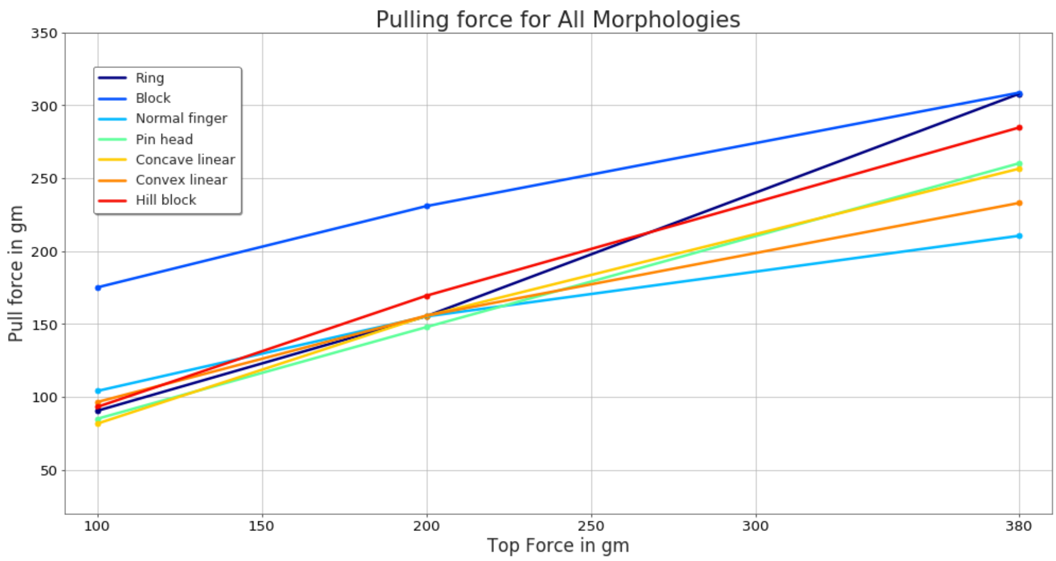
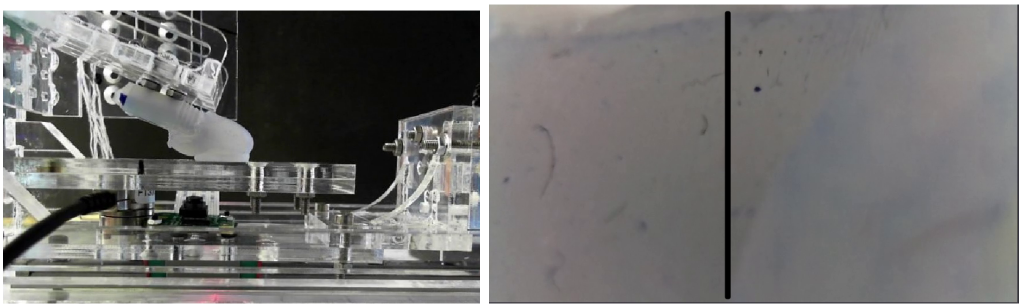
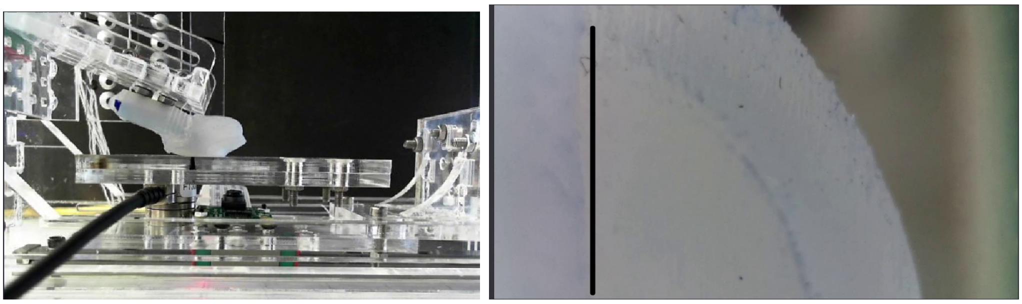


Figure 4.21: Hill Block morphology pulling force compared with the previous morphologies



(a) Ring morphology from the side **(b)** Ring morphology from the bottom

Figure 4.22: Ring morphology during 380 *grams* force when the pulp touches the acrylic plate



(a) Ring morphology from the side. **(b)** Ring morphology from the bottom.

Figure 4.23: Ring morphology during 380 *grams* force when the pulp is sliding on the acrylic plate.

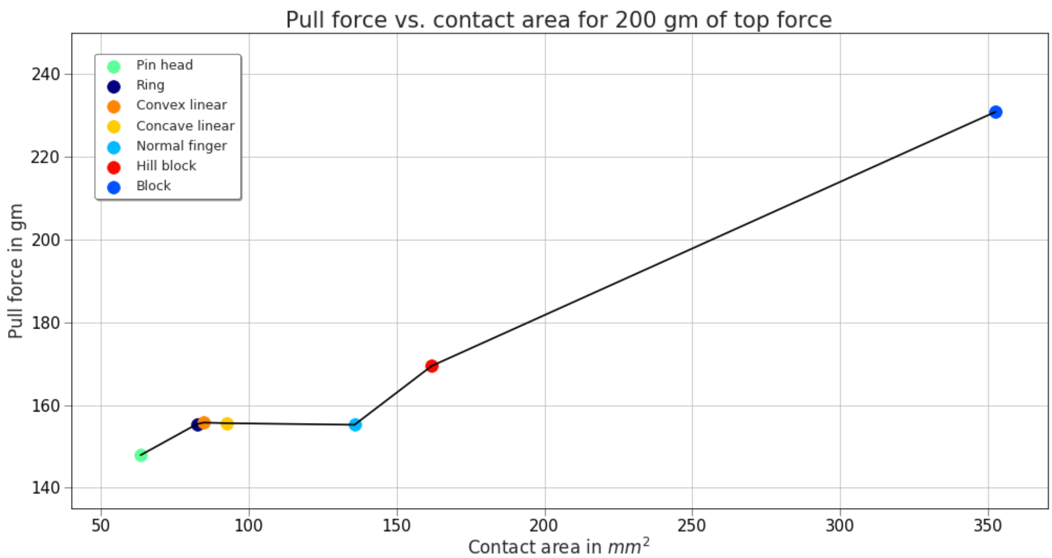


Figure 4.24: Pulling force vs contact area for 200 *grams* force.

4.3 Composing Different Materials in a Morphology

After the results and analysis of the Hill Block morphology, a new design change in the morphology was proposed. The new design included a different material which is stiffer and have very low friction coefficient. Therefore 5 small screws were embedded in the Block morphology which were protruding from the thinner side from the pulps and the base of the screws were embedded in the Block pulp which makes the screw hold them in place while manipulation tasks. The 3D model of the Screw Block morphology is shown in Figure 4.25. As it became clear from the Hill and Block morphology that in the low force zone we need not only low contact area but also low friction profile, which could not be possible until we have used same silicone material for low contact and force zone. Therefore such a different design is needed to be tested which embodies a material with rigid structure and has low friction resistance. As the finger pulp are very small in size so that even the highest contact area pulp which is block morphology pulp, could have very smaller size second material in comparison, therefore metal screws were selected for this design.

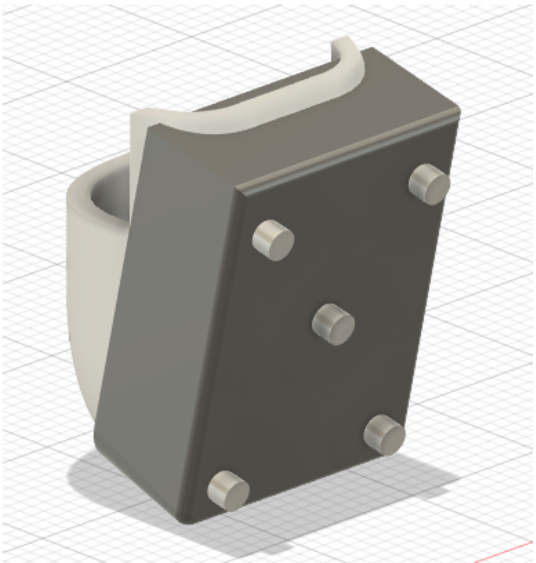


Figure 4.25: 3D model of Block morphology with embedded screws

The contact area and force results for Screw Block morphology is shown in Figure 4.26

Here it can be visualized in the plot of contact area for Screw Block morphology(Figure 4.26), that contact area is smaller compared to normal pulps and other previous morphologies(Figure 4.21). Also the friction profile plot shows that the

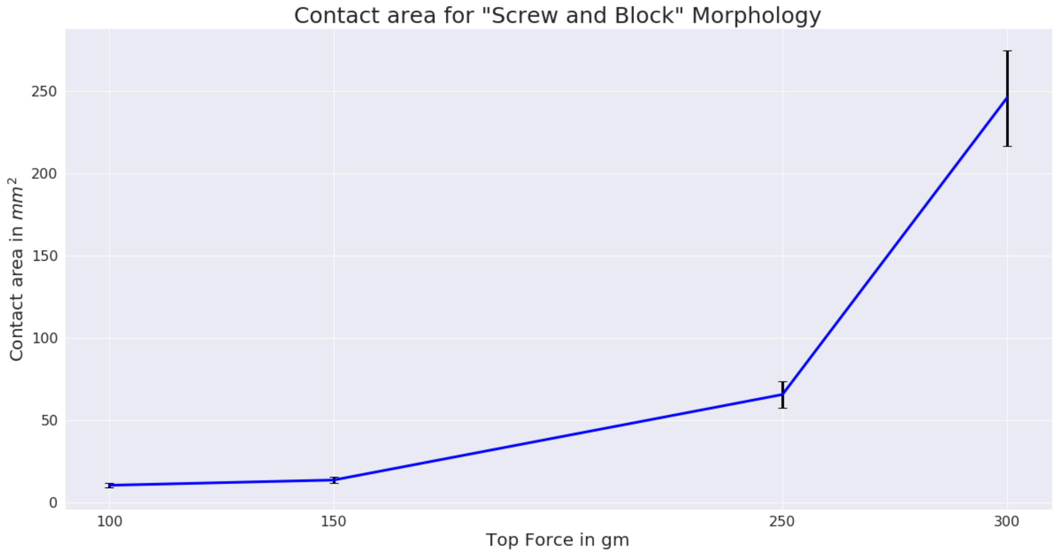


Figure 4.26: Contact area plot for the Screw Block morphology

pulling forces are smaller (see Figure 4.27) compared to other morphologies for low applied force region (see Figure 4.21). Therefore this morphology could results in the desired manipulation where the contact area and pulling forces are low for a specific range of applied forces and contact area and pulling forces are high for a range of applied forces.

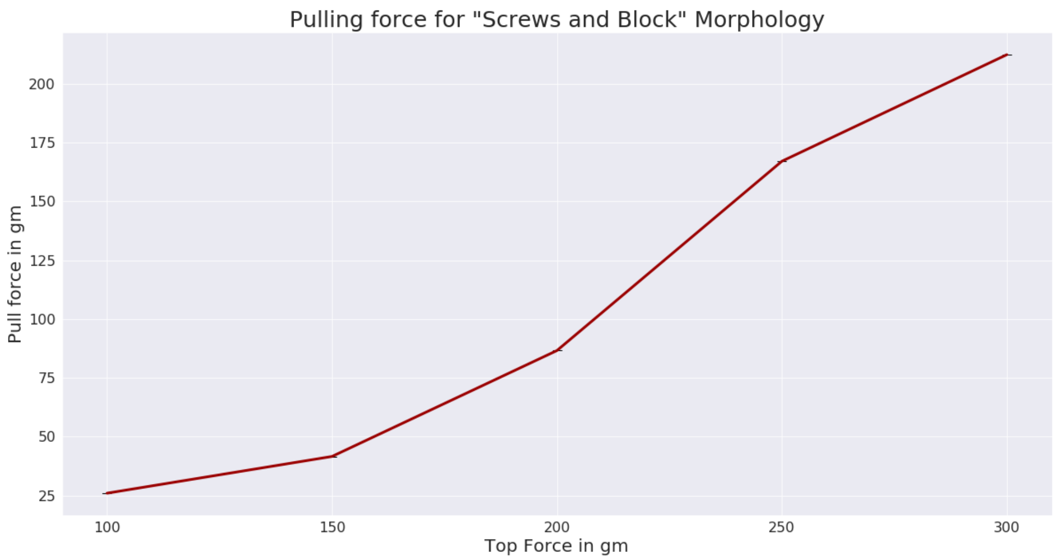


Figure 4.27: Friction profile plot for the Screw Block morphology

5 Evaluation Experiments

For testing the different morphologies created, grasping and manipulation test were conducted on them. The RBO Hand 3 finger actuator was mounted on acrylic plates with comparable distance, so that an object can be grasped. Four actuators were mounted, two with normal RBO Hand 3 finger pulp and two with a testing finger pulp. It was made sure that the distance between the actuators while actuated is same for both normal finger pulps and modified finger pulps. Also two acrylic plates were put to the sides of the actuators, this made sure that there's less lateral compliance. While grasping with the RBO Hand 3 actuators, the actuators comply on the sides of the object when they are actuated to in the higher percentage range. The acrylic plates on the sides reduced the lateral compliance to some extent and made possible to grasp some heavy objects. The setup for doing grasping experiments in shown in Figure 5.1

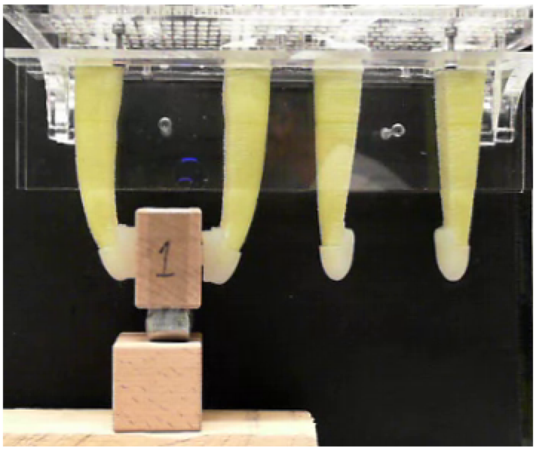


Figure 5.1: Grasping setup for testing finger pulp on actuators.

For the grasping test, an object of 100gms was grasped and the actuators were de-grasped slowly to see the sliding effect of the object. For doing the given manipulation task, the actuators were first actuated with a high air mass so that the test object is grasped firmly. After that the air mass was deflated slowly to perform the action of de-grasping slowly. For the Hill Block morphology the contact area plot (see Figure 4.20) suggests that when the actuators are grasped in high force range, there should be high contact area . But when the actuators in the low range of force the contact area should fall to minimum. This effect will let us have a mechanical function which is governed by the contact area.

But during the grasping experiments for Hill Block morphology, it did not perform as expected. While comparing the results for the Hill Block with normal pulp morphology it perform similar to the normal pulp morphology in the lower forces region and the object did not fall off or slide gradually. The reason for such behavior was that the small Hill in the Hill Block morphology made the same contact area as the normal finger pulp. Also both were same silicone material, which have same friction profile and thus it behaved similar to the normal pulp morphology.

Again same grasping test were done on Screw and Block morphology like the Hill Block morphology. The results of slipping of an 100 *gms* object is shown in Figure 5.3. Here it is evident from the data that range for a 100 *gms* to object to slip or fall is very narrow for Screw Block morphology and it is very high for the normal morphology. This range makes the actuation range for actuator also small and thus on the software side of the control mechanism the complexity is reduced. If this range is known, than it becomes easier to control the grasping and slipping of an object which minimizes the complexity in control. Therefore it is shown that it is possible to create a mechanical function in the pulp morphology of a soft actuator which can offload the computation from software to hardware. And it's possible to understand the morphological computation of a soft actuator by creating a predefined behavior in it by understanding the properties like contact area and friction forces.

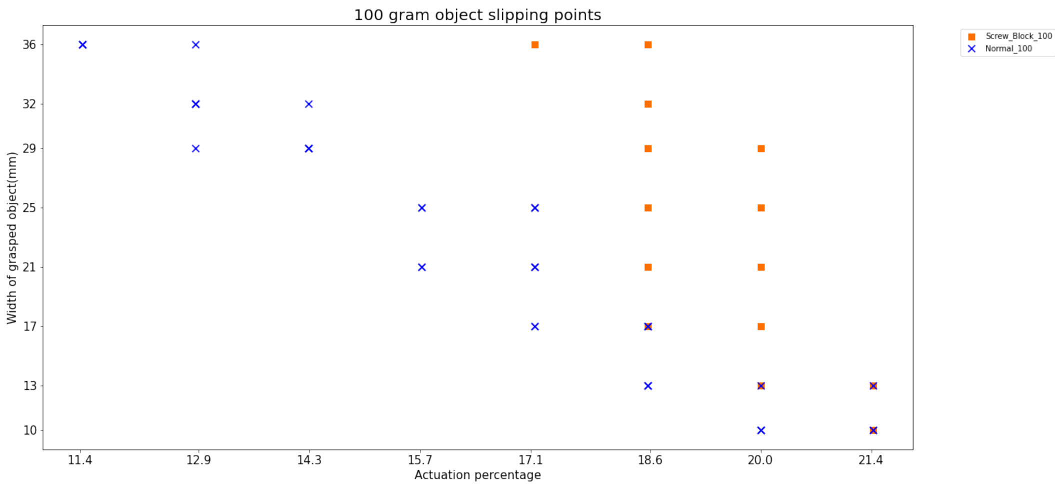


Figure 5.2: The plot shows the points where the 100 *gms* object will fall for a normal morphology and the Screw Block morphology.

A slipping experiment was done on a bottle to test the above results in a real test case scenario. The result for the test are shown in Figure 5.3 for the new morphology and in Figure 5.4 for normal finger. Here both the fingers have similar distance between them when acuated to 10% value of maximum air-mass. The new morpphology was able to slide on the bottle easily whereas the normal fingers get stuck on the bottle and needs to be hold so that the normal finger can slide on it.

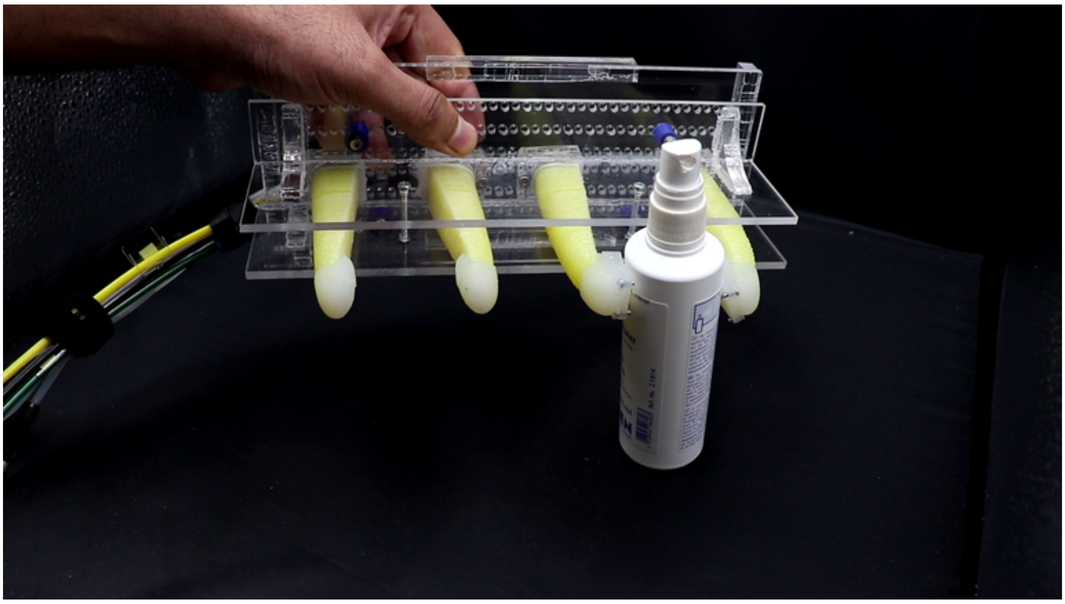


Figure 5.3: The sliding manipulation experiment where the new morphology slides on the bottle with 10% actuation.

Figure 5.4: The sliding manipulation experiment where the normal finger get stuck on the bottle with 10% actuation.

5.1 Failure Modes and Limitations

As the design of the Screw and Block morphology is a bit non conventional and does not look anthropomorphic, it needs to be tested for the limits in its design. The small pin like structure in the flat morphology of the pulp can get stuck in the materials like fibers and cloth and the soft robotic hand can get stuck in the environment, therefore testing for different surface materials is the test for failure modes. The new morphology was tested for lifting a object placed in a net like fabric and the screws of the morphology gets stuck in net fabric and the object didn't fall when it should be. Also another limitation is that the edge of the block morphology gets in the contact if the surface being slid upon is a curved surface. A possible workaround to this problem is to insert a linear stiff material on the edges of the block morphology, instead of the screws. This linear stiff material will restrict the soft silicone to be able to touch the surface while sliding across variable width object. Video of these experiments are provided in the supplementary material and shows the failure modes.

6 Conclusion and Future Work

As discussed in the beginning of the thesis that it is difficult to model contact-rich manipulation tasks like sliding and grasping of objects. And a possible scenario is to model the problem of control in a bottom down approach, where the control comes first and the rest of the control system with software and hardware is designed based on the it. This approach reduces the complexity in the software control as some part of the control is outsourced to the hardware.

It is proposed that by modifying the hardware properties of the soft robot like contact area and friction profile the software control can be me made simpler by offloading the control to hardware. A example of such offloading was given in this thesis where the control of sliding and grasping can be made simpler by modifying and knowing the behavior of soft actuator surface(which is the finger pulps). It was shown that sliding manipulation task was reduced in control complexity by creating the actuation ranges where the soft actuator will likely grasp an object and the actuation ranges where the soft actuator will likely slip across a object(creating slip effect).

The offloading of control on the hardware becomes possible by modifying the first contact structure of soft robot, which is the soft finger pulp. It was made by introducing different materials in the soft finger pulp. Using different materials in the soft finger pulp creates two friction profile and also restrict the expansion of contact area. Similar approach is utilized by Spiers et al. in [29], where friction profile changes by changing the contact surface. [29] and the work in this thesis, creates a base for the future work, where modifiable grasping surface looks like the solution to the complex grasping and manipulation tasks. A variable friction profile surface actuator can be created by applying soft silicone on the actuator for heavy grasping. The actuator surface will also have holes in it which has magnetically actuated second material. When the second material is actuated the surface profile changes to the profile of the second material.

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