

**NANYANG
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**DESIGN OF AN ADAPTIVE FINGER WITH
ENCOMPASSING GRASP CAPABILITY FOR
PARALLEL GRIPPERS**

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**DESIGN OF AN ADAPTIVE FINGER WITH
ENCOMPASSING GRASP CAPABILITY FOR
PARALLEL GRIPPERS**

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A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirements for the degree of
Master of Engineering

2019

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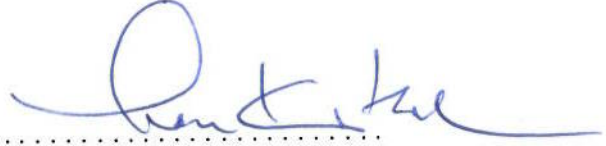
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The contributions of the co-authors are as follows:

- Prof K. H. Low provided the initial project direction and edited the manuscript drafts.
- I prepared the manuscript drafts. The manuscript was revised by Prof K. H. Low.

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ABSTRACT

Adaptive grasping was an emerging technology due to the demand to fulfil the task requirement of having one robotic picker to cope with items of variable geometry attributes. The parallel gripper was widely and commonly used in robotic automation because of its simple one DOF mechanism. Thus, the motivation was to enable parallel gripper to perform adaptive grasping.

The thesis presented the design of an underactuated adaptive finger for the standard parallel gripper. Adaptive finger mechanisms were surveyed, reviewed, and kinematics for adaptive grasping were studied to design a novel mechanism for parallel grasping.

Experiments show parallel gripper attached with the adaptive finger could form pinching and encompassing grasp, which fulfilled the capabilities of an adaptive gripper. The adaptive fingers demonstrated that when performing encompassing grasp, it forms three to six contact points on objects with regular and irregular shapes.

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1. INTRODUCTION

Robotic manipulators coupled with end-effector had been used extensively in automation especially in pick and place operations, which involved monotonous, repetitive, labour-intensive and stressful on the body. Tasks that were critical and possibly prone to human error could cause undesirable production downtime or bottleneck.

End-effector is the interaction point between the manipulator and the target object, which also means end-effector is designed to interact effectively with the target object. Grasping is the act of seizing or gripping the object. The end-effector grasps and secures the object to allow the manipulator to manipulate it to the desired position and orientation. The designer or engineer would seek to optimise the quality and consistency of interaction between the object and end-effector.

To achieve quality and consistency in grasping, many parallel grippers were made especially for specialised or specific tasks. This was because of its robustness as well as the simple one-degree actuation design. These parallel grippers mainly installed with stiff fingers. Thus, it can perform very well only for a specific task. The automation industry had widely accepted the parallel grippers as the demand for automation in manufacturing plant increased. However, in recent years the need for automation in a logistic warehouse that requires handling items of different shapes, sizes and weight. A new generation of manufacturing plants that need to customise various product types emerged.

For instance, a bakery production line uses robots with packing grippers to pick up cookies from the conveyor belts into a packaging container. For every different cookie, the workers need to manually change the fingers and sometimes the gripper to allow the gripper to perform a specific

task. The adaptive gripper was designed to tackle the automation challenge to handle a broader range of items, with a minimum number of robots deployed. If the gripper was adaptive, the possibility of the same set of the robotic gripper to perform several tasks was higher, and this will reduce the time of tool changeover and calibration. However, the consideration of having to balance the mechanical design components for robustness or adaptability was crucial. The higher versatility in mechanical design always translates to lesser robustness.

Parallel grippers were widely used by the hobbyist and for factory productivity. The parallel gripper used for production was also known as the industrial-suited or simply the industrial parallel gripper. The industrial parallel gripper was designed and made in consideration for high robustness, consistency, and cost-effectiveness.

1.1 Motivation

In the automation industry, the industrial parallel gripper was used for object manipulation such as pick and place application. Industrial parallel grippers allow the finger of different shape and size to be installed to tackle object of various forms. However, the demand for end-effector that can cope with an item of different sizes and shapes was increasing, making the non-adaptive gripper unusable. Industrial adaptive grippers were available, and they were usually cost higher in comparison and involved complicated mechanisms and controls [1]. The motivation was to create an adaptive finger for the parallel gripper. The purpose was to allow the automation industry to use the cost-effective industrial parallel gripper and enhance it into an adaptive gripper.

Adaptive fingers will allow the existing users of industrial parallel grippers to upgrade and adopt the adaptive fingers and widen the graspability for the automated operations. Also, this will

encourage factories to purchase or reuse the readily available industrial parallel grippers which can be low cost and easily maintainable since they were well established in the market and spare parts were readily available.

Changing from gripper A to B usually require reprogramming and process changes in the automation line. As the control of the parallel gripper was practically identical after changing from stiff to adaptive fingers, the changes in programming will not be profoundly affected. The control was similar because the movement, reach, and direction was the same regardless of the type of finger adapted to the parallel gripper. By enabling the adaptive capability in the parallel gripper, this will encourage the adoption of the simple parallel gripper in automation due to cost-effectiveness.

From the author's experience as research assistance, he was facing challenges in designing a solution for the industry. For instance, he participated in the Amazon Picking Challenge in 2015 at IEEE ICRA Seattle, USA, and Amazon Robotic Challenge in 2017 at RoboCup in Nagoya Japan, he witnessed the difficulties and inspired to invent a universal, low-cost adaptive gripper, which he believed would solve the automated logistic items picking problem for the industry [2, 3]. During the competition, the items used for the challenge was picked by the competition organiser as they were of different shapes, sizes, and weights [4].

Further encouragement and motivation were driven by the need of automation projects such as the logistics problem in the airport to solve automated luggage management; hospital logistics in linen management, food, and pharmacy; and automated assembly line which assembly involved parts that were different in shapes and sizes. The mentioned industrial projects were part of the work and experience of the author. Thus, the spark for inventing the adaptive finger parallel gripper.

1.2 *Problem Statement*

The industrial parallel gripper had been the used in automation industry for 30 or so years since its first real production for real industrial applications [5]. However, existing adaptive mechanism could not be applied directly to the parallel motion gripper. Mainly, the adaptive gripper deploys grasp motion that turns or curls the finger towards the target object, which the linkages adapt or wrap around the target object to create multiple contact points and secure grasp. Another problem was that the actuators needed for the existing adaptive finger mechanism, which would require actuators in the finger joints.

The existing adaptive finger mechanism was not able to apply on current parallel motion gripper due to the kinematic design. Also, the design needs to be adaptable, which means the changes needed in terms of programming, hardware and cost for the change were minimal.

Overall, the main concern for mass industry acceptance of adaptive gripper was that the cost was too high. If the mechanism of the adaptive gripper can be simplified, the value of the gripper can be reduced significantly. Thus, potentially allow the automation industry to upgrade or use robots in their business. From the literature review, one of the problem statements was derived, that the grasp points on the target must be balanced. Imbalance grasp point will cause grasp instability.

1.3 Objectives

The principal objective of this research was to understand and design the mechanism for adaptive fingers for parallel actuated end-effector. The author is not aware of any available adaptive fingers for the the parallel gripper. Instead, there were adaptive grippers that had complicated mechanisms and generally costly for industry to adopt the technology. Thus, this motivated the study of design mechanisms applicable to the parallel gripper, which the adaptive finger should be able to perform encompassing and pinching grasp. These characteristics, encompassing and pinching grasping, defined many adaptive grippers available. Thus, the capability of the adaptive fingers must be at least able to do those two types of grasping method.

For the past 30 years, there were parallel grippers with two-finger, three-finger and four-finger, and these grippers had been used and still functioning in many factories. It was one of the objectives to be able to reuse the existing parallel gripper and turn them into more appropriate machinery for today's demanding industrial applications. Due to the design of most of the current parallel grippers, where conventionally the finger the attached fingers were without actuators or underactuated. Also, it can be a challenge for sensors connected to the fingers, due to the lack of wiring on the existing parallel gripper. Ideally, the fingers should be without actuators to reduce the need for extra installation, power supply and components. Companies were making mechanical parallel grippers for different application and loading. Thus, the fingers must conveniently adapt to different kind of parallel grippers.

Besides that, another objective was to design a scalable mechanism. Parallel gripper that was used in the market now was of different sizes ranging from micro parallel gripper that was only a few millimetres for electronics with large parallel grippers that handle boxes. Thus, adaptive

fingers should be scalable. The size and structural strength can be scaled based on the application and envisioned to have the same look and capabilities.

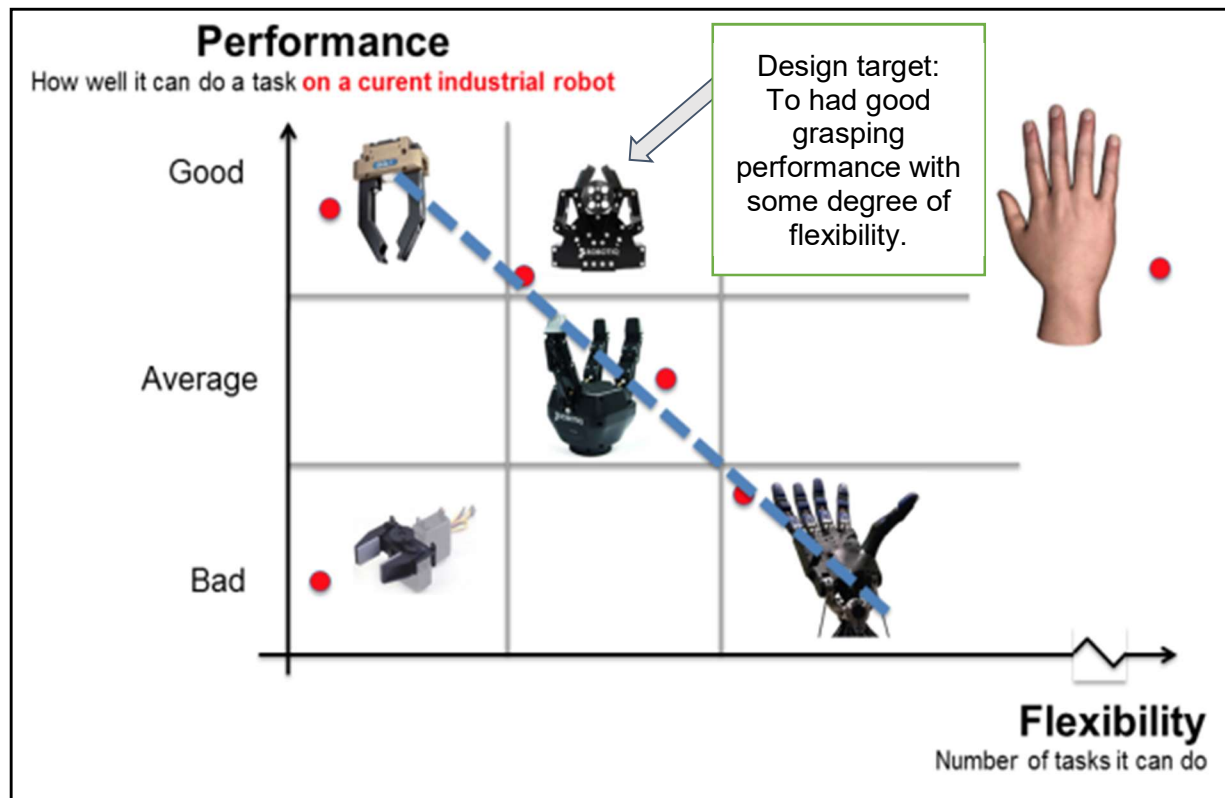


Figure 1.1: Performance vs flexibility in gripper category [6].

Figure 1.1 shows the performance vs flexibility of gripper design, and flexibility in this context was the adaptability of the gripper. It was known that for excellent performance and consistency, the gripper was designed to have few moving parts, to obtain higher predictability. Thus, this research project, the balanced gripper that uses just enough linkages to perform enough flexibility in grasping. The balance will be demonstrated in chapter three and four.

In summary, the objectives were to design the mechanisms of an adaptive finger for parallel grippers that can perform encompassing and pinching grasp. The main capability enhancement for the gripper was to be able to adapt to more objects. Thus, the critical parameter for this design was the number of contact points. There should be without additional actuators other than the existing

actuators in the parallel gripper so that it can be adapted conveniently. The mechanisms should be scalable to fit the various parallel grippers. The motivation was to invent a device that enables the industry to use the readily available parallel gripper for everyday robotic automation tasks.

1.4 Scope of Work

To fulfil the objective, all existing adaptive mechanisms to be reviewed and studied to see if adoption and innovation can be made to suit our application. Once all the possible methods from the existing mechanisms were identified, the functions of each finger will be classified and evaluate if any of the current technologies can be adopted or inspiration can be found from the literature review.

Possible dynamics adaptive mechanism will be explored heuristically; in macroscale. The differential mechanism could not be applied directly to the parallel motion of a gripper. Mainly, the adaptive gripper deploys grasp motion that turns or curls the finger towards the target object, which the mechanism adapts or wraps around the target object to create multiple contact points and secure grasp. The existing adaptive finger mechanism was not able to be converted and applied on existing parallel motion gripper due to the kinematic design. The details on the current adaptive gripper mechanism will be presented concisely, and the scientific problem will be defined for this research.

After the mechanisms of the fingers were defined, 3D motion simulation will be made to ensure the movements of the mechanisms behave as designed and make sure it can perform as predicted when simulated on a parallel gripper. The fingers will be tested on grasping real objects to evaluate if the fingers can perform in real-world situations, instead of just in simulation. The list

of items found in the Amazon picking challenge will be chosen to use as the benchmark of the most common logistics items in fulfilment centres [4].

From the experiment results, the author wanted to find out if the adaptive finger can perform in logistic related tasks. Also, the adaptive finger could scale down to test its scalability in terms of sizes to fit the different applications and different parallel grippers. Logistics in healthcare had always been an immediate issue. Thus, commonly available pharmacy items were used to test the scaled-down fingers and to determine the usefulness and adaptability of these fingers.

1.5 *Outline*

This thesis was structured as follows: -

Chapter 1 defines the problem statements and a general approach overview of the argument for the thesis. Most importantly, this chapter lists the objectives of the research work.

Chapter 2 provides an overview survey of the existing adaptive finger mechanism design. From the current gripper drive, the type of adaptive grasping mechanism will be classified. Lastly, the ability to grasp and hold should be able to be defined and quantified.

Chapter 3 presents a design of the adaptive finger, starting from inspiration, prototyping and development of the final product. The novelty of the adaptive mechanisms will also be discussed, together with the pros and cons compared to the existing type of adaptive finger.

Chapter 4 experimental setup, method and results will be shared to show the real-life performance of the gripper.

Chapter 5 summarises the thesis, discussion on the challenges and list of future work. This chapter will also end with the highlight of the significant original contributions to knowledge from this research work.

2. METHODOLOGY

2.1 Literature Review

The literature review in this report was interested in studying all the available gripper drive mechanism movements and subsequently showing the most frequently used mechanism. Knowing the parallel gripper was the most commonly used mechanism, the adaptive fingers available will be used as comparison and inspiration and researched on that to enable adaptive grasping for the parallel gripper. A study beyond parallel gripper will be done to understand if other gripper drives that could be cheaper and better than parallel mechanisms. The primary reason for this research work was to create a relatively low-cost gripper to push automation with robotics forward.

Classical parallel grippers and other grasping methods were reviewed to understand and reasons to use mechanical gripper, instead of using other means of a grasping method that can solve the problems mentioned. The other grasping method evaluated based on the graspability and the estimation of cost. In general, the estimation of the cost by the number of components and complication of linkages. All the component materials assumed similar. Thus, no material comparison was made.

In the second part of the literature review, the content will be focusing on the adaptive mechanisms of the robotic fingers. The survey was to view all the available type of finger mechanisms and find inspirations can be drawn from the existing adaptive finger technology. Lastly, a review of the definition and the methodology to quantify the grasp and hold quality to conduct meaningful experiments to compare the finger that was designed.

2.1.1 Classical Grippers Design

Before deciding on using the parallel gripper mechanism, a study had been done on the grippers for automation. Parallel gripper for traditional automation has been used for many problem-solving applications. Thus, the gripper design approach was also an application target specific where adaptive capacity was not the primary objectives because the fingers can be designed for the application [7]. The adaptive finger was not widely used because the automation in the past does not need frequent customisation. The following studies also to survey all available and related gripper technology to study the mechanism if they can be adopted and used directly for the adaptive gripper.

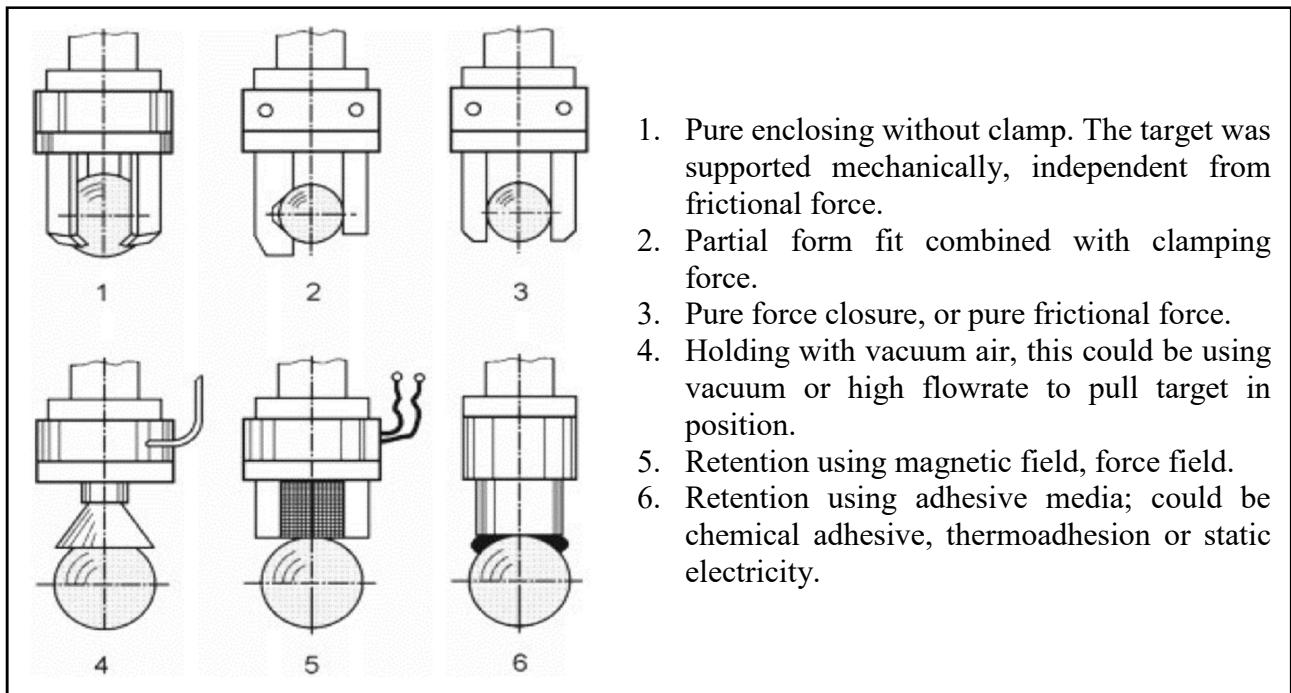


Figure 2.1: A classical way of automation gripper design approach for a spherical item [7].

Figure 2.1 shows that the consideration of prehension of a spherical object in an automation thinking, where all the methods mentioned were not adaptive, but they were a rigid method to

grasp a spherical object. However, in today's automation or logistic application, target items were getting complicated in size and shapes. Thus, an adaptive finger cannot be overlooked.

Figure 2.2 shows more grasping methods, and many were a specific grasping method for certain operations or materials. The magnetic gripper was designed to isolate magnetic material from a non-magnetic material. Non-contact grippers such as the acoustic and laser were designed to handle items that were sensitive to contacts. Needle grippers were designed to handle fabric-like materials that were porous. Frictional gripper and jaw gripper were the mechanical finger grippers which make physical contact with targets and probably the universal grasping method of

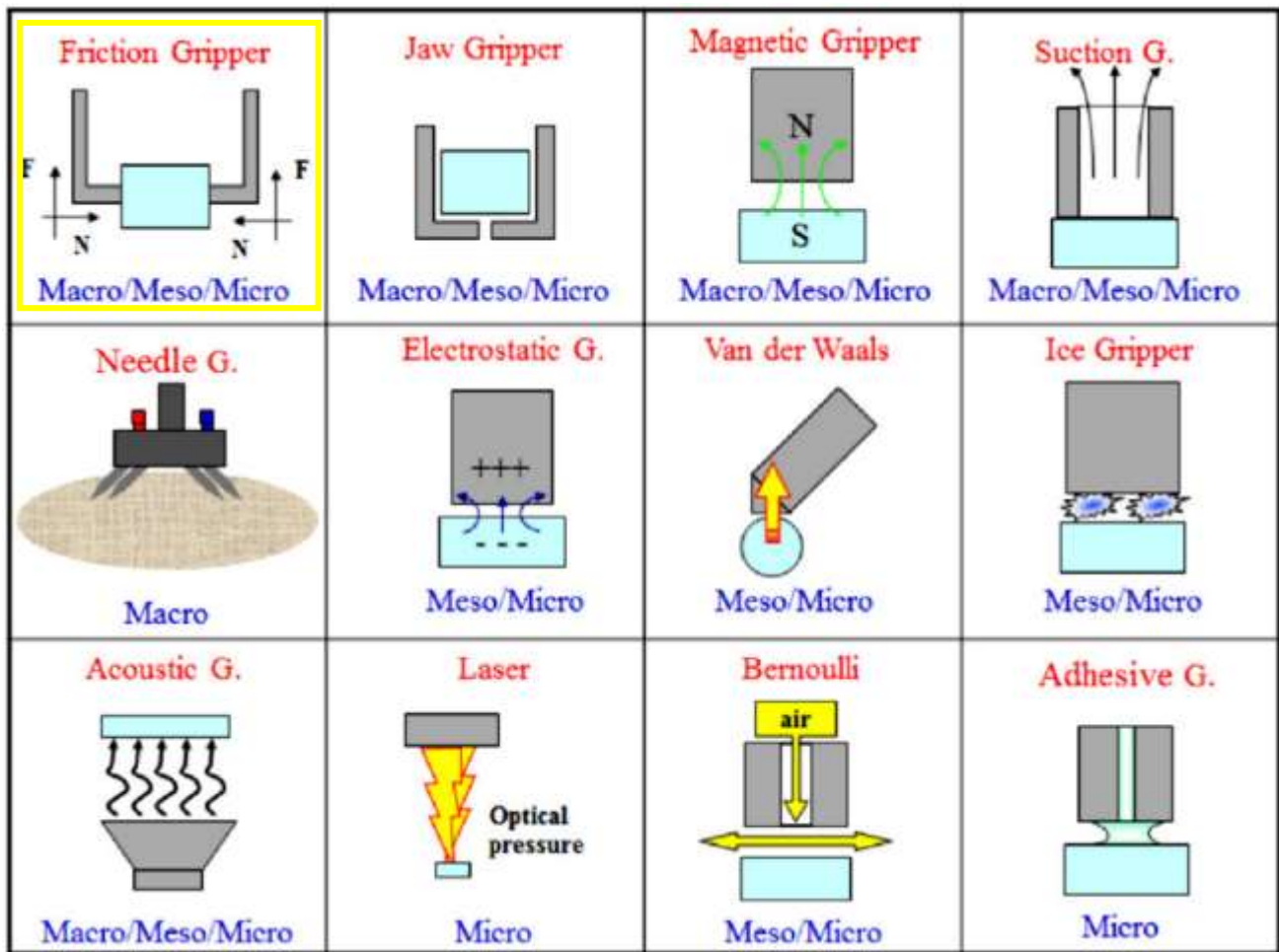


Figure 2.2: The possible grasping methods; direct contact and non-contact grasping methods. Frictional Gripper (first at top left) was graphically shown together with other grasping methods for comparison [8].

Custom stiff finger grasping method can be low cost and even having a secure grasp. However, parallel grasp with a rigid finger can pick an object of all solid material, but not all orientation. For example, the suction method cannot pick up porous materials such as a net or fabric; a magnetic gripper cannot pick up a non-magnetic item, and needle gripper cannot pick an object with the delicate surface or hard surface such as a piece of glass. Thus, for the study, the author chose the mechanical gripper because for simple logistic application mechanical contact would be universal and suitable for our research.

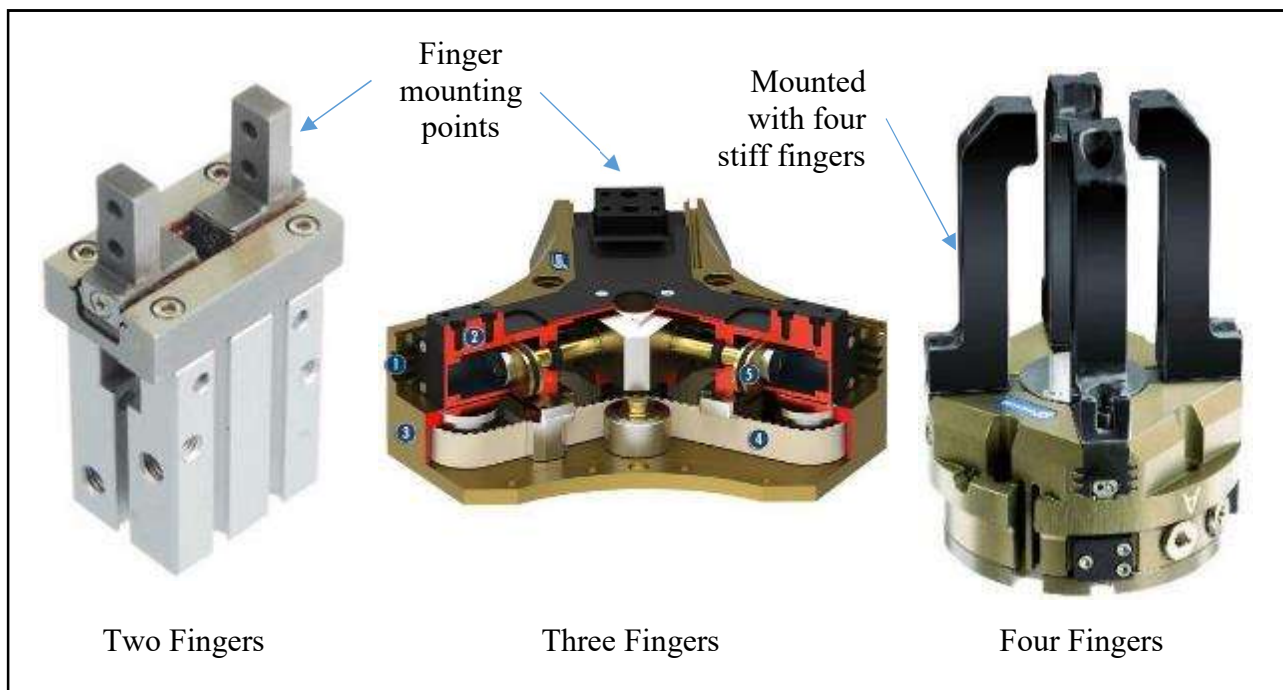


Figure 2.3: The Schunk grippers with variations of two, three, and four fingers [9, 10 11].

Before diving into the details of all the type of finger mechanisms, Figure 2.3 shows one of the objectives for this research work, which was a set of parallel grippers that the adaptive fingers can be attached and use for picking. The gripper could be in two, three, and four fingers and all the fingers were moving parallelly to each other to form the grasps.

These parallel grippers were the pioneer of the robotic automation grippers which was very common in the industry. These parallel gripper moves in high precision, simple in terms of

mechanism, low on cost and easy to be implemented and programmed. For parallel gripper, the potential to increase the grasping range by manipulating the aperture of the gripper giving it more flexibility in automated processes [5].

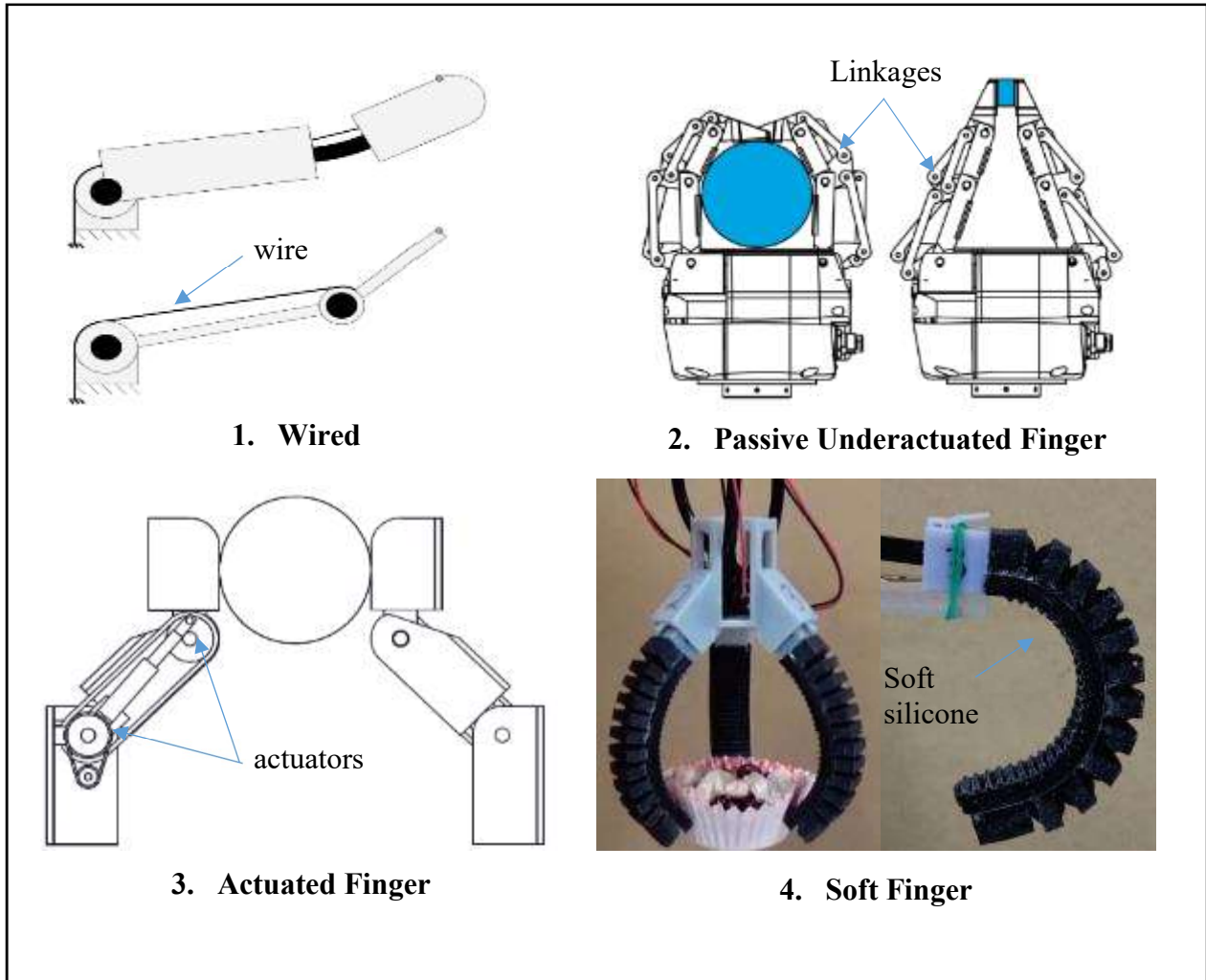


Figure 2.4: Type of adaptive finger; 1. Wired (can be pneumatic or servo pulley was driven, to tension wire for movement); 2. Passive underactuated finger (linkages in mechanism cause the curling movement of the fingers); 3. Actuated finger (can be pneumatics or servo, usually servo due to the size constraint); 4. Soft finger (pneumatically drove to inflate cavities in the silicone to move the fingers) [9,12,13,14].

Figure 2.4 shows the four types of adaptive fingers and examples of adaptive fingers. There were many adaptive fingers had been invented [11-13,15-31], and they can be further categorised as: -

1. Wired;
2. Passive mechanical joints;
3. Active actuated joint; and
4. Soft fingers.

Wired fingers were widespread, and many publications can be found because it was very easily implementable. The mechanical principle was straightforward for cable or wire was driven fingers, as the linkages were underactuated and wire applies tension to curl the fingers. From the mechanism, this needed further actuation to create tension on the fingers. Similar concept as wired actuation, some grippers utilise smart materials (shape memory alloys, shape memory polymers and lead zirconium titanate) for complex control [32]. Thus, it was not suitable for our application on the parallel gripper.

The actuated finger had motors built in the finger joints, or they had actuated degree of freedom, commonly more than one DOF in one finger. Actuated fingers had flexible controls on each joint which gives the fingers advantages in precision control and controlled grasp quality. However, for extra control, it had more complicated mechanisms extensively, thus making it more expensive. Necessarily, an actuator or servo motors will also be had to include controllers and power supply unit, which add up to the number of parts and cost of the gripper. Thus, to design a low-cost gripper, actuated fingers were very unlikely. They were placing individual motors in the

joint like the PASA Fingers instead using wires to individually drive each joint, as the Shadow Hand can better manage the space in the fingers [13, 19].

The soft finger was very popular in the food and agriculture industry due to its softness, which gently handles the target object [33]. The characteristics also very beneficial to logistics, which targets also needed to be handled with care. Similarly, with the wired fingers and actuated fingers, soft finger needed further actuation, which ultimately cost more. Also, the due to its fingers which need to be cast and the technology was not commonly available now, the cost of producing was high, and time was taken to produce also longer due to the complication. Also, because of the soft nature of the finger, usually the grasping approach was limited or mainly from top-down [14].

The passive finger which the finger linkages interact with the target object to perform encompassing grasp, or in some design, the movement of linkages curl the finger. For instance, the Festo Fin Gripper finger was one type of finger that interacts and forms multiple contact points with the target. The Robotiq three fingers gripper utilise the linkages to form an encompassing grasp, which it can curl the fingers without interacting with a target object [12]. Such flexible gripper research also been used for relatively fragile and object with different stiffness and shapes to ensure contact forces were distributed to reduce the chance of damaging the item [32, 35].

Thus, from these different finger mechanisms, the design direction of the fingers was to have a mechanism that does not had an additional actuator, ideally using linkages or underactuated means to perform a quality grasp. The mechanical grasping method may seem the simplest and not too technologically advanced, those precisely the reasons for this method to be the most popular, reliable, and relatively low cost.

To better descript the novelty of the design of the adaptive finger, more comparison of the adaptive fingers will be presented in chapter 3.2. The material was very similar to the literature

review thus for comparison purpose; the literature review was shortened for this portion, avoid the content being repeated.

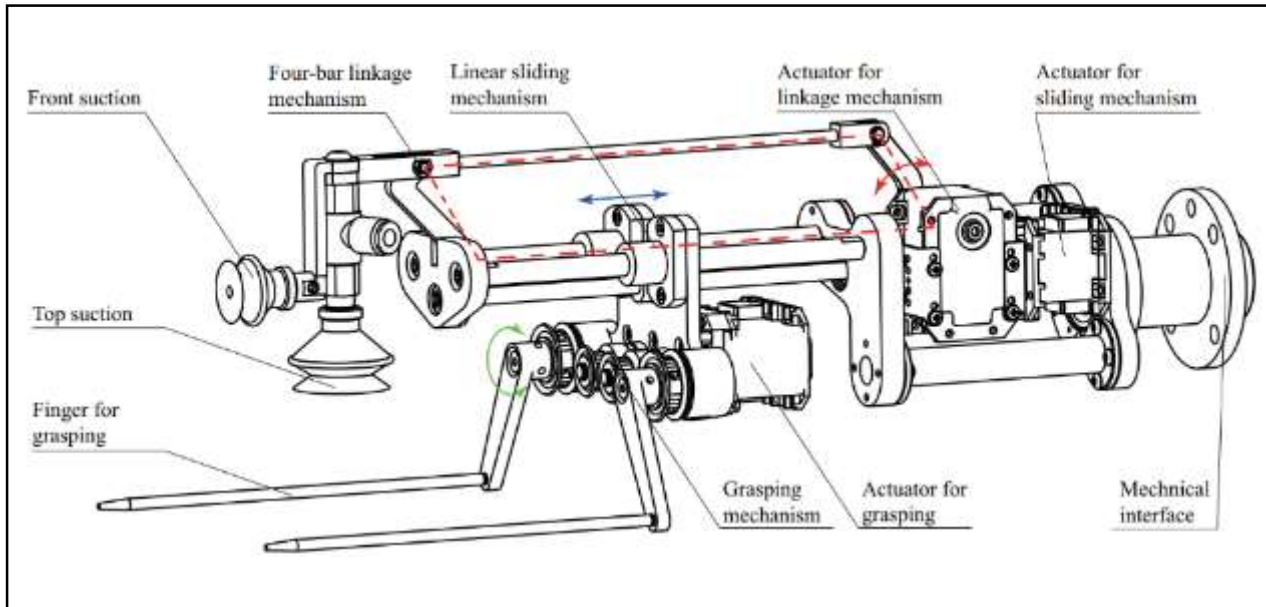


Figure 2.5: The mantis gripper that combines both suction and parallel fingers for logistics application. It can pick with only suction, only finger or combination of both [36].

The author previously also had co-invented a gripper and grasp planning algorithms for Amazon Picking Challenge in 2015 [4], about six months before he enrolled in this master's research work [36]. Figure 2.5 shows the mantis gripper which was being used for application involving grasping items with different sizes and shapes. The success rate of the grasp from the experiment was 68%. The success rate needs to take into the consideration of the grasping algorithm accuracy as well.

2.1.2 Adaptive Mechanism in Robotic Fingers

Based on all the mechanical gripper in the market and published research, the Robotiq two fingers adaptive finger was taken as the benchmark as it was the most popular industrial adaptive gripper that was functional, relatively selling well in the market and suited most logistic application which

the author wants to tackle. Figure 2.7 shows the benchmarked adaptive systems, with the two unique grasping methods of pinching and encompassing, and examples of graspable items.

The kinematics of the two phalanx joints was also very simple and yet effective. The parallel pinch grasping was still possible but only limited to specific grasp area. There was other research publication of adaptive fingers found [29, 29, 30], however, there were way more complicated compared to the adaptive mechanisms, which had more joints, and this makes it less robust, and basically, the mechanisms were very similar to the Festo Fin fingers. Figure 2.6 shows the adaptive capability that does not require finger.

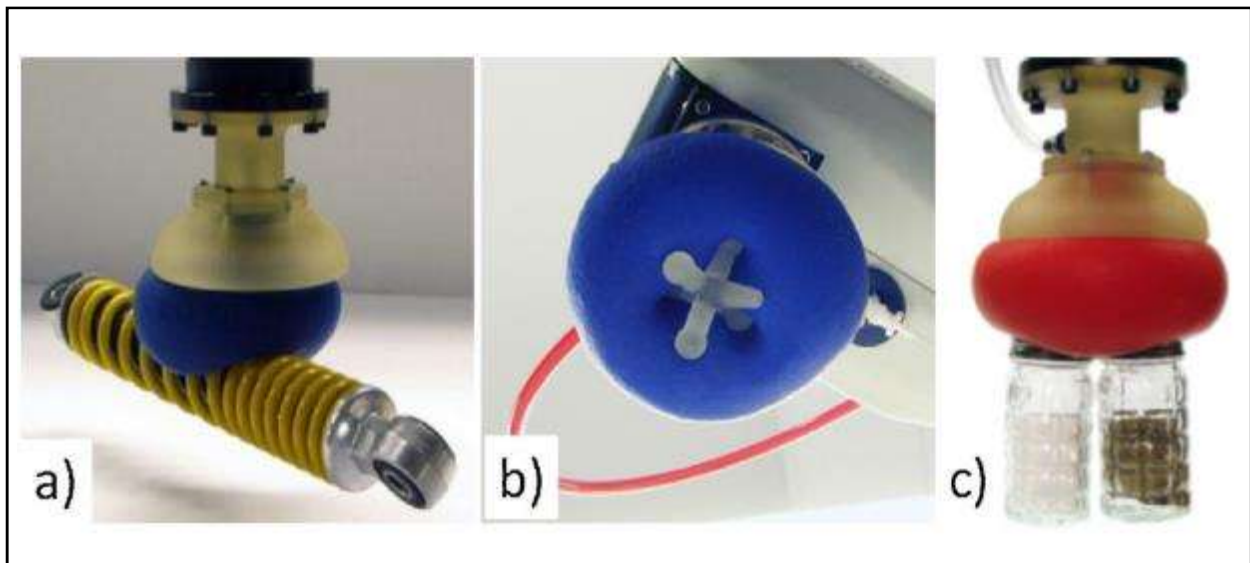


Figure 2.6: Universal gripper that utilises granules and vacuum to create frictional grasp.; a) picking an irregular and porous cylinder shape shock absorber, b) picking a plastic part that was irregular shaped, c) picking two round plastic containers at the same time [8].

The universal gripper was one of the adaptive grippers that claim to be able to grasp objects with different shapes and sizes. The technology was also simple, where it uses granules and insert into a rubber balloon shaped container and attached to vacuum suction. When the vacuum sucks out the air from the rubber balloon, the granules compact and grasp the target item. Thus, during grasping, the gripper will approach the item and encompass the object. The rubber and the granules will conform to the shape of the item by the force applied by the manipulator. After sufficient

contact made with the object, the suction will cause the granules to be compacted together forming the grasp.

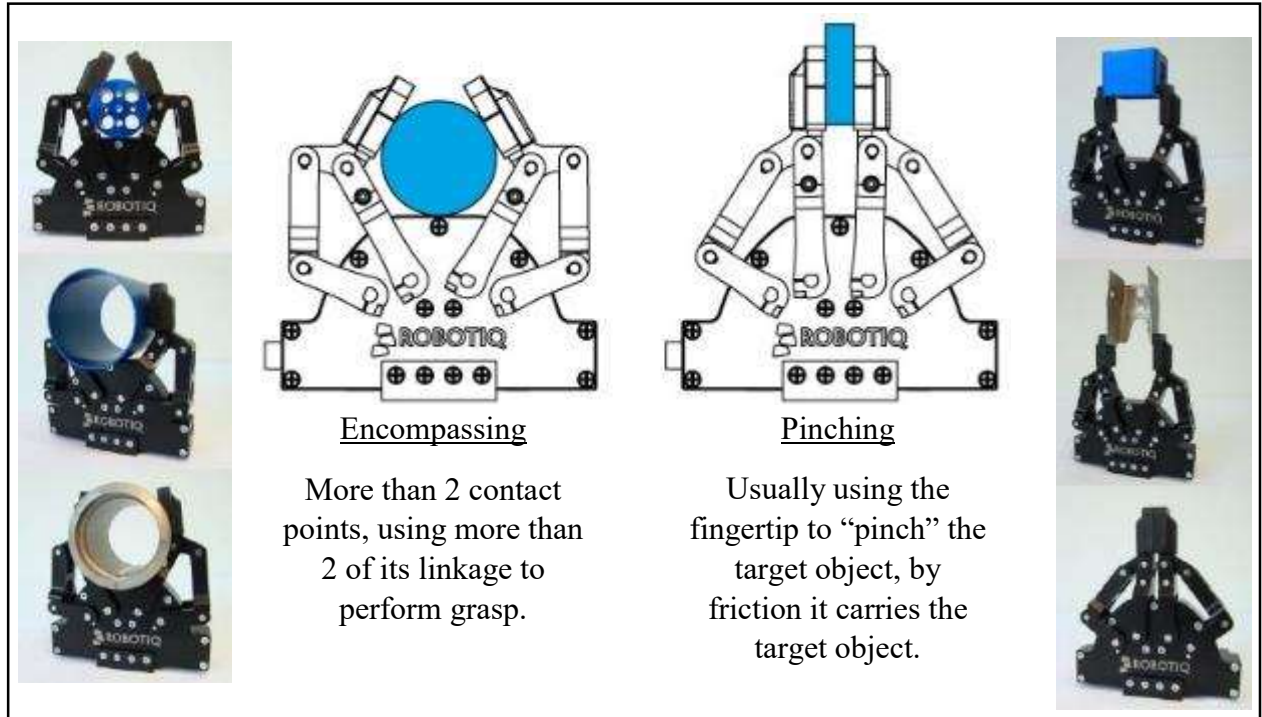


Figure 2.7: Robotiq adaptive gripper was showing encompassing and pinching grasp with sample items showing the efficiency and effectiveness of the gripper. Left figures show its encompassing grasp capability, and on the right, the figures show the pinching grasp [12].

This gripper was universal and able to target to pick up many different types of items. However, the requirement to grasp was more complicated and restricted. The gripper usually must reach the item from a top-down approach because it needs a fixed surface to push itself on the item. Thus, it limits the grasp planning from picking the item from the side. Also, the grasper was relatively bulkier compared to mechanical.

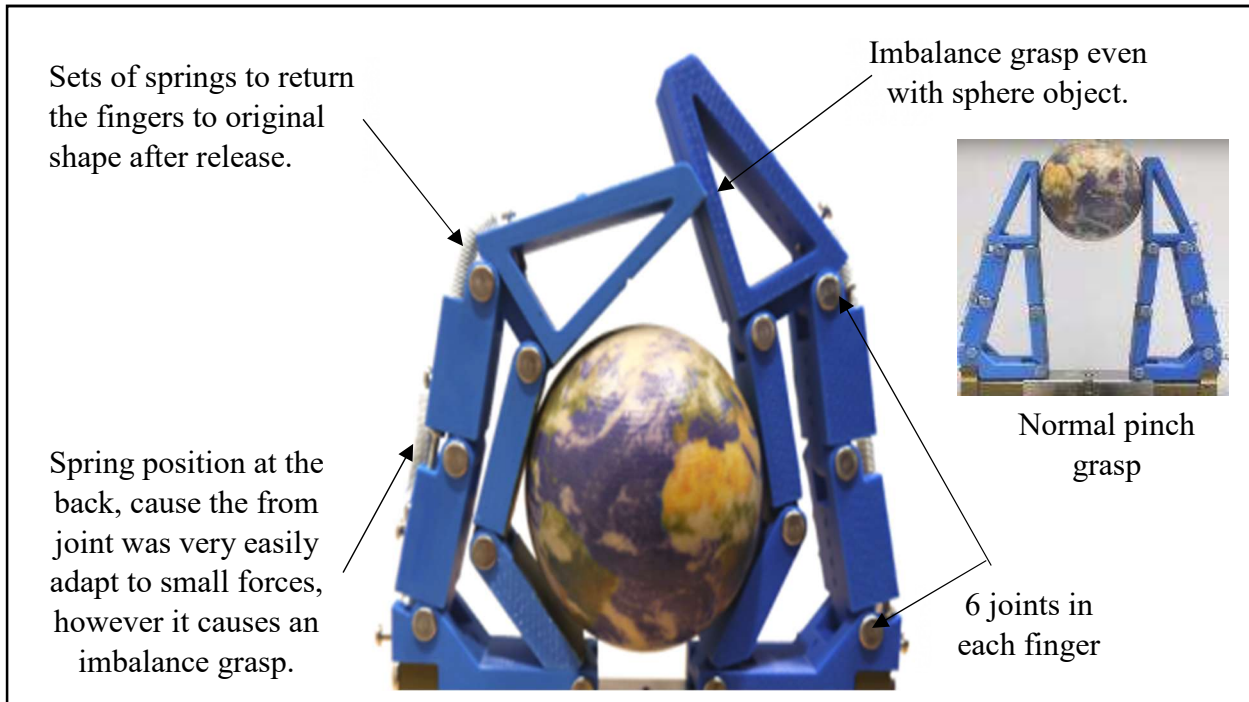


Figure 2.8: The research of underactuated adaptive fingers on the parallel gripper. The finger had many springs and joints making it hard to control and predict [11].

Figure 2.8 was an adaptive finger for parallel gripper created in by Birglen, which was being studied and initially wanted it to be implemented it but realised several issues, and the issues were listed and elaborate in Chapter 3.1, under the structural mechanisms design challenges. From Figure 2.7 and Figure 2.8, observation can be made that the pinch grasp was similar. However, the encompass grasp was not as stable, and the aFinger design had overcome several of those issues. One critical point on the design of the adaptive finger was the adaptive grasping must be symmetrical to form a balanced grasp with almost equivalent force on each contact point to avoid the fingers from creating moment force on the target object. The moment might cause rotation (if the frictional force was insufficient), and due to the rotation, the object might slip and fall.

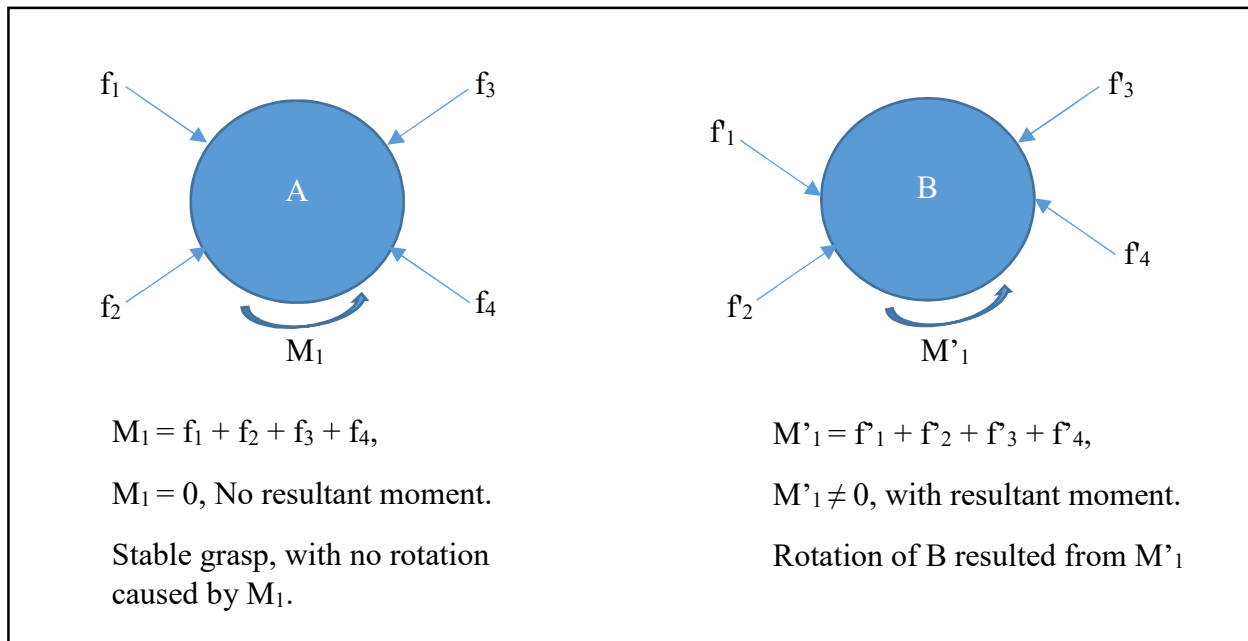


Figure 2.9: Balance VS. imbalance force on an object.

Figure 2.9 shows how an imbalance in force on the target object. Imbalance grasp will affect the grasp quality. From the observation in Figure 2.8 and

Figure 2.10, the author also noticed that the ratio of the fingers needed to be optimised.

The imbalance in grasping was very likely to cause by the fingertip of the gripper met first before a proper encompassing grasp was formed.

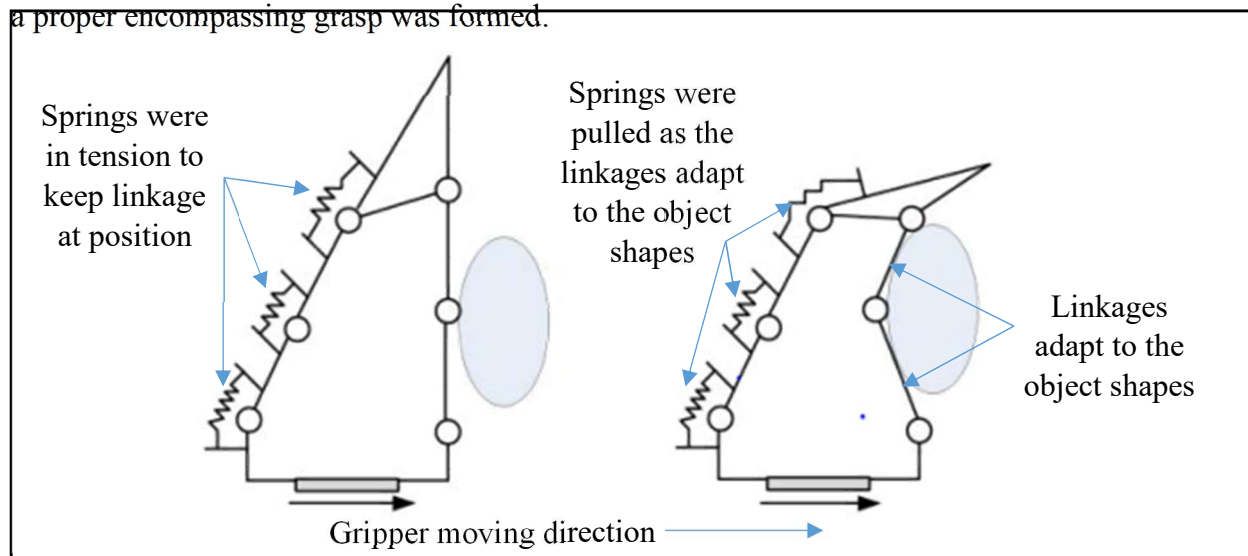


Figure 2.10: Underactuated Robotic Gripper had a mechanism composed of three phalanges and springs to ensure finger return to position after releasing of a grasp [38].

Figure 2.10 shows the design of underactuated robotic gripper with adaptive fingers for objects grasping tasks. The design was very similar to the design of the adaptive finger by Birglen [11]. The gripper was attached to a parallel end-effector of Schunk LWA 4D manipulator.

Figure 2.10 shows both grippers from Birglen [11], and Gao [37] had the configuration and functions of the same linkage to enable both pinch grasp and encompassing grasp. The fingers comprised of six linkages, a simplification from two sets of four-bar linkages. The three springs were placed at the opposite end of the contact surface to enable the self-restorability of the linkages. In this arrangement, the springs in between pull the connected phalanges to their initial position. The ratio of the finger's phalanges proximal: middle: distal was $1:1:1$, which gives the grasping area ratio of pinch area: encompassing area to $1:2$.

Figure 2.11 shows the summary of the adaptive gripper technology, which defined its capability and the advantages that can be derived from listing and categorising each capability. The summary helps in getting the design consideration in the right direction.

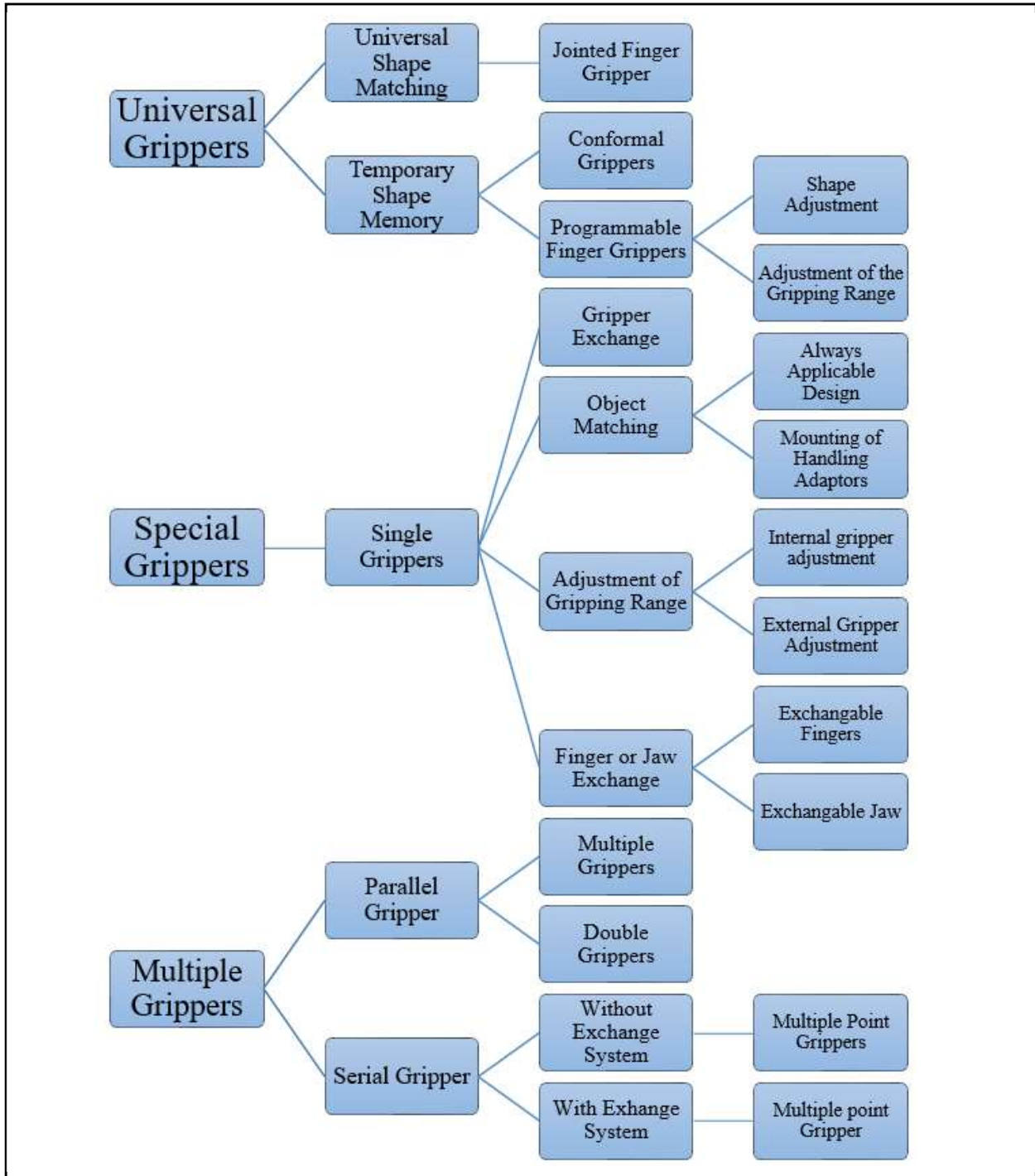


Figure 2.11: Summary of tree structure form defining the capability and the advantages of different gripper type [7].

2.2 Define and Quantify the Ability to Grasp and Manipulate.

For this research work purpose, it was to be able to invent an adaptive gripper that can work (grasps) well, and the benchmark to be compared with when designing an adaptive gripper was with the adaptive gripper mentioned the Robotiq two fingers gripper. Also, the traditional computational formulae [7] can be applied in the gripper for target contact situations were listed in Table 2.1.

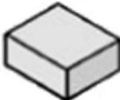


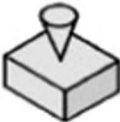
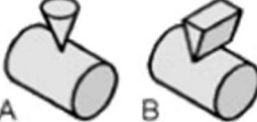


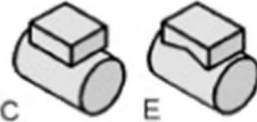

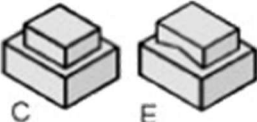


k	Object form		
	cuboid	cylinder	sphere
			
1			
2			
3			

Figure 2.12: Defining contact points between the gripped objects and tip of grippers [7].

The adaptive finger will be used mainly for grasping object rather than manipulation. Object manipulation involved moving an object in a different direction and require grasping to secure in all direction. However, for worst case scenario, it can be assumed that the object was always held by frictional force and it can be calculated and estimated the grasp force, whether it

was point, line or surface contact. The total force on grasp surface pressure can be divided if there were more than two contact points and assume the forces were distributed equally [38], a high-quality grasp can be performed (higher contact force, distributed to more than two contact points).

For this project, the author focused on designing two segments for encompassing, and the grasping of a sphere free body diagram can be defined as shown in Figure 2.13. The figure shows the grasping in three orientations, where the object was grasped at three different angles. The reader can imagine that all the object had the gravity acting down the page. Figure 2.13a shows the object was held on by a gripping and frictional force. Figure 2.13b shows the object was picked from top typically, where the first two phalanges were closed securing the object. Figure 2.13c shows the object was sitting on one of the fingers, and the weight was on one finger while the other finger was securing from the top.

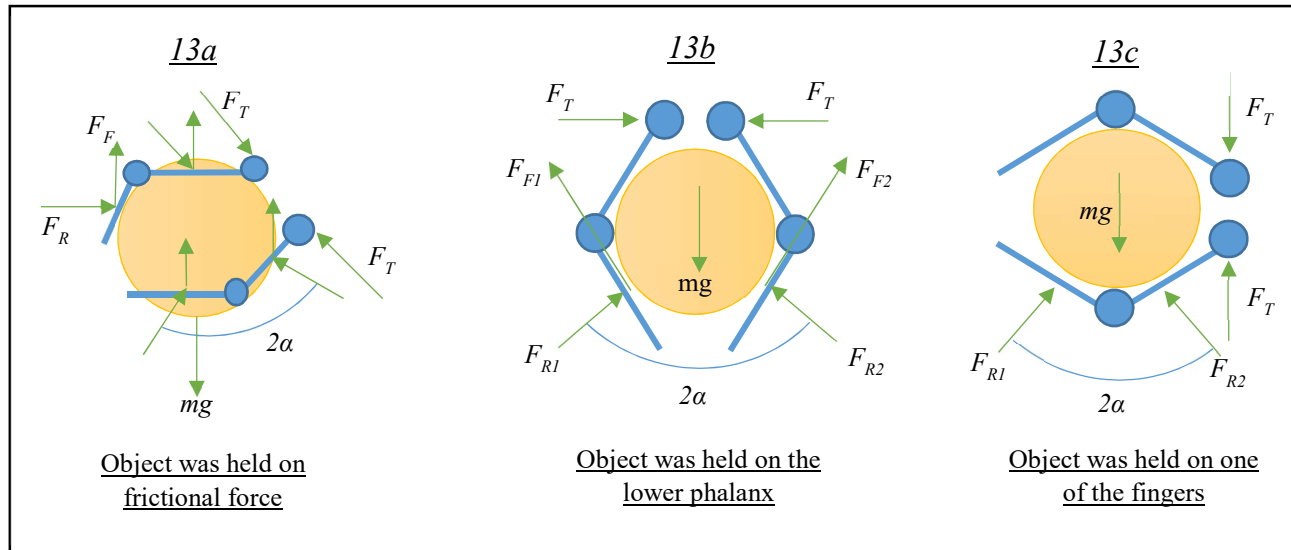


Figure 2.13: Free body diagram of two finger grasping; 2.13a: object held on frictional force; 2.13b: object was held on the lower phalanx; 2.13c: object was held on one of the fingers [7].

F_T : Gripping force [N]

μ : Coefficient of static friction between attachment and work part.

m : work part weight [Kg]

g : Gravitational acceleration [= 9.8 m/s²]

F_R : Resultant Force [N]

F_F : Frictional Force [N]

α : Angle [Degree]

A condition in which item grasp does not drop statistically, Assuming the most efficient grasp force enough to counter the frictional force:

$$\text{For 13a: } 2F_T > \frac{mg \sin \alpha}{\mu} \quad (\text{Eq. 2.1})$$

$$\text{For 13b: } 2F_T > \frac{mg \tan \alpha}{\mu} \quad (\text{Eq. 2.2})$$

$$\text{For 13c: } F_T > mg \quad (\text{Eq. 2.3})$$

(only one finger force needed to grasp the item.)

The contact forces for each case:

$$\text{For 13a: } F_K = \frac{mg}{4\mu} \quad (\text{Eq. 2.4})$$

$$\text{For 13b: } F_{K1} = \frac{mg}{2 \cos \alpha} \quad (\text{Eq. 2.5})$$

$$F_{K2} = \frac{mg \tan \alpha}{2 \cos \alpha} \quad (\text{Eq. 2.6})$$

$$\text{For 13c: } F_{K1} = \frac{mg \sin \alpha}{2 \sin \alpha} \quad (\text{Eq. 2.7})$$

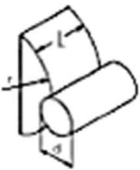
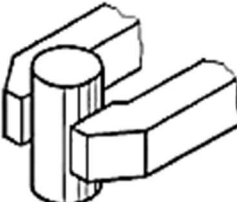

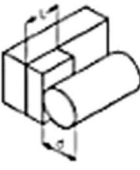

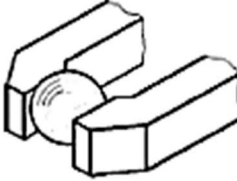


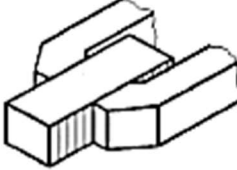
$$F_{K2} = F_{K1} \quad (\text{Eq. 2.8})$$

From the Figure 2.13 and the equations above, Figure 2.13a was a pure friction mating when forces were acting in a parallel jaw gripper, and the adaptive finger was forming two contact points on the object, while Figure 2.13b was shape and friction mating and Figure 2.13c was the shape force mating.

From Table 2.1, from the line contact, point contact or surface contact, the surface pressure, p was direct proportion with the gripper force. The grasp stability was dependent on the surface

pressure, the location of the grasp points and friction coefficient of the finger surface. These three factors and the focus define grasp quality of this research, or the variable was the location of grasp points. Location of grasp point also mentioned in Figure 2.9, showing the imbalance grasp point will cause instability in grasping.

Table 2.1: Computational of grasp pressure concerning the contact method and jaw shape [7].

	contact	surface pressure p	gripper jaw shape
line contact		$p = 0,418 \sqrt{\frac{F_K \cdot E_r}{L} \left(\frac{2}{d} + \frac{1}{r} \right)}$	
		$p = 0,418 \sqrt{\frac{F_K \cdot E_r}{L} \left(\frac{2}{d} - \frac{1}{r} \right)}$	
		$p = 0,418 \sqrt{\frac{2 \cdot F_K \cdot E_r}{L \cdot d}}$	
point contact		$p = m \cdot \sqrt[3]{\frac{F_K \cdot E_r^2}{r^2}}$	
		$\frac{d}{2} < r$	
surface contact		$p = \frac{F_K}{a \cdot b}$	

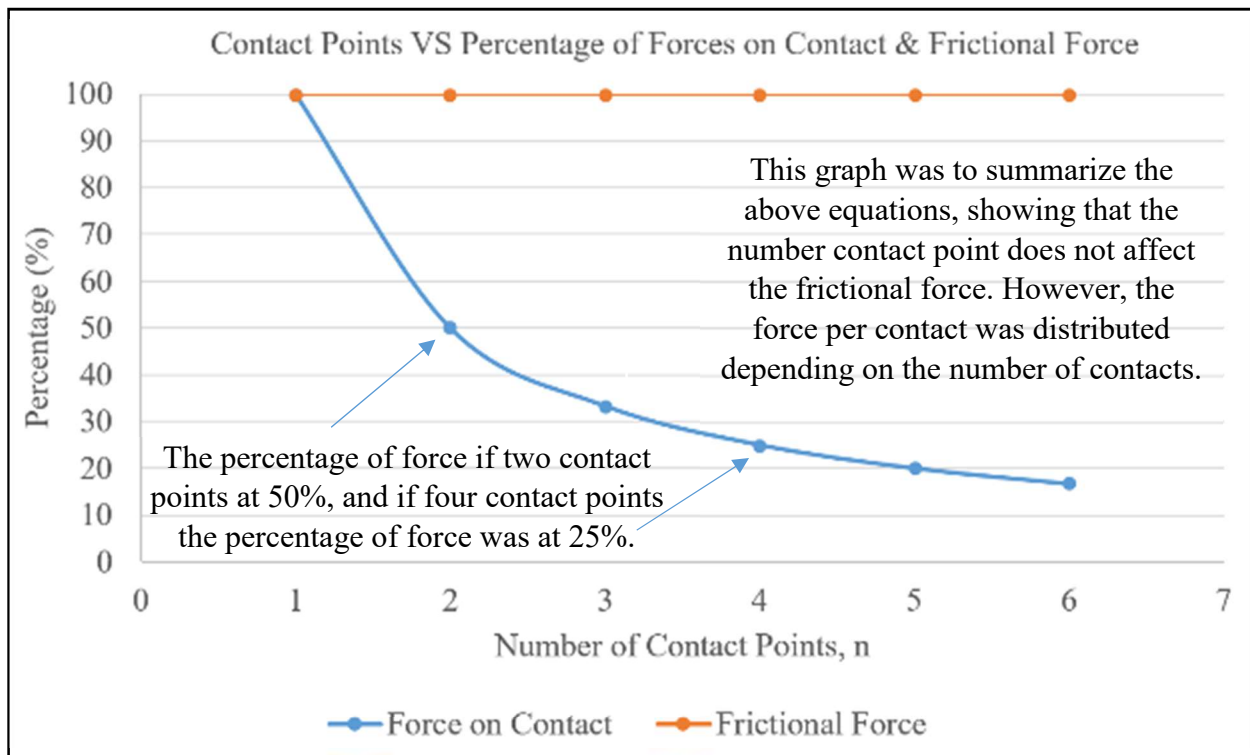


Figure 2.14: Contact points vs percentage of forces on contacts and frictional force.

Figure 2.14 shows the contact points effects on the forces on contacts and frictional forces. Frictional forces remain the same regardless of the number of contact points and total forces required to hold the item remains as $F = mg/\mu$. The coefficient of static friction between the finger surface and the target object can be manipulated to improve the grasp quality. The force needed to hold the item was inversely proportional to the number of contacts.

To handle fragile objects such as a glass which was heavy and sensitive to pressure, four points contact will be better than two points contact, as each point would be halved on four points ($0.25 F$ on each point) compared to two points ($0.50 F$ on each point). The unique advantage gives adaptive fingers the ability to grasp fragile items with reduced risks of damaging it.

Assuming the object can only sustain the maximum surface pressure, P_{max} , if there were two points the forces were distributed, that was the same if there were more than two contact

points. The gripper can apply higher force to increase the frictional forces, without damaging the target. Also, two contact points grasp on an object was less stable compared to three or more grasp points. This increase the limitation of the degree of freedom (DOF) of the object which will prevent the object from rotating if the object centre of gravity (COG) was not in line with the grasp point. When the grasp points were not in line with the COG, it will create a rotation and might introduce slip from the inertia.

Table 2.2: Grasp-ability; XXX – highly effective; XX – effective; X – graspable, nil – not applicable [8].

Grasping Principles	2D shapes				3D shapes			
	fabrics	leather plies	paper sheets	metal sheets	plastic parts	rubber parts	foods	bags
Mechanical grasping	XX	X	X		XXX	XX	XXX	XXX
Ingressive grasping	XXX						XX	XX
Electromagnetic grasping				XXX				
Electrostatic grasping		XX			XX			
Suction cups		XX	XX	XXX	XXX	XXX		
Air jet grippers		XX	X	X	XX	XX	XX	
Cryogenic grippers	XX						XX	X

However, when there were three contact points, additional DOF was being limited. The object is more secured and less likely to rotate or slip. Thus, for quantifying grasp quality, it can be simplified as many contact points it was forming a grasp. The higher the number of contact

points, regardless was the point, line, or surface grasp, the higher the grasp quality. Figure 2.9 in section 2.1.2 shows how grasp stability can be improved by having balance grasp force on the target to avoid rotation on the object that may cause slippage.

From Table 2.2, the mechanical gripper had the highest grasp-ability and most compatible with all items. The metal sheets were unable to be picked due to the shape incompatibility. If the sheet metal was placed standing, the sheet metal would be picked. Thus, the mechanical grasping principle was still the ideal grasping method for general-purpose robotic picking.

2.3 Discussion & Summary

From the literature review, the parallel gripper had the simplest mechanisms and had a long history in automation and robotics application. The parallel gripper also dominated the market of the gripper in the industry. Thus it makes sense to convert the existing grippers and give them a new life as an adaptive gripper.

Table 2.3: Advantages of adaptive fingers compared to the stiff finger summarised from the literature review.

	Adaptive Finger	Stiff Finger
<i>Irregularly shaped items (e.g. Spoon, animal shaped toy, bowl, and so forth)</i>	Able to adapt to the shape create more than two contact points for stable grasps.	Only can make two points contact, need precise picking points.
<i>Fragile objects (e.g. Glass, paper box, and so forth)</i>	More contact points were created to lower grasp pressure to minimise damage.	Difficult to control the force by balancing frictional force and grasp pressure of the gripper.
<i>Number of Parts</i>	There were more parts due to the integrated mechanisms. Thus the cost was much higher compared to the stiff fingers.	Designed specifically for the application, and the number of parts was low. Usually one to three parts depending on complexity.

However, from all the existing adaptive finger mechanisms, there were no mechanisms that can be directly adapted to a parallel gripper. Thus, the motivation to invent and design a functional finger for the parallel gripper. The challenge was to design mechanisms that must fit into an existing mechanism. During the design process, it was essential to identify such challenges clearly, and these challenges will be discussed in the next chapter.

From the grasp quality study, there were the closed form and friction grasp. Encompassing grasp forms closed-form if it was picked the target from the top and depend on frictional force to hold the items if it was picked from the side; where pinch grasp was all depending on the frictional force. Thus, even if the fingers can form encompass grasp, the frictional force was still a big factor. Thus, it was known that it must be designed for fingers that form three or more contact points to be better than the current fixed finger grasping.

It can be summarised that adaptive mechanisms had a minimum of three contact points on the target object to create a firm grasp, even with low frictional force. In order to enable adaptive grasping, the gripper was also can had one adaptive finger and one fixed finger to reduce further cost, which still able to create a minimum of three contact points. Parallel gripper also helped in ensuring the contact points were parallel which was crucial to minimise the risk of the target object from rotating. From the literature review, Table 2.3 can be summarised that the advantages of the adaptive finger had over the stiff fingers.

3. DESIGN OF AN ADAPTIVE FINGER FOR PARALLEL GRIPPER

From the literature review and background, the motivation was to design adaptive finger for the parallel gripper. For this project, the inspiration was to name the adaptive finger as “aFinger”, and the “a” stands for “adaptive”. From here, the report will start using aFinger to represent the name of the adaptive finger. In this chapter, it will be demonstrated how the design was achieved and the challenges in designing the mechanisms for the parallel gripper.

The development process of a typical gripper had been stated in the VDi guideline by Pahl and Beitz [39]. The outline of the steps shown below and the design process putting the attention on objects with different shapes and sizes from everyday e-commerce items: -

- a) Task requirement;
- b) Conceptual design;
- c) Evaluation of technical and economic efficiency;
- d) Size and functionality optimisation;
- e) Design and 3D modelling definitive.

3.1 Design Challenges in General End Effector

Before going into the conceptual design, this section discussed the design challenges faced in general, when designing an end-effector. The end-effector was usually the end part of a robot manipulator that physically interact with the objects and the surrounding environment.

An end-effector in the automated working environment especially, a good and well-considered design can improve the robot efficiency, offsets and improve robot inaccuracy caused by sensors or the dynamic environment and gives the robot more flexibility in performing different tasks in one routine. There were two essential design considerations which make an excellent industrial end-effector:

1. *Design to increase the reliability of the systems: This was to design a gripper that consistently performs as intended and have a minimum or no human intervention when running in automated mode.*
 - a. Fully encompass parts with the fingers of the end-effector.
 - b. Fingers should align with the grasp direction
 - c. Do not deform when grasped an object
 - d. Grasp parts securely, by ensuring no slippage and rotation of the object.
 - e. Finger length was lessened to reduce deflection when grasping at the fingertip.
2. *Design to increase the throughput of the systems: This was to design a gripper that ultimately increases productivity, which also includes consuming fewer resources (workspace, energy and so forth)*
 - a. Minimise workspace of the end-effector.

- b. Tapered fingertip to allow access in a constrained environment and displace non-target object easily.
- c. Adaptive capability and avoid tool change.
- d. Grip multiple parts with a single grasp.
- e. Allow multiple end-effectors on one manipulator.
- f. Grasp parts securely.

In summary, the author may not have incorporated all the design points mentioned above; however, most of these crucial points were considered when doing the conceptual design.

3.2 *Conceptual Design*

For this process, the author started with looking at on the available literature, existing adaptive gripper with the similar capability and try to design it heuristically by sketching on paper, iterate the design repeatedly to obtain the final prototype design.

From literature, the highlights of the crucial points and relevant information about the solution were the ability of adaptive fingers and the importance of achieving pinching and encompassing grasp. Also, the author learned that if the prototype of the adaptive finger made using the 3D printer, will save cost and cut short fabrication time. Many linkage kinematics were reviewed and especially useful to eliminate some initial ideas and able to innovate different type of linkages patterns to inspire to create the aFinger finally.

From existing products, may found many adaptive fingers, from simple to complicated industrial grade mechanism. However, all the mechanical adaptive gripper or other adaptive fingers found could not be fitted onto a parallel gripper. From Figure 2.1 to Figure 2.8, some of

the very different adaptive grippers can be observed. Some of them were readily available of which were effective but come at a higher cost whereas others were relatively cheap but not as robust.

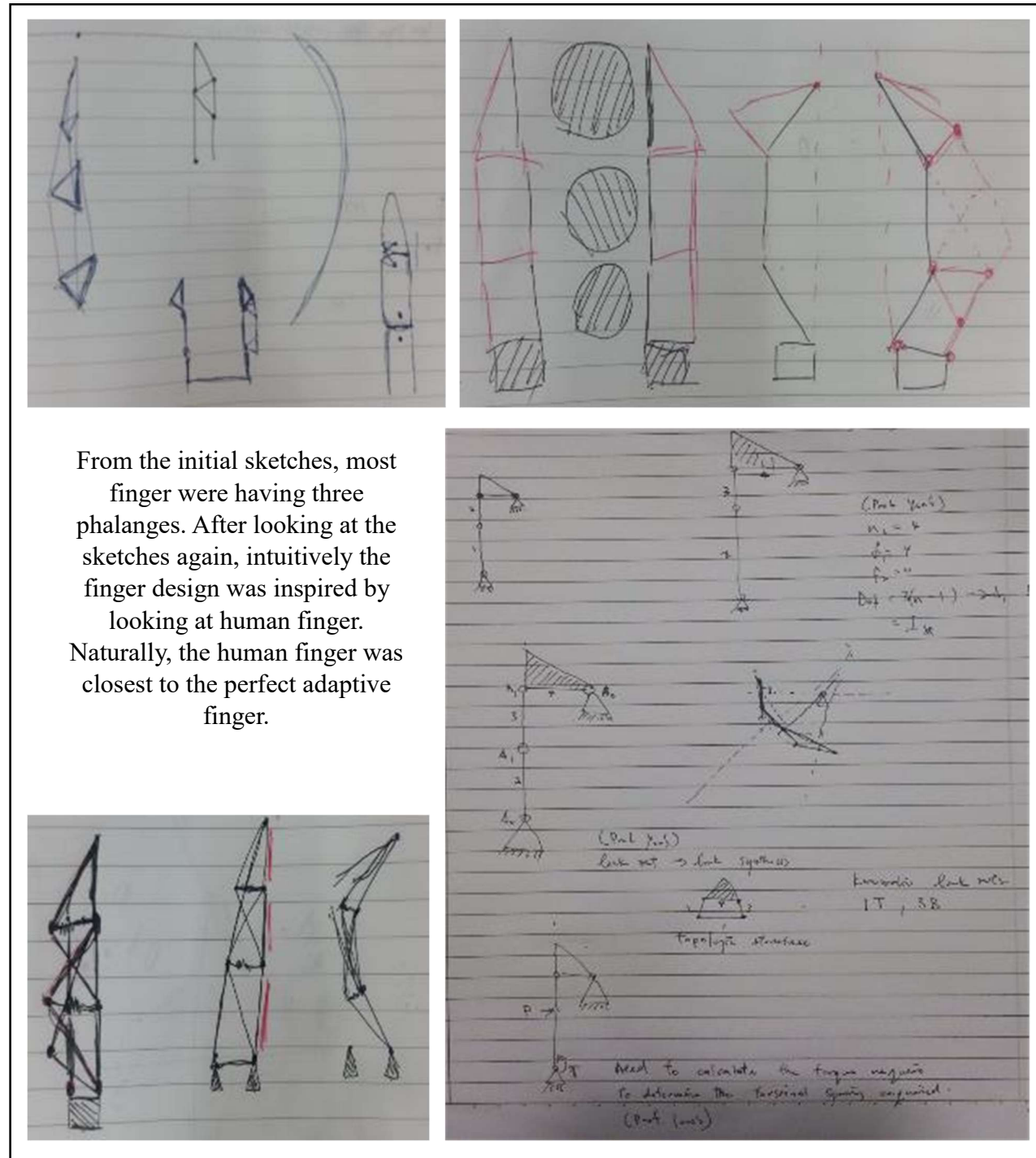


Figure 3.1: Sketches of initial ideas.

From

Figure 3.1, there were some of the initial sketches that the author did while brainstorming for a solution to create an adaptive finger mechanism. From the drawings, the author converts the images into linkages to do linkage simulation and then, used 3D models to help further in visualisation and optimisation of the design.

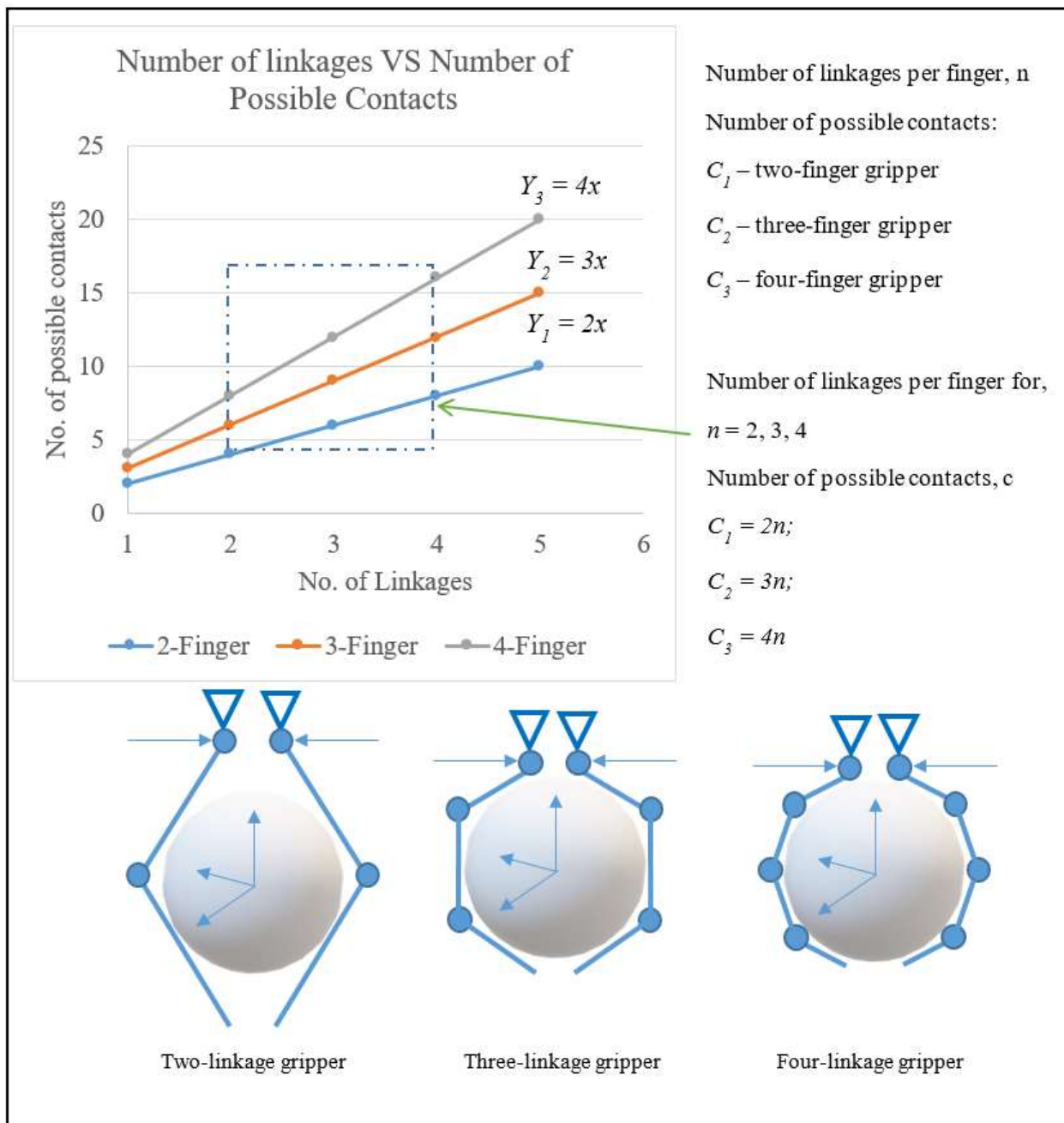


Figure 3.2: Increase in the number of linkages shows more possible contacts formed on a circular object.

From the conceptual design, Figure 3.2 shows the summary of the design consideration of having a different number of linkages:

One-linkage: Only able to form two point contacts. Unable to perform encompassing grasp.

Two-linkage: Able to perform encompassing grasp with a minimal amount of linkage to create more than two contact points.

Three and more linkages: Able to perform encompassing grasp, able to generate more than two contact points. The more linkages per finger, the more contact points it can form.

For this research application, two linkages per finger were enough to perform encompassing grasp. More linkages will only add on to the cost. However, more linkage benefits in distributing the contact force.

As a starting point, the author starts to explore the linkage design, and for basic mechanism design, the most basic moving mechanisms were the four-bar linkage. The linkage design and simulation were done on the Linkage simulation software [40]. To be specific, the focus was in the planar four-bar linkages with four revolute joints (planar quadrilateral linkage), instead of the three revolute joints and a prismatic (slider-crank linkage), or the two revolute and two prismatic joints (double slider). The reason for using the planar quadrilateral linkage was because joints were cost-effective to fabricate and robust compared to the slider joints.

Figure 3.3 shows the primary four-bar linkage that will be manipulated to suit this application. A planar quadrilateral linkage had four rotating points, and it can be arranged in two distinct positions. In Figure 3.3, it shows the arrangement “AB-AC-CIG-BG” where the coupler link was not beside the fixed link, and the other possible arrangements were “AB-CIG-AC-BG” or “AB-CIG-BG-AC”, which had the coupler link with a fixed link [41, 42].

For this application, there was no additional actuation (it should work as an underactuated mechanism). The return mechanism would be a spring, tension or compression which would be returned to its original position to be ready to perform another task. The spring design and specification can be made base on the location and type of spring used, and the table for spring calculation can be found in Appendix A.2.

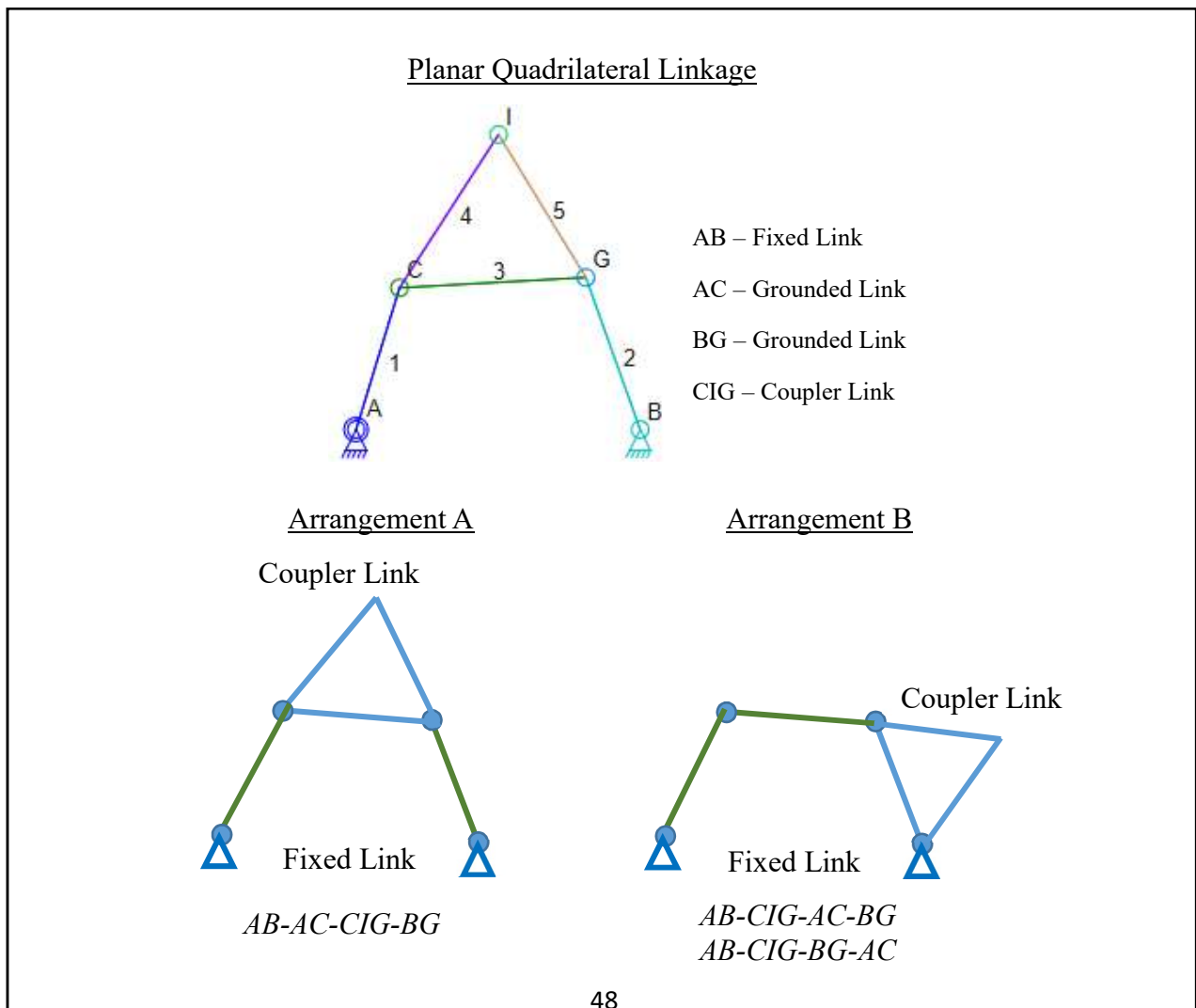


Figure 3.3: The arrangement of the planar quadrilateral linkage.

The possible adaptive finger arrangements for A and B were shown in Figure 3.4. Figure 3.4a shows two linkage contacts, and Figure 3.4b shows a three linkage contacts adaptive fingers. The adaptive fingers were both four-bar linkages with torsional springs, and it can return to position after external forces were removed.

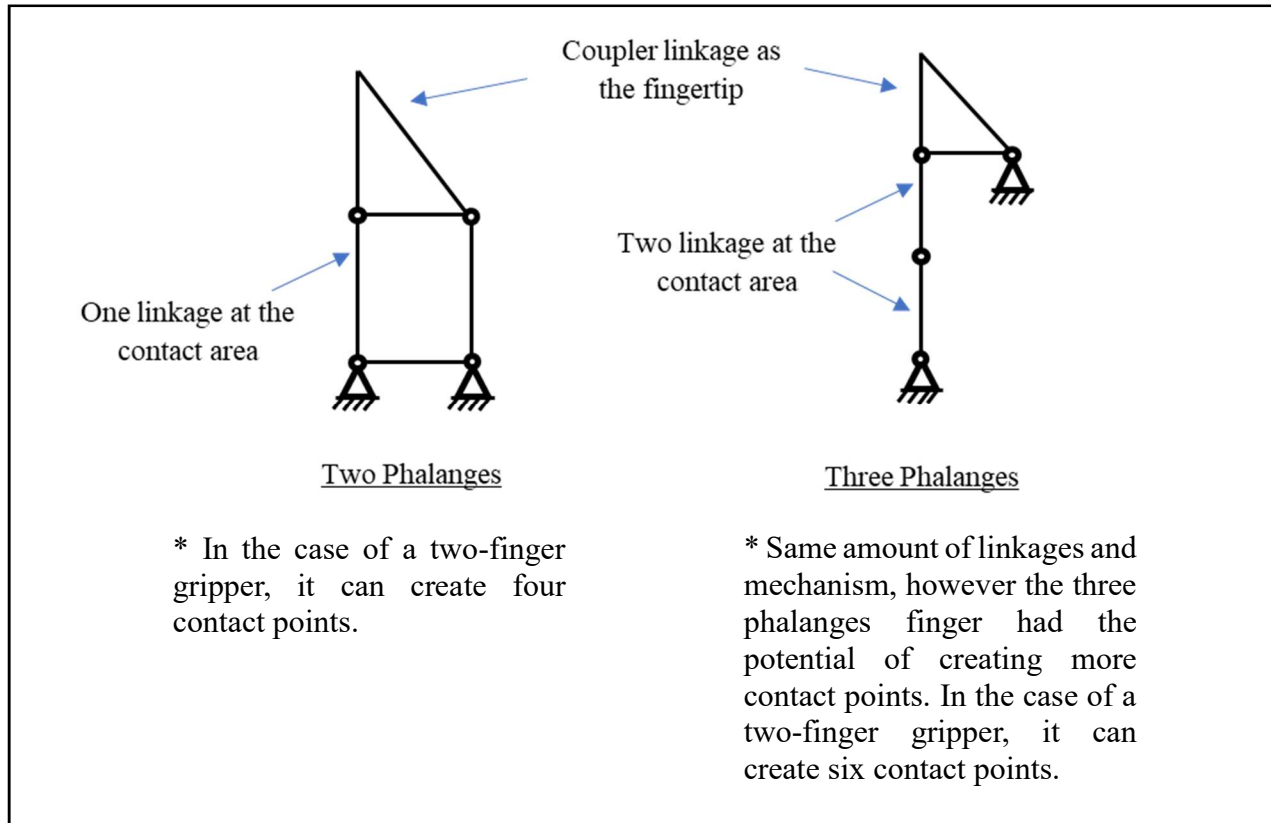


Figure 3.4: Possible adaptive finger mechanism from planar quadrilateral linkage; 3.4a: Two phalanges; 3.4b Three phalanges.

From Figure 3.4, the three phalanges arrangement had an advantage over the two phalanges finger as an adaptive gripper. In an earlier discussion, more contacts on the object had the

advantage of lowering contact force on the object, preventing potential damage to the object. Thus, for this project, it was better to decide on working on optimising the three phalanges finger for the adaptive finger for the parallel gripper. In the behaviour design for the finger, it also shows some considerations that the three phalanges finger was better compared to the two phalanges finger.

3.3 Behaviour Design

The mechanisms of the adaptive finger were to perform a movement to achieve proper grasping by having three or more contact points with the object. From figure 19, there were two possible arrangements for the fingers. Figure 3.5 shows the undesirable behaviour of the linkages which does not form an encompassing grasp.

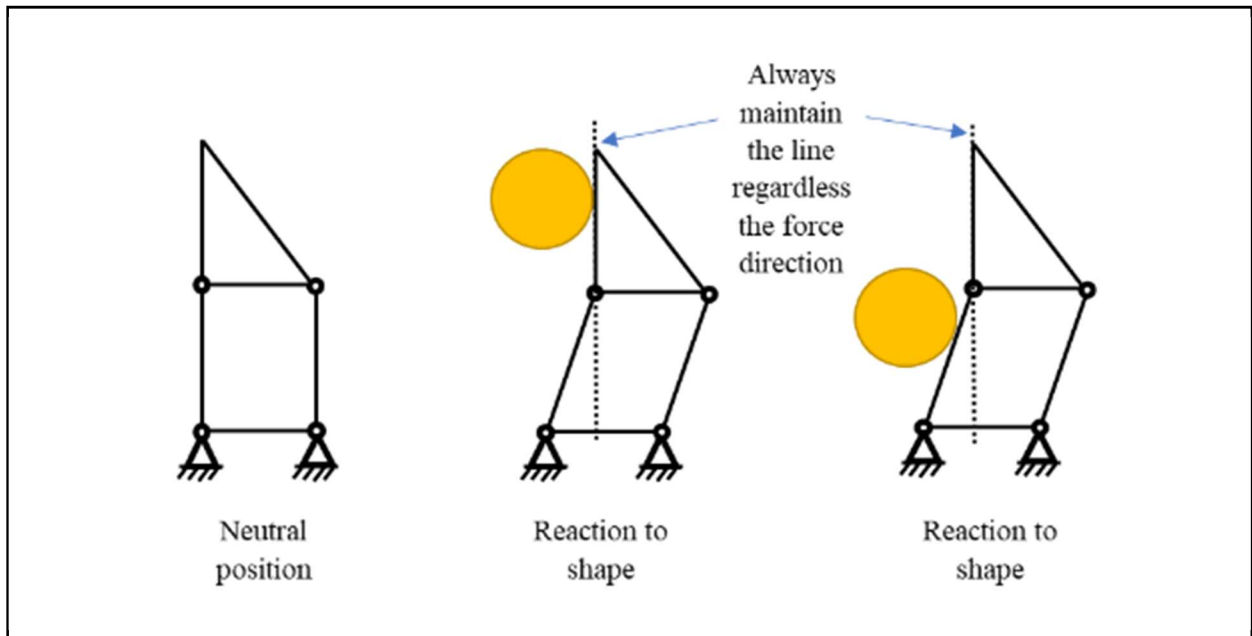


Figure 3.5: The kinematic diagram of both fingers and the associated linkage of one finger.

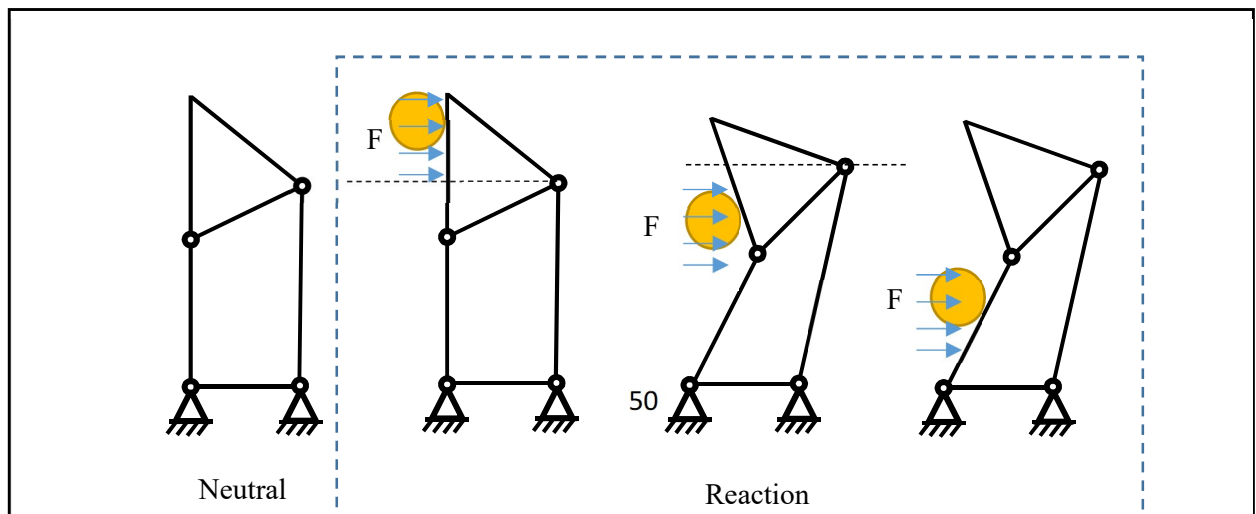


Figure 3.6: The kinematic diagram of both fingers and the associated linkage of one finger.

Thus, the behaviour design of the finger needed to be defined. Figure 3.6 shows how the linkages should wrap around the shape of the object. Following mechanism behaviour design will all focus on the three phalanges finger as the three phalanges finger was able to create more contact points compared to the two phalanges finger.

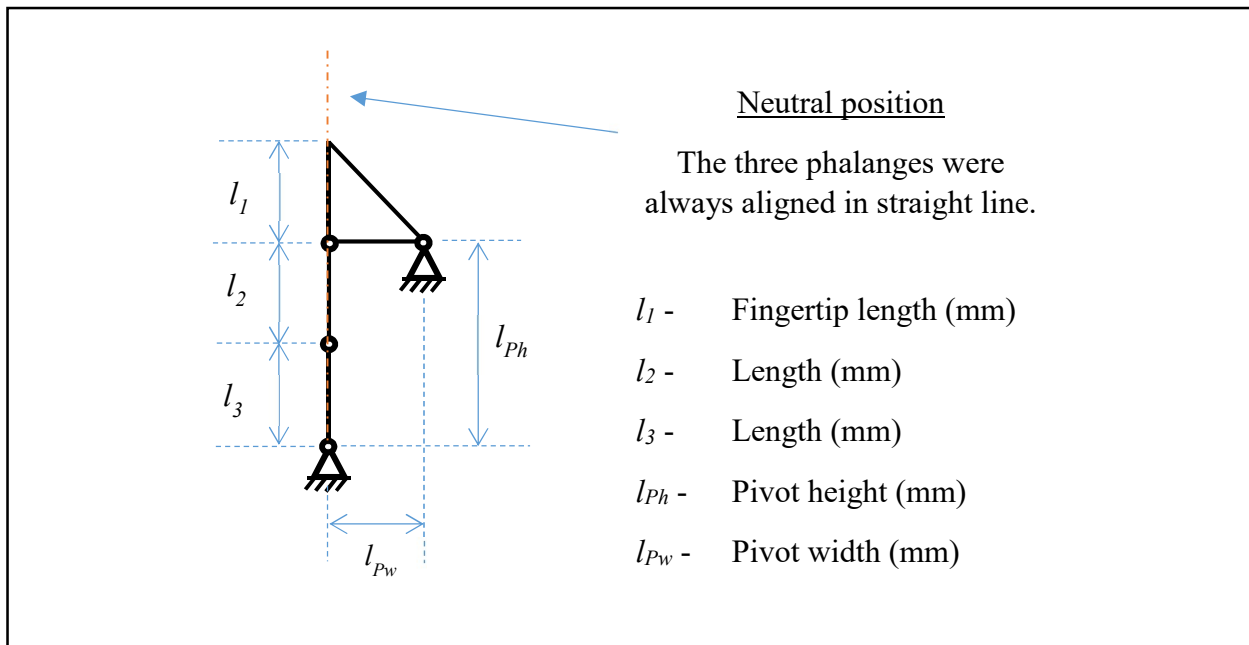


Figure 3.7: The five variables of the adaptive fingers. Manipulating these variables will change the behaviour of the finger when in contact with the object.

Appendix A.5 shows linkage simulation software used to simulate the effect of variation of phalanx lengths on the fingertip movement. By manipulating the five variables in the mechanism software, the behaviour of the finger can be observed from the motion lines. Figure 3.7 shows the parameters, $w = \{l_1, l_2, l_3, l_{Ph}, l_{Pw}\}$ that being manipulated heuristically to study the behaviour of the mechanism initially.

3.4 Kinematics Analysis

For the kinematics analysis, the focus was on classifying the kinematics and study the movements of the links, especially those that had an impact on the effectiveness of adaptive grasping. The kinematic diagram and associated linkage of the gripper were shown as below:

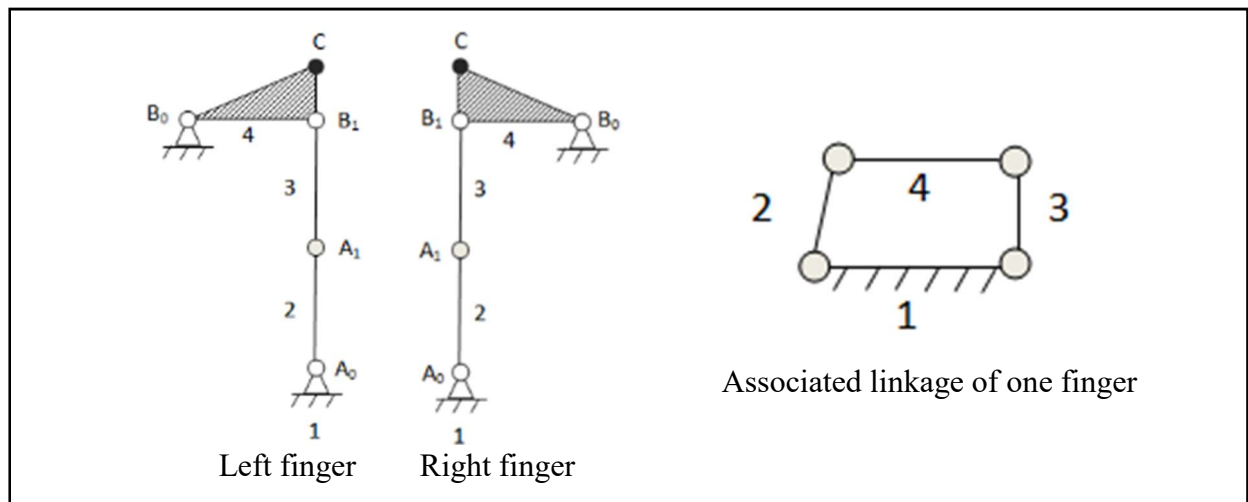


Figure 3.8: The kinematic diagram of both fingers and the associated linkage of one finger.

Figure 3.8 shows the kinematic diagram of both fingers, and for this design, the left finger and right finger share the same kinematics, only oriented in the opposite direction. There were four links and four revolute joints in the kinematic diagram of each finger. Point C represents the position of a fingertip at link no.4. According to *Gruebler's equation* [43], the number of the degree of freedom for each finger can be calculated as follows:

$$\text{Degree of freedom, } F = 3(n-1) - 2f_1 - f_2 \quad (\text{Eq. 3.1})$$

$$= 3(4-1) - 2(4) - 0 = 1 \quad (\text{Eq. 3.2})$$

$$\text{where } n=4, f_1=4, f_2=0$$

The kinematic link set solution of one finger with $n= 4$ and $F= 1$ could then be calculated as follows:

$$n-(F+3) = T+2Q+3P+\dots \quad (\text{Eq. 3.3})$$

$$4-(1+3) = T+2Q+3P+\dots=0 \quad (\text{Eq. 3.4})$$

$$T= 0, B= 4$$

The above calculation shows that the mechanism of one finger was a four-bar linkage with one degree of freedom and the associated linkage consists of only four binary links.

The moving path of point C which was the fingertip was designed to be as close as possible to joint B_1 to avoid collision with the opposite fingertip. Fingertip collision will hinder further grip motion and hence affects the minimum diameter of the items that could be grabbed by the gripper. The moving path of point C was manipulated in simulation software by adjusting the distance between point C and B . From Figure 3.9, it was the results of the first iteration of the design, where it had the minimal fingertip path on the parallel line.

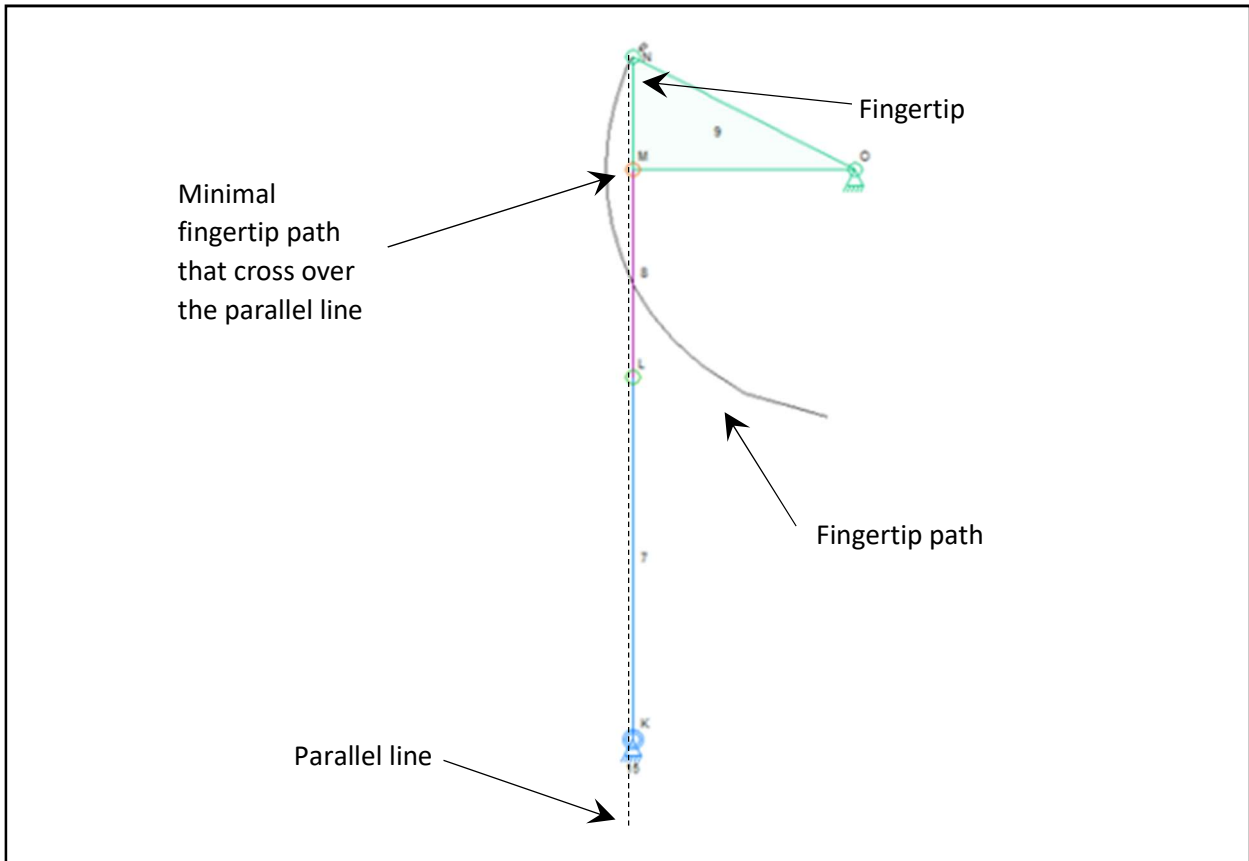


Figure 3.9: The path of the fingertip; it should have a minimal crossover path over the parallel line.

3.5 Structural Design Challenges and Objectives

Before examining the design details of the aFinger, the review was done on all the challenges in the design. Below were the design work end objectives to be achieved: -

- a. **Adaptive grasping**, which the fingers can perform pinch and encompass grasp. Mapping the functionality based on the favourite Robotiq two finger adaptive gripper, which also capable of pinch and encompass grasps passively.

b. **Without additional drive or actuator in the finger.** Instead of having extra motors or tendon to actuate the mechanisms of the fingers, the finger mechanism was to achieve the objective passively. Having additional actuators will hinder the simplicity of the whole operation, and it was crucial especially if the design was to achieve low-cost application. Having an electric or pneumatic actuator will involve wire or hose routings which also complicate the design of the finger.

c. **Low cost.** It will defeat the purpose of redesigning if the cost of the aFinger was same or higher than the existing adaptive grippers. Low cost will also motivate adoption. It was planned that the design will be tested by the industry and was used widely for logistic purposes. If the cost was high, it does not justify for the industry to adopt this adaptive finger since the market already had the adaptive fingers.

d. **Scalability.** Parallel gripper in the industry comes in different sizes. The finger design must be scalable and to fit on a small parallel gripper that can carry small marbles, to one that can carry large aluminium tubes. The reason for this capability was because, in the logistic application, the robot had to handle small packages such as a letter to a large bag for airport application.

In short, the specific design objective and priority were to design a low-cost passive adaptive finger, which can be adapted to the parallel gripper of various sizes for a wide range of application.

3.6 *Structural Design and Force Analysis*

In this section, firstly the structural design and force analysis, mainly on the design factors that enable the fingers to support grasped object structurally, will be presented instead of depending on the torsional spring. The structural design starting point was inspired by human fingers because, in the author's opinion, a human finger was the most efficient grasper natural world had created. In Devi's paper, a human hand link structure was shown, and each phalange was of different length [44]. Alessandro's paper also mentioned the concept design of a hand exoskeleton [45]. It demonstrated the location of the distal, intermediate, and proximal phalanges and shown in a simplified model.

When designing the length of the linkage, heuristically, it can be identified phalanx length ratio of 5:3:2 (Proximal: intermediate: distal), with 1:1 (proximal: intermediate + distal). Also, it tried to simulate with four or more linkages in a similar arrangement, by having more sections between the intermediate and proximal. It was learned that with more sections, there would be more contact points. However, it forms a more massive curve, making the finger bulkier. In the author's opinion and experience, achieving four contact points was enough for adaptive grasping.

Appendix A.3 and Figure 3.11 shows an example of how heuristically it was possible to discover the behaviour of the finger by changing one parameter at one time. Set one shows it in the initial position and can quickly notice the changes in the l_4 . The angle in degree was measured by the rotation of the proximal clockwise. From that comparison alone, noticed two changes in behaviours: -

1. The radius of the fingertip path decrease, as l_4 increase;

2. The behaviour of the corner from between distal and intermediate phalanx. The rate of change of the angle decrease, as l_4 increase;

3. The maximum angle before the mechanism stall.

From the example of Figure 3.10, the most critical factor that affects the performance was the maximum angle before the mechanism stall. Noticed that the larger the maximum angle before the mechanism stall, the better the force contact point distribution. In the case of a smaller angle, the object will still acquire four contact points. However, the contact points were not distributed evenly. Thus, it may not achieve high quality encompassing grasp.

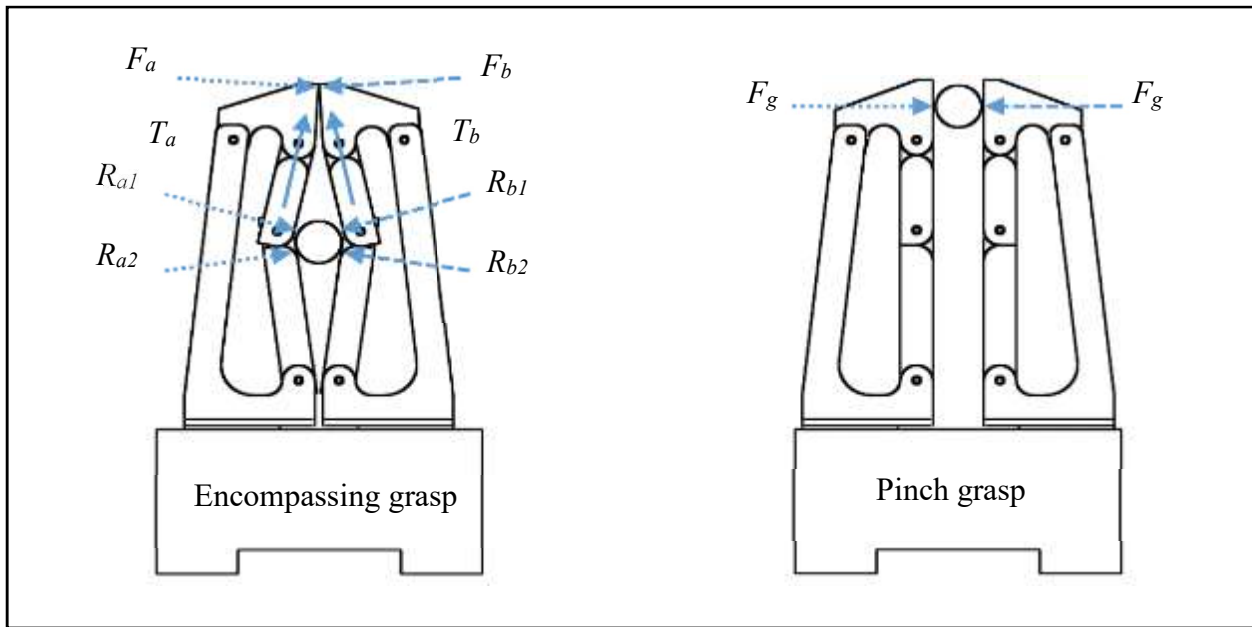


Figure 3.10: Grasping an object with a small diameter, shown in the encompassing and pinch region.

Structurally, it had been mentioned how the pinching and encompassing region works. Also, it can be achieved encompassing grasp of a small round object with the aFinger. From the left encompass grasp illustration at Figure 3.10, it can be observed that when the aFinger was grasping any object in the encompassing region, the fingertip will curl in and meet before the base limit meet. When the fingertip meets, F_a and F_b were pushing on each other, forcing the fingertip to return to

its position. From the previous section, it was known that when the fingertips were moving back to the initial position, T_a and T_b were created and resulting in R_{a1} , R_{a2} , R_{b1} , and R_{b2} , and these forces were tangential to the object surface, creating a firm grasp.

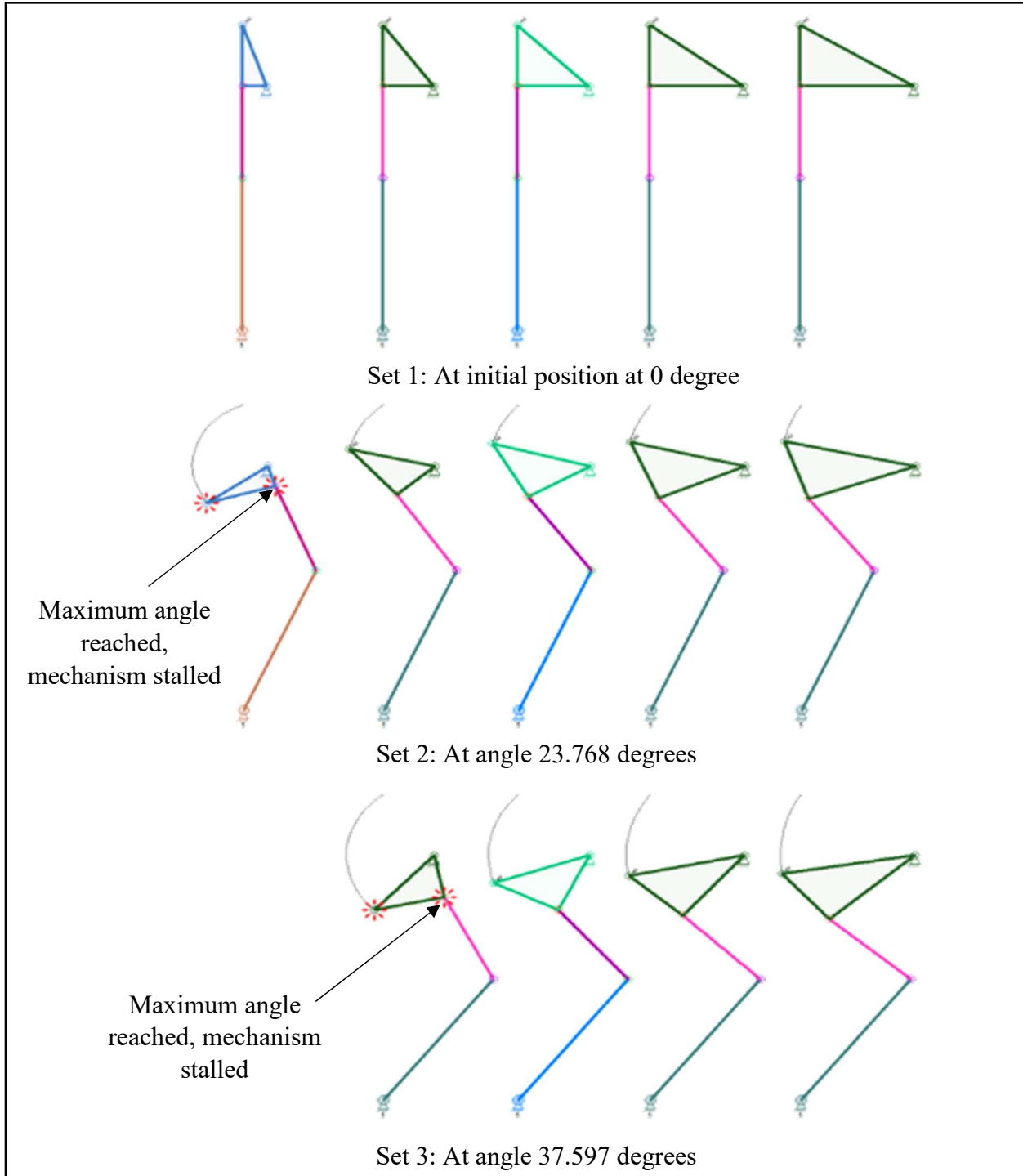


Figure 3.11: A heuristic technique used to explore the behaviour of the linkages. Changing one parameter at one time too and study the behaviour.

For force analysis, since it was not needed to have the active force to activate the system as the focus in the dynamic studies was to show that the linkage design was robust. To make it more robust, the design of the linkages such that during grasping, the grasping force was taken entirely by the mechanical structure.

Force equations:

$$F_1 \sin \theta + F_2 \cos \phi = F \text{ (force from gripper)} \quad (\text{Eq. 3.5})$$

$$\text{From } \Sigma F_y = 0: F_1 \sin \theta = F_2 \cos \phi \quad (\text{Eq. 3.5})$$

$$\text{From } \Sigma M = 0: F_1 w \sin \theta + F_2 l \cos \phi = F_1 w \sin \theta + F_2 l \cos \phi \quad (\text{Eq. 3.6})$$

$$\text{Simplify: } F_1 \cos \theta = F_2 \sin \phi \quad (\text{same as } \Sigma F_y = 0) \quad (\text{Eq. 3.7})$$

which θ , ϕ and F were fixed values, (dependent on geometry and object settings)

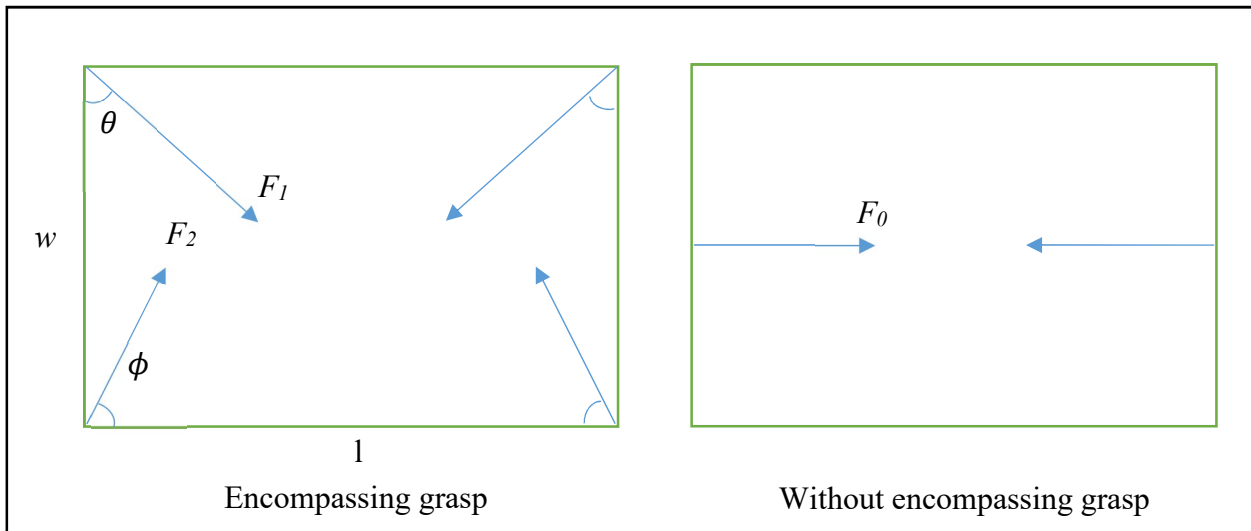


Figure 3.12: Free body diagram of the box being grabbed, as the box, was the boundary, and arrows were the regular forces from the linkages.

Figure 3.12 and the force equation was to show the advantage in gripping strength over a standard parallel gripper with stiff fingers which only had two contact forces on it. The effectiveness

of the gripper would be given by the ability to prevent slipping with the same force. For a standard parallel gripper, the vertical friction force provided (to prevent slipping) is:

$$\text{Max frictional force} = 2\mu F \quad (\text{Eq. 3.8})$$

While for our gripper,

$$\text{Max frictional force} = 2\mu (F_1 + F_2) = 2\mu F \quad (\text{Eq. 3.9})$$

For the same applied force. The total frictional force was the same.

From Figure 3.10, it can be seen how the aFinger holds the object by its structure. From the left illustration in Figure 3.10, if the object was relatively large enough for the gripper to grasp without the fingertip meets, the stress and strain from grasping force will still be supported by the structure instead of the torsional spring. The characteristic of the four-bar linkage arrangement when four contact forces were equal, the forces will try to drive the two linkages, intermediate and proximal, which will stall the movement of the linkages. It showed that the structure of the finger was fully bearing the stress and strain of the grasping force, and it was being validated in the experiment and evaluation section.

3.7 *Novelties*

The author was comparing the novelties of the fingers with the conventional adaptive grippers from research work and commercially available gripper, mainly study on the finger design and mechanism. From the literature review, it can be combined with the useful features and capability of the different fingers and innovate on getting the mechanism workable for the parallel gripper.

Most of the adaptive grippers available were designed in whole, as the fingers and gripper come together as a system. Thus, the finger mechanism could not be applied directly to a parallel

gripper. As the mechanism usually involves the finger curling towards the object, which was activated by turning the finger linkage towards the target object or providing a tension force on the cable to curl the finger to wrap on the target object, just like how a human finger would curl when muscles were pulled.

For instance, the Robotiq two finger adaptive gripper was an excellent gripper with the high-performance adaptive capability [12]. The unique finger mechanism design works by having an actuator to rotate one of the linkages. Then the multiple mechanisms will enclose the target to form a one or more contact points on the Three were also several grippers that use similar actuation methods [18, 21, 29] which driven without tendon or cable. Extensive research had been done on the tendon or cable actuated fingers as well [15, 16, 17, 19, 20]. The aFinger was designed for parallel movement, which moves in parallels from left and right grasping the object in the middle. The aFinger mechanisms were designed to adapt to the shape of the object and forms multiple contact points, thus forming a closed and secured grasp.

The Multi-Modal Gripper [22], demonstrated the effectiveness of the combination of different type of fingers on one gripper. Each finger design had its purpose and speciality, and this shows us it was challenging to design a general finger mechanism that can be used on a wide variety of application.

The existing adaptive finger available was Festo Fin Ray fingers [25, 26] that allow the user to replace gripper fingers and enable the gripper to have the adaptive grasping capability. The finger was made of soft materials, and mechanical structures that were inspired by the fin of rays, and this combination allows it to adapt to the target object gently. However, the Fin Ray fingers adopt the regular triangular structure. Thus, it was unable to pinch an item in parallel when it was used in the parallel gripper. The pinch grasp was especially essential when picking thin objects, i.e. picking a

rod with relatively small diameter from a flat surface or a deformable bag. The Fin Ray fingers were mainly installed in gripper that rotates the fingers towards the centre when grasping, and because of the triangular shape, then rotating towards the centre it can form encompassing grasp. This example was illustrated in Figure 3.13.

Another existing adaptive finger design, PASA finger [13] was a parallel and self-adaptive underactuated finger with pinching and encompassing grasp capability, which it had very similar grasp capability as the aFinger. However, PASA finger mechanism requires the internal motor to drive the fingers, which create more flexibility and control. Unlike the aFinger, which only requires a resilient means for actuation. The aFinger is compatible with the parallel gripper, without having to provide external power and no additional programming needed. Also, in terms of grasp force, the PASA finger had a limitation due to the size of the actuator that can be inserted in the joint of the fingers. However, for the proposed finger, the grasp force was wholly dependent on the gripper closing force.

In comparison, both the PASA and proposed finger were attached on the same parallel gripper. The PASA finger maximum grasp force was dependent on the torque generated by the actuator, and the maximum grasp force of the proposed finger depends on the mechanical structure. The thickness, t , of a mechanical structure of the proposed finger can sustain higher force than the torque of an actuator with a diameter of, t .

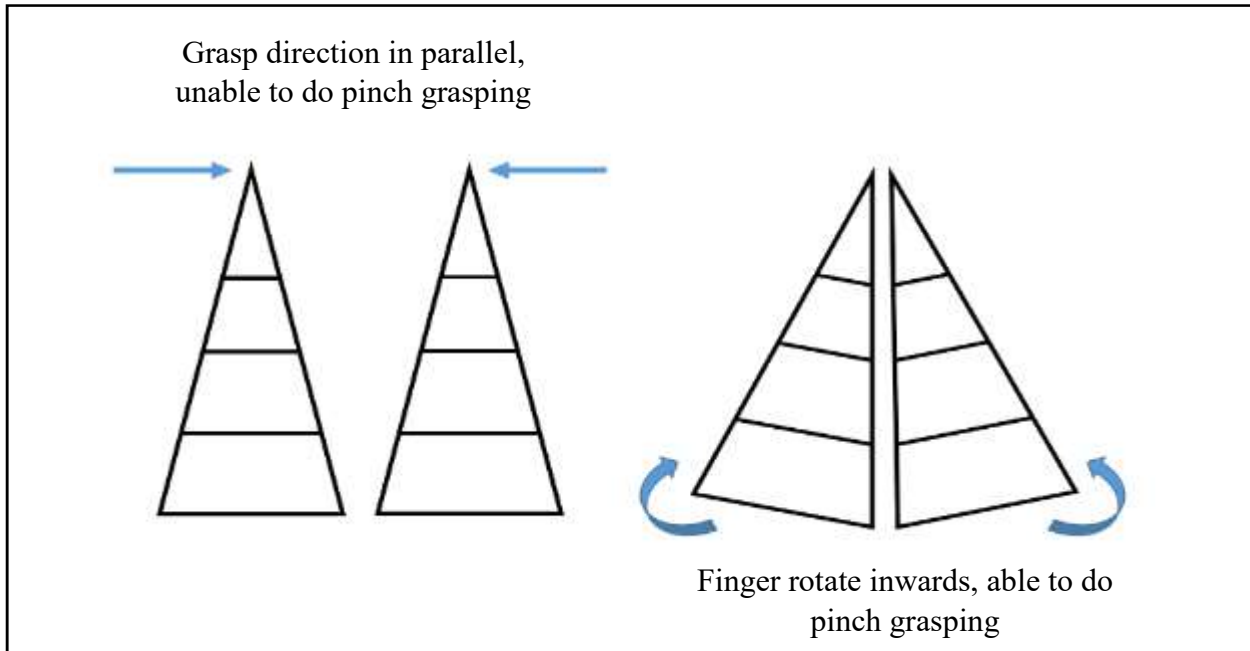


Figure 3.13: Illustrated was the triangular structure of Fin Ray finger. They were unable to perform parallel pinch when attached to a parallel gripper because the base of the finger will meet before the tip of the finger. Thus, the left picture shows that it needs some rotation to pinch.

The aFinger was designed to be scalable. If the fingers follow specific sets of design parameter, it can be scaled to suit the required mechanical strength needed to perform the desired task. The stress and strain on the finger must utterly dependent on the structure itself, to be freely scalable. This was because the design of the resilient means could be limited; for instance, a torsional spring must be huge if need to grasp something heavy. Thus, aFinger had achieved a design that grasping force was whole on the finger structure, but not on the torsional spring. The torsional spring was to bring the linkages back to the initial position.

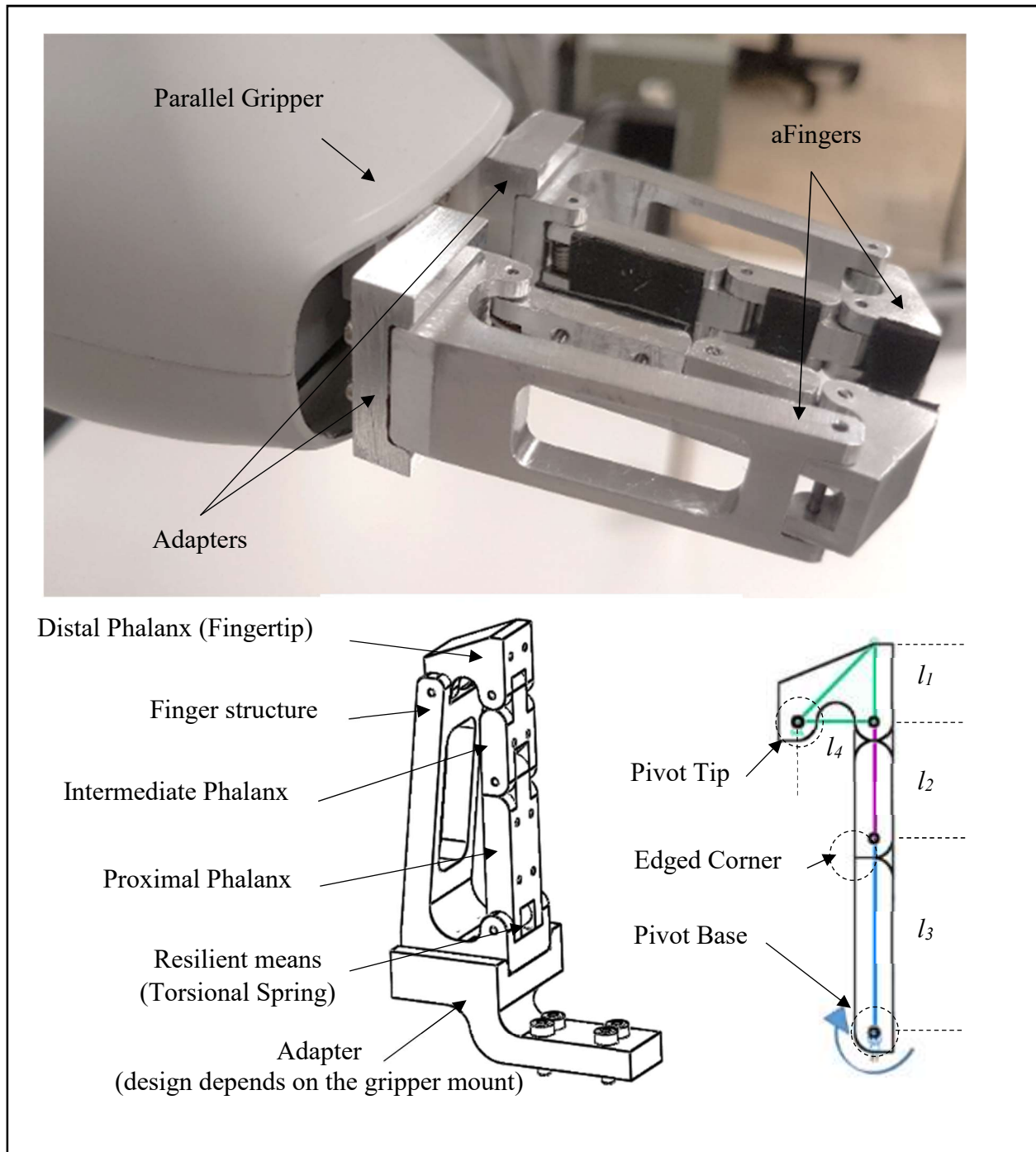


Figure 3.14: The aFinger attached to a parallel gripper, with a custom-made adapter to match the mounting holes. It also shows the essential components in the aFinger.

The aFinger was also designed to adapt to various existing parallel gripper by using a custom-made adaptive plate. With an adaptor, the aFinger generally can be fitted on to any parallel gripper, be it had two fingers or more. Figure 3.14 shows the aFinger with an adaptor, together it

can be fitted onto the ABB YUMI servo gripper [47]. Parallel gripper generally had the same configuration, which having two blocks moving toward each other [9- 11]. This concept of the industrial gripper also allows the parallel gripper to adopt any rigid fingers; thus, the adaptive fingers can also be adapted easily on the parallel gripper. This design will encourage users to adapt aFinger onto any of their existing parallel grippers easily.

The aFinger adaptive mechanism links were uniquely arranged and optimised for grasping. The mechanism was a unique four-bar linkage arrangement, having two links in parallel and one perpendicular to the others. The links were designed and explicitly arranged to perform these two specific grasps: pinching grasp and encompassing grasp. The perpendicular link forms a coupler and acts as the fingertip, and its vital role was to perform pinching grasp: -

1. Pinching in the fingertip region;
2. Pinching in the intermediate and proximal phalanges region. Figure 3.14 shows the phalanges location of the finger structure.

The other two linkages (intermediate and proximal), were to perform encompassing grasp. The aFinger does not depend on an actuator, or even the torsion spring to exert a force on the target object. The force on the object was entirely dependent on the structure of the aFinger. The unique four-bar linkage arrangement of the aFinger, only allows one driver linkage. Thus, all other linkages were dependent, i.e. if the force was acting on the distal phalanx, the intermediate and proximal phalanges will react accordingly. It can be seen from Figure 3.15, the separation of the pinching and encompass grasp was on the line, normal to the pivot tip. Encompassing grasp only works with an object that was not box-like. For the box-liked item, the aFinger will contact the whole flat surface that was parallel to the finger surface.

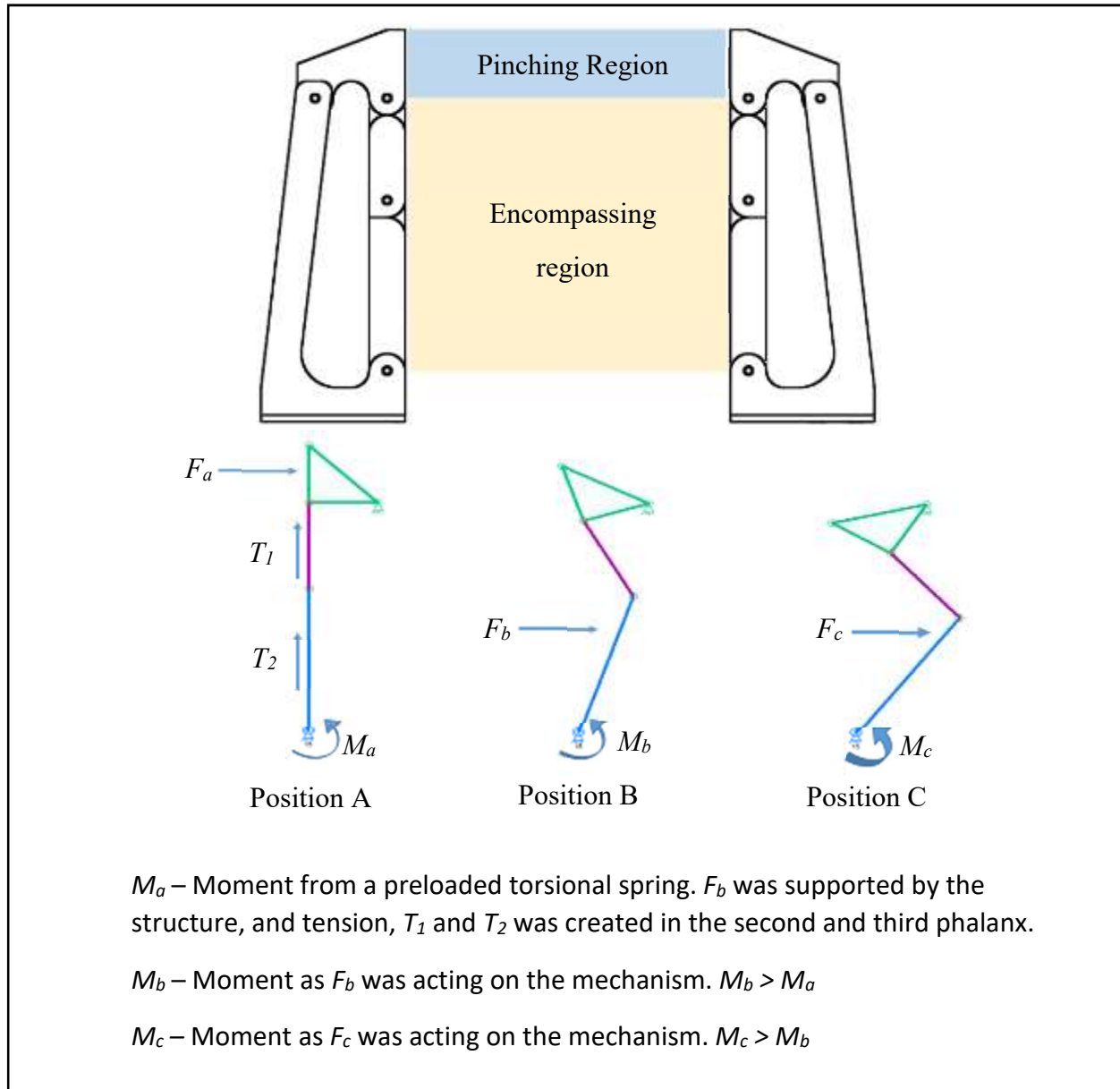


Figure 3.15: Top image identifies the pinching and encompassing the region of the aFinger. The pinch region was directly above the pivot tip, and the encompassing region was between pivot tip and pivot base. The line image shows the linkage reaction when external force applied to them.

The aFinger was moving in parallel, it did not require curling movement, and it still had pinch and encompassing separation, which all these characteristics make the aFinger easy to do grasp planning. The pinch grasp planning was direct. Viewing from the fingertip, when grasping, it moves in a straight line, for other adaptive fingers, the movement was a curve. This means that the

grasp planning needs to position the gripper according to the width of the target object, to acquire accurate contact point.

From the line image of Figure 3.15, it had the finger in three different positions; position A , B and C . Position A was when the force was above the pivot top. When the external force F_a was applied, it creates a moment on pivot fingertip that will rotate and result in T_1 and T_2 , T was the sum of T_1 and T_2 . It the total tension, T , plays an essential role in aligning all the phalanges and allowing a parallel grasp in the pinch region. Position B and C explain the forces F_b and F_c , and moments M_b and M_c , $F_b < F_c$, and the results $M_b < M_c$. M_a was the constant torque provided by a torsional spring, and the spring was essential to return one of the linkages to the original position. As it was known for four bar linkage with one DOF, when one linkage returns to the position, another linkage will also follows. This was important because it gives the designer freedom during scaling of the finger.

Thus, it can be summarised that the capabilities of the aFinger, which also reflected the main novelties of the aFinger as follows: -

- a. Mechanisms that works in parallel motion that perform pinch and encompassing grasp.
- b. Underactuated design: The design only uses one spring to ensure finger mechanism return to the original position after release grasp.
- c. Scalability: Design grasping force to be supported by finger structure instead of spring.

4. EXPERIMENT AND EVALUATION

The experiments were designed to evaluate the performance of the aFinger: -

1. Pinch and encompassing grasp capability;
2. Quality of grasp (by measuring the number of contacts formed);
3. Scalability.

For the first experiment, the author wanted to find out if the aFinger attached to a parallel gripper can adapt to the object different geometrical attributes. In scalability experiment, he had experimented with two different setups with aFinger in different sizes, one small and one big. This experiment was to show if the mechanism can work even in different size. To evaluate the quality of grasp, he looked at the number of contact points between the fingers and the target object. With the experiments conducted using mechanical prototype, picking items with different shapes and sizes, he had concluded on the performance and capability of the aFinger to be effective with results showing the encompassing grasp forming 3 and more contact points.

4.1 Experiment to Validate the First Prototype

For the experiment, a set of aFinger had been 3D printed to be evaluated to find out if any weakness can be found in the initial experiments. The objective of this experiment was really to find out the initial performance of the designed fingers.

Figure 4.1 shows the eight items had been chosen that had a unique characteristic that the author think was suitable for this initial experiment to find out the performance of the aFinger. These items consist of cylindrical, block, cone, soft and irregular, which covers all the general shapes of the items that are to be grasped.



Figure 4.1: The chosen eight items used for first experiments.

Figure 4.2 shows the 25 items that Amazon Picking Challenge 2015 used during the competition to validate the state-of-the-art grasping from the top institute from all around the world [4]. The items were used as a reference for this experiment. However, the author simplified it by categorising the items based on the shapes. Figure 4.1 shows the selected items and Table 4.1 shows the shape category of the items.



Figure 4.2: The items used for Amazon Picking Challenge in 2015. A similar class of items were used in 2016 and 2017. The numbers indicate the additional scores due to the complication (defined by Amazon) in grasping those objects [4].

The gripper will perform grasping from the front instead of from the top down. From observation of warehouses, the items were placed on the shelves instead of baskets. It was more common for the logistic warehouse to store the items in the shelf where the manipulator needs to approach the items from the front of objects rather than top down. Thus, for this experiment, the item grasping will be performed from the front of the object.

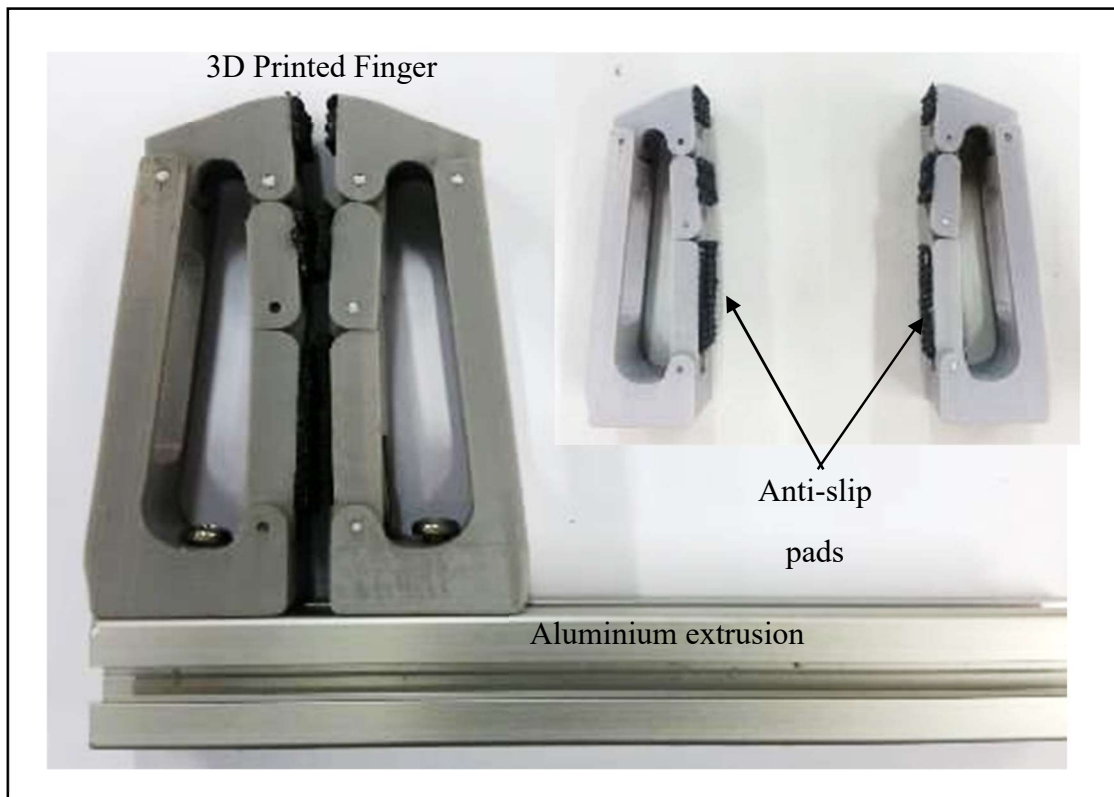
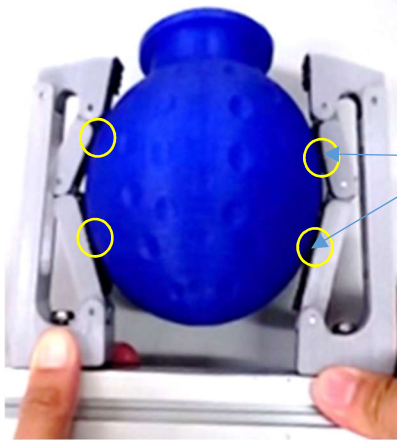


Figure 4.3: 3D printed aFinger mounted on an aluminium bar for parallel movement and shown the anti-slip pads.

Figure 4.3 shows the prototype mounted on the aluminium bar to simulate the parallel movement of the fingers. Also, the fingers were mounted with anti-slip pads to simulate all the adaptive grippers available in the industry. It was essential to have the pads to increase the frictional coefficient and prevent the direct metal contact from preventing surface damage of items [40].

For the experiment, the author was also evaluating the pinch and encompass the region of the finger. In the case of precise vision feedback, it was possible to plan for grasping at pinch or encompass region. At times where gripper needed to compensate for the error made by computer vision, the author also wanted to evaluate the performance of the adaptive finger when grasping in a random location (pinch, encompass or in between pinch and encompass region). For the details of the region, it was shown in Figure 3.15.



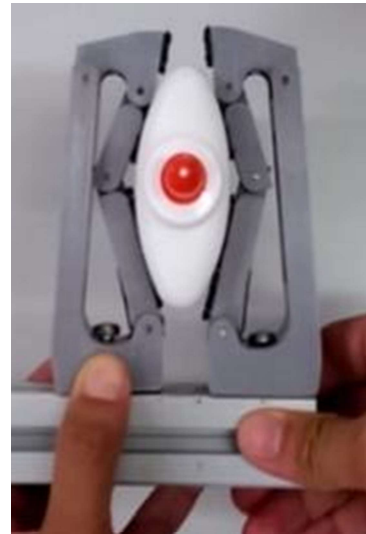
1. Clamp the object with the adaptive finger (for prototype one, only estimated force using fingers to hold the items. For prototype two, constant force of 20 N were applied on the item).
2. Object were lift away from the table upwards until the it was fully supported by the fingers.
3. Visually, count the contact points of the object with the adaptive fingers (in this case, four contact points were observed).
 - More images at Appendix A.5.



Picking the school glue at standing position at random orientation and grasping region. From observation, four contact points formed,



Picking the school glue at standing position at pinch region. Two contact points were formed.



Picking the school glue at standing position at encompassing region. four contact points were formed.

Figure 4.4: Example of grasping an irregular shaped' object; 4.4a was picking the object randomly and landed at the encompass position; 4.4b was grasping at pinch region, and 4.4c was picking at the encompassing region.

Figure 4.4 shows an example of how the finger was acting on the school glue, an oval like object. This setup of the gripper had been tested many times, and the results were as predicted. The images of the results were shown in Appendix A.5 and the grasp contact formed was presented in Table 4.1.

Table 4.1: Grasping results from the 3D printed prototype. It shows the contacts formed from the grasping.

Picking at Random Region								
Object name	Shape Characteristics	Contacts Formed from Attempts						Average number of contacts
		1	2	3	4	5	6	
Safety glasses	Oval	4	6	6	5	4	4	5
School Glue	Cylinder	4	3	2	4	4	2	3
Sticky note	Rectangular	2	2	4	6	4	4	4
Stack of cups	Conical	4	4	4	2	4	4	4
Soft toys	Irregular	2	4	4	4	4	2	3
Ducks toy	Irregular	4	4	2	4	2	4	3
Plastic cups	Cylinder, irregular	4	4	4	4	2	2	3
Tin of snacks	Cylinder	4	4	4	2	4	4	4
Picking at Pinch Region								
Object name	Shape Characteristics	Contacts Formed from Attempts						Average number of contacts
		1	2	3	4	5	6	
Safety glasses	Oval	2	4	4	2	2	2	3
School Glue	Cylinder	2	2	2	2	2	2	2
Sticky note	Rectangular	2	4	2	4	4	2	3
Stack of cups	Conical	2	2	2	2	2	2	2
Soft toys	Irregular	2	2	2	2	2	2	2
Ducks toy	Irregular	2	2	2	4	4	2	3
Plastic cups	Cylinder, irregular	2	2	2	2	2	2	2
Tin of snacks	Cylinder	2	2	2	2	2	2	2

Picking at Encompass Region								
Object name	Shape Characteristics	Contacts Formed from Attempts						Average number of contacts
		1	2	3	4	5	6	
Safety glasses	Oval	4	6	6	5	4	4	5
School Glue	Cylinder	4	4	4	4	4	4	4
Sticky note	Rectangular	4	4	4	6	4	4	4
Stack of cups	Conical	4	4	4	4	4	4	4
Soft toys	Irregular	4	4	4	4	4	4	4
Ducks toy	Irregular	4	4	4	4	4	4	4
Plastic cups	Cylinder, irregular	4	4	4	4	4	4	4
Tin of snacks	Cylinder	4	4	4	4	4	4	4

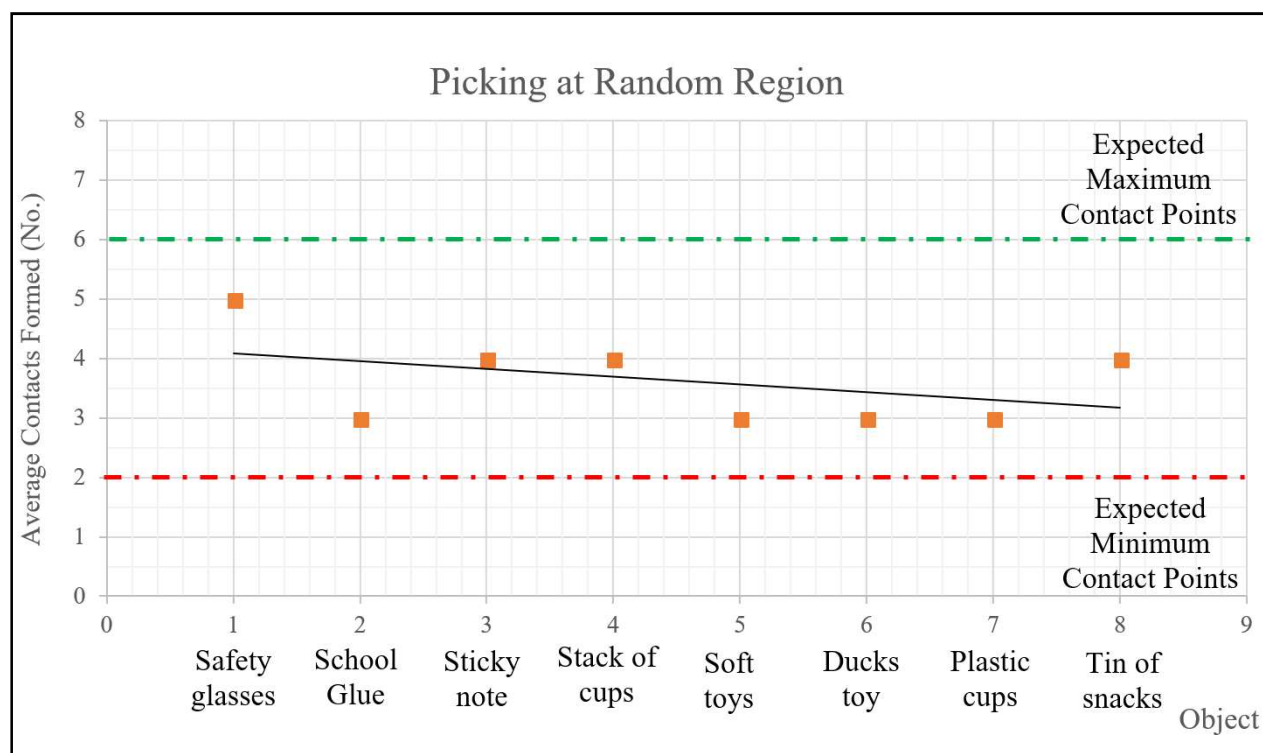


Figure 4.5: 3D printed aFinger results of contact formed, picking in the random region.

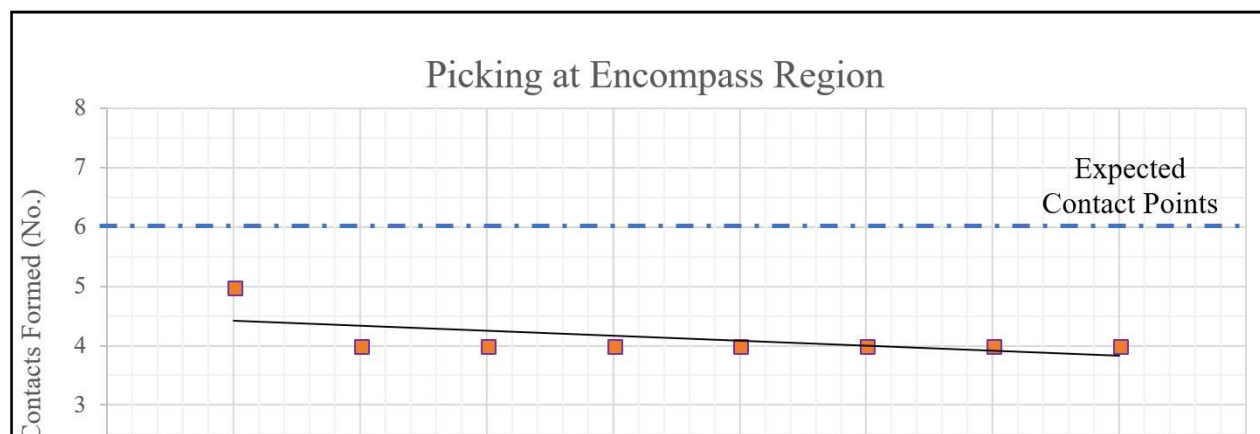


Figure 4.6: 3D printed aFinger results of contact formed, picking at pinch region.

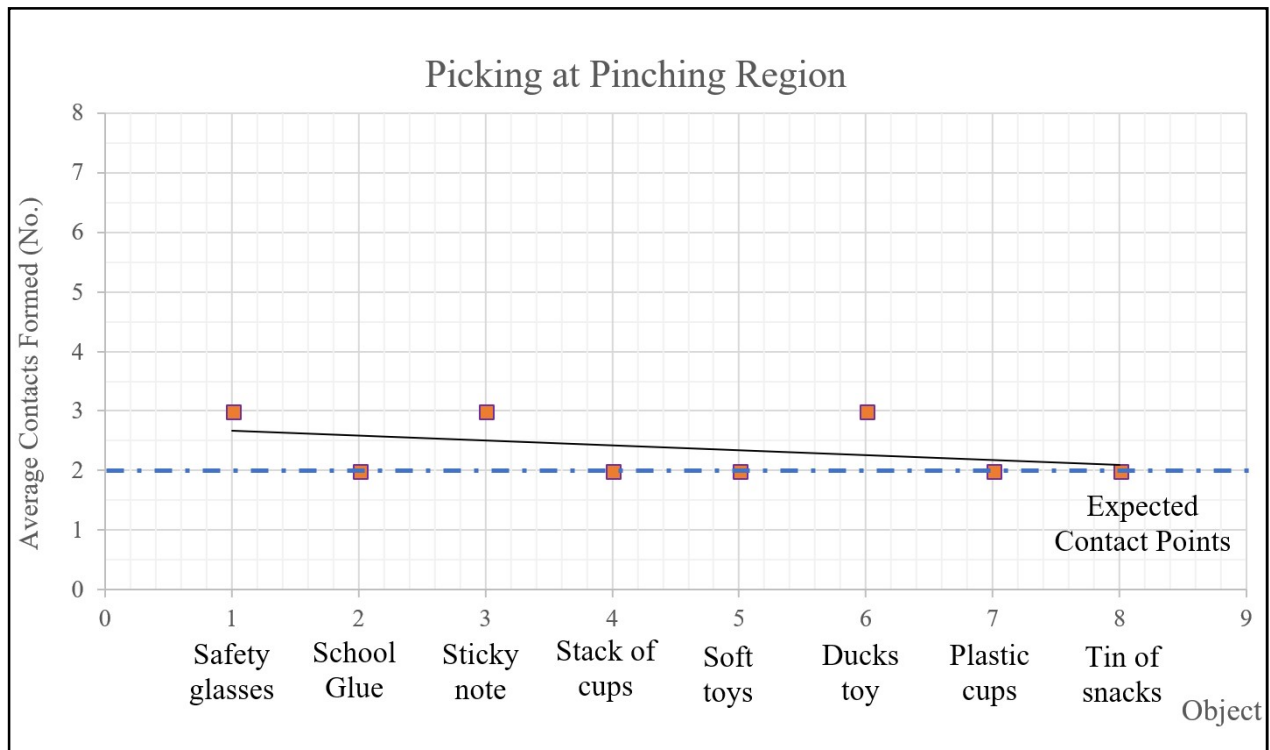


Figure 4.7: 3D printed aFinger results of contact formed, picking at encompass region.

Figure 4.5, Figure 4.6, and Figure 4.7 show the contact points form during the experiment plotted from the data in Table 4.1. Figure 4.5 shows the graph when the gripper was grasping in the random region of the finger. In Figure 4.5, it had two lines, the expected maximum contact points at six, and the expected minimum contact points at two. It had two lines because the gripper

was picking from the pinch and encompass, which had expected two and six contact points respectively. For all the times, the contact points formed observed were in the average of four contact points

Figure 4.6 shows the graph when the gripper was grasping at the pinch region, and in the graph, there was one line that indicates the expected contact points at two. The contact points were predicted to form two contact points because the author purposely using the pinch region which had supposedly to have two parallel phalanges to make contact at the centre of the target object assuming the centre of gravity of the target object was at the centre of the object. However, the grasping contact formed for all the items have an average of two contact points. Some objects at pinch region have four contact points because the object length was longer than the phalanges at the pinch region, forcing the object to form contact with the intermediate phalanges.

Figure 4.7 shows the graph when the gripper was grasping at the encompassing region, and in the graph, there was one line that indicates the expected contact points at 4. All objects grasped had 4 or more contact points. Some objects had more than four contact points because the length of the object was longer than the intermediate and distal phalanges, extending to the proximal phalanges forming. The contact point formed were above the expected at four contact points on average, performing slightly above the expected value.

As expected, all the results shown were above or within the expected values. In summary, the fingers were able to grasp all the items with confidence. However, there were some improvements noted and included in the second prototype.

4.2 *Experiments to Validate the Improved Version*

In this experiment, a set of aFinger was being fabricated that was being attached to a servo driven parallel gripper. Appendix A.1 shows the dimension of the adaptive fingers. The gripper had a total opening of 50 mm and grasping force of 20 N. Figure 4.8 shows the finger comparison between the standard ABB YUMI [46] parallel gripper fingers and the version adapted with aFinger.



Figure 4.8: Comparison of the first rigid fingers and aFinger; and at the bottom, the comparison of a size difference of fabricated aluminium aFinger and 3D printed aFinger.

To evaluate the adaptability, it had a set of 3D printed fingers that was 100% scaled up, attached to an aluminium extrusion to simulate the parallel movement. From the grasping evaluation using the finger with different sizes (small aluminium fingers and the larger 3D printed fingers), it will be discussed on the grasp quality by the number of contact points, between the fingers and the target object.

For the target object, general shaped items were picked which were cylinder (used both thin and thick version to test the finger grasp capability), triangular, boxed-like, multi-edges (more than 5 edges, and for this purpose, the octagonal shape object was chosen for this experiment), and sphere (which had tapered surface compared to cylinder shape). The items were as listed in Figure 4.9.

All objects were secured, and able hold on with 20 N of gripping force. The objects were held down, with the gripper at perpendicular to the floor. If the grasp quality was reduced, the object will drop or slip. The object was trying to be pulled down from the grasp to test the grasp quality; all objects were held firmly and hard to pull out. If the objects were pulled out forcefully, the gripping material would damage.

Similarly, the objects will be approached from the front and performed in random, pinch and encompass region, closing at the centre of the target object. The end-effector was programmed

to move to a fixed location, and when executing grasping, it will remain fully closed until it reaches 20 N.

4.3 *Qualitative Experimental Results*

From Figure 4.8, observation can be made to see the behaviour of aFinger in a pinch and encompass grasp. The aFinger can perform the pinch and encompass grasp, even when it was scaled up the finger joints to 100%. The aFinger behaves as the author predicted and mentioned.

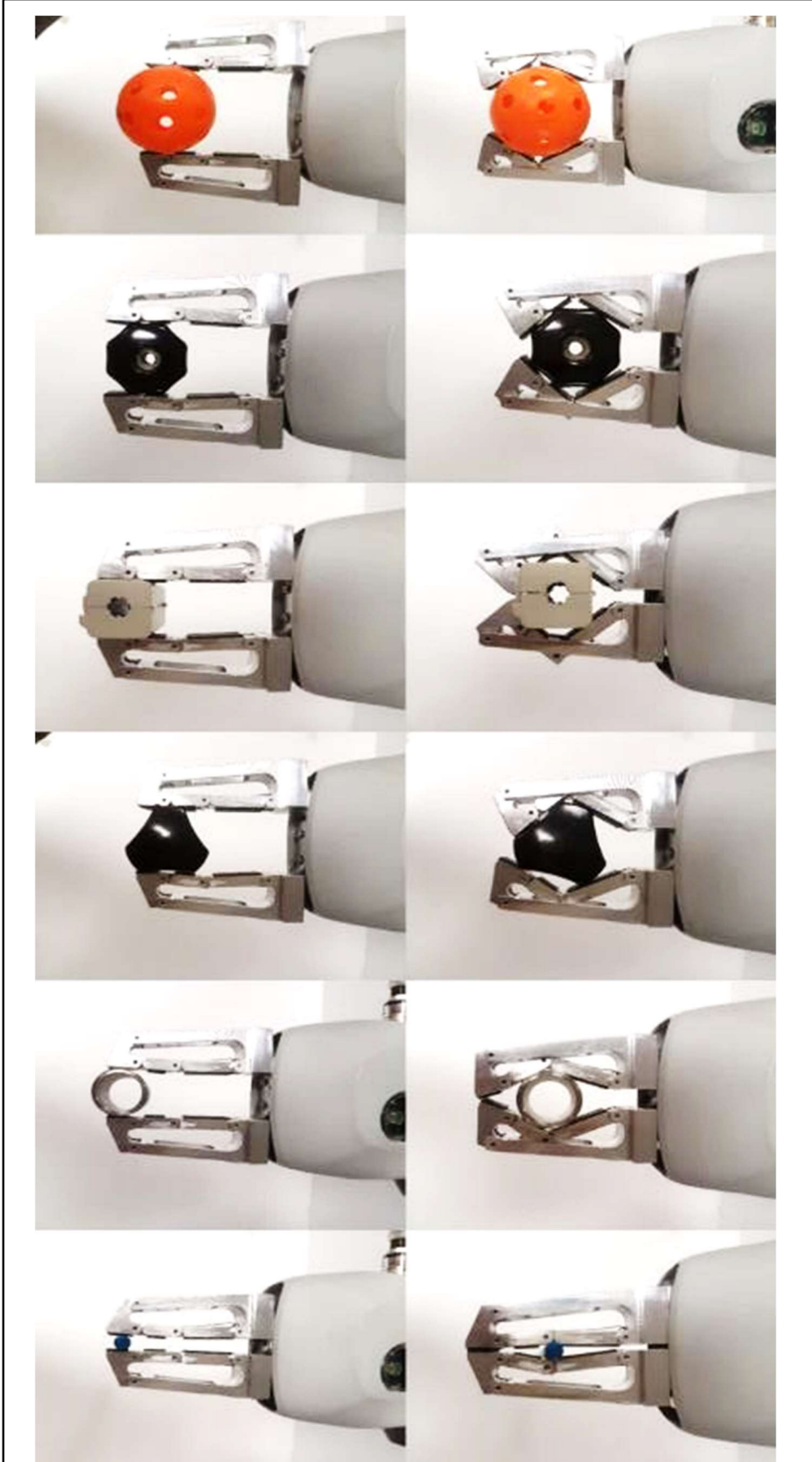


Figure 4.9: The experimental results using six items; from left, cylinder hollow (represent small diameter), cylinder hollow (represent large diameter), triangular knob, box, octagonal knob, hollow rigid sphere. The top row was demonstrating the pinch grasp and bottom row were encompassing grasp.

Table 4.2: Grasping results from the improved version of the prototype. It shows the contacts formed from the grasping.

Picking at Random Region								
Object name	Shape Characteristics	Contacts Formed from Attempts						Average number of contacts
		1	2	3	4	5	6	
Cylinder Pin	Cylinder, small	4	4	2	4	4	4	4
Cylinder Hollow	Cylinder, lager	4	4	4	4	2	2	3
Triangular Knob	Irregular	3	4	6	5	4	3	4
Box	Rectangular	4	4	4	4	4	4	4
Octagonal Knob	Octagonal	4	4	6	4	4	6	5
Hollow Rigid Sphere	Sphere	2	2	4	4	4	2	3

Picking at Pinching Region								
Object name	Shape Characteristics	Contacts Formed from Attempts						Average number of contacts
		1	2	3	4	5	6	
Cylinder Pin	Cylinder, small	2	2	2	2	2	2	2
Cylinder Hollow	Cylinder, lager	2	2	2	2	2	2	2
Triangular Knob	Irregular	3	4	4	3	3	4	4
Box	Rectangular	4	4	4	4	4	4	4
Octagonal Knob	Octagonal	4	4	4	4	4	4	4
Hollow Rigid Sphere	Sphere	2	2	2	2	2	2	2

Picking at Encompassing Region								
Object name	Shape Characteristics	Contacts Formed from Attempts						Average
		1	2	3	4	5	6	
Cylinder Pin	Cylinder, small	4	4	4	4	4	4	4
Cylinder Hollow	Cylinder, lager	4	4	4	4	4	4	4
Triangular Knob	Irregular	4	5	4	6	5	4	5
Box	Rectangular	4	4	4	4	4	4	4
Octagonal Knob	Octagonal	6	6	6	6	6	6	6
Hollow Rigid Sphere	Sphere	6	6	6	6	6	6	6

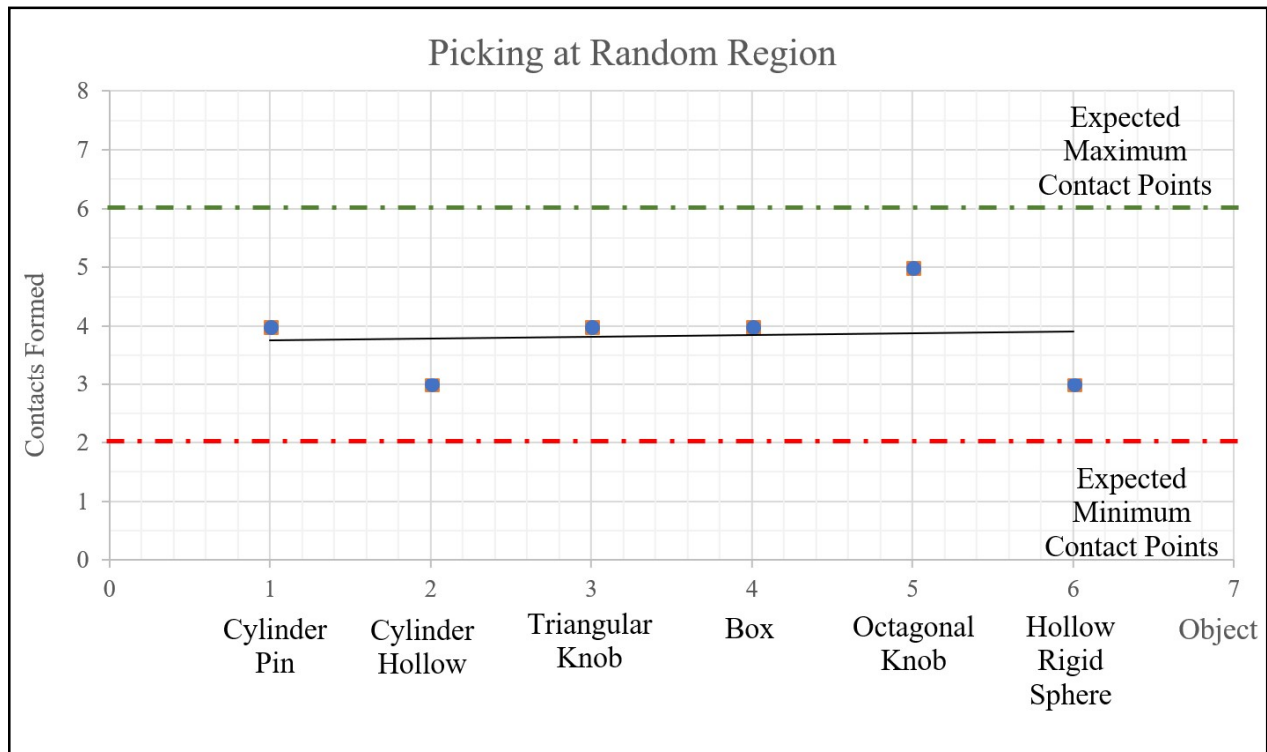


Figure 4.10: Fabricated aFinger results of contact formed, picking in the random region.

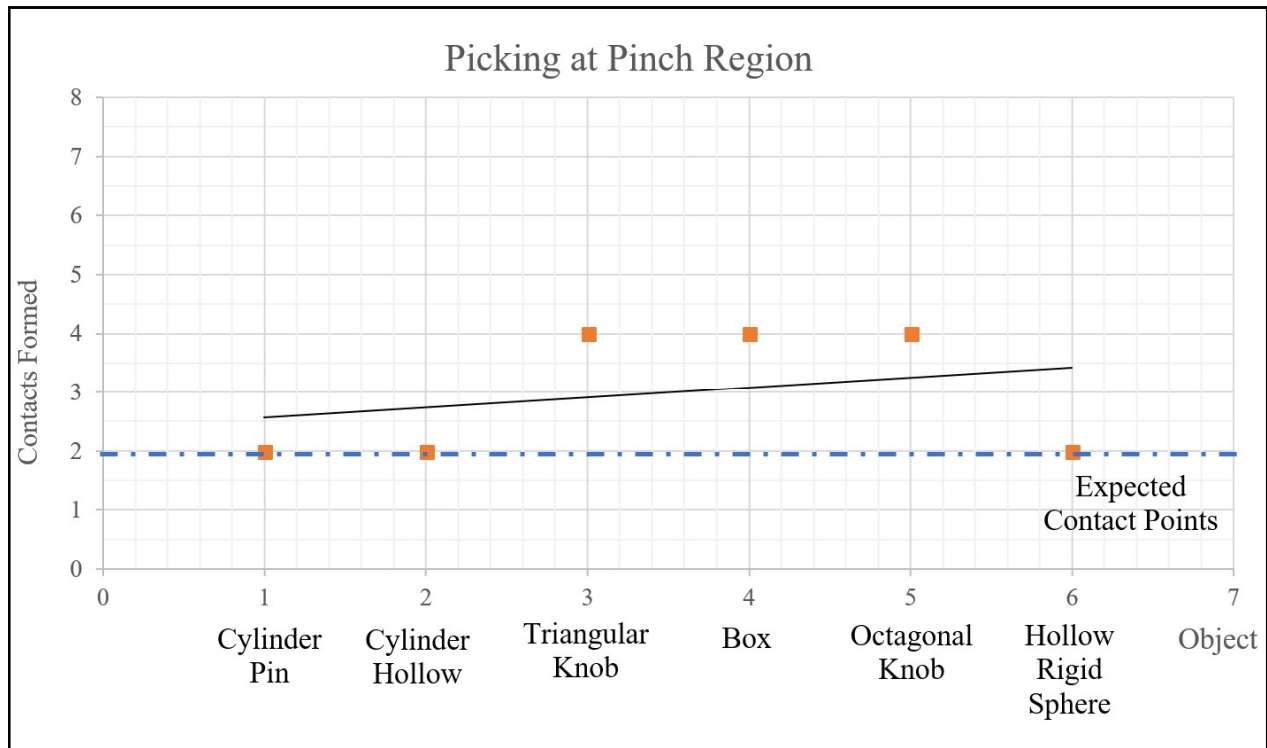


Figure 4.11: Fabricated aFinger results of contact formed, picking at pinch region.

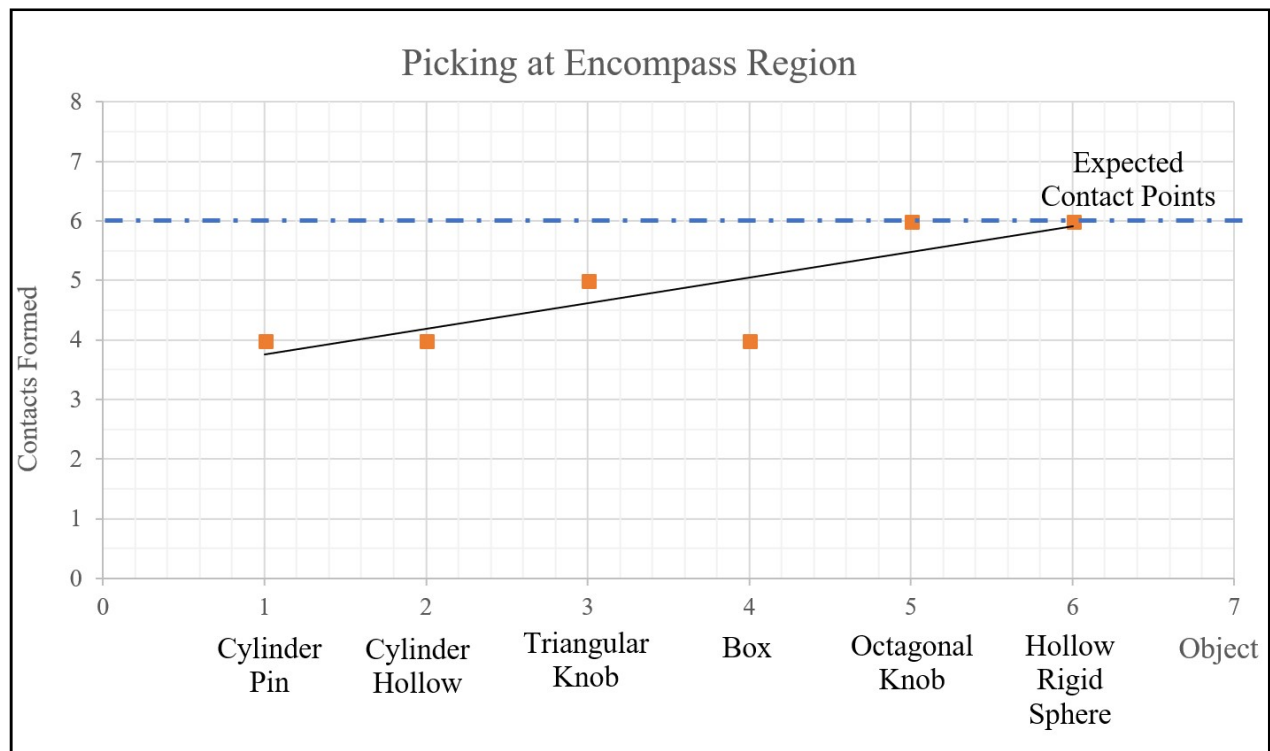


Figure 4.12: Fabricated aFinger results of contact formed, picking at encompass region.

Figure 4.10, Figure 4.11 and Figure 4.12 show the contact points form during the experiment plotted from the data in Table 4.2. Figure 4.10 shows the graph when the gripper was grasping in the random region of the finger. In Figure 4.10, it had two lines, the expected maximum contact points at six, and the expected minimum contact points at two. It had two lines because the gripper was picking from the pinch and encompass, which had expected two and six contact points respectively like the initial experiment for the 3D printed fingers. The contact points formed observed had on average four contact points. This shows that when using the gripper, at a random position, three or more contact points are formed.

Figure 4.11 shows the graph when the gripper was grasping at the pinch region, and in the graph, there was one line that indicates the expected contact points at two. Similarly, the contact points were predicted to form two contact points because the robot was programmed to move the

centre of the target object at the pinch region. However, the grasping contact formed for all the item on average three contact points. Likewise, some objects at pinch region had four contact points formed because the object length was longer than the phalanges at the pinch region, forcing the object to form contact with the intermediate phalanges.

Figure 4.12 shows the graph when the gripper was grasping at the encompassing region, and in the graph, there was one line that indicates the expected contact points at four. The contact point formed were above the expected at five average, performing slightly above the expected value. All objects grasped had 4 or more contact points, and some objects had more than four contact points due to the size.

4.3.1 Summary of Experimental Results

From all the results compared with the prototype and the fabricated fingers, both sets of fingers can perform encompassing and pinch grasp. From both the experiments, it was consistently observed that the more significant objects formed more contact points. From the list of items, one can observe that there were only two contact points when grasping a hard object if he was using the first parallel fingers, and as well as the pinch grasping with the adaptive fingers. The encompassing grasp will create a minimum of three contact points for the asymmetrical objects.

The prototype was tested on a set of items which were different from the set of objects used with the fabricated fingers. The comparison of performance was not directly comparable; however, both set of objects had similar attributes. Due to the sizes of the fingers were different; therefore the objects for the experiment were different. The performance of both prototype and fabricated

fingers were good and formed some contacts within expectation forming 3 and more contact points when performing encompassing grasp.

The author also noticed the ease of control and behaviour prediction of the aFinger for pinch and encompassing grasp, and this will significantly help when he was integrating computer automated grasp planning. The gripper only involved open and close motions; thus for good grasp quality, it was wholly dependent on the design of the finger joints. For aFinger, the torsional spring was placed in front of the front joints. Even though the joint was not easily formed due to the torsional spring, it became an advantage to have a balanced grasp. With the added advantage, each grasp was ensured to be appropriately aligned with the centre before encompassing was performed. As mentioned in chapter 2.2, the more grasping contact points, the better the quality of grasp. From the experiment, he can see that each item was grasped firmly without causing any rotation or shear.

5. DISCUSSION, CONCLUSION, FUTURE WORK

5.1 *Discussion and Conclusions*

From the literature review process, the author found that the design of an adaptive finger can be involved such as the Robotiq gripper three fingers that had more than ten parts in one mechanism [6, 12], and more straightforward adaptive gripper such as the Festo Fin Gripper [23, 24]. All these adaptive grippers can achieve the objective of encompassing and pinch grasp. However, from the step-by-step design process, the author found the by manipulating the length of each phalange, it dramatically affects the performance of the finger. Adaptive fingers that had $1:1:1$ ratio will have a room for improvement [28, 29, 30]. This means that the length of the phalanges still can be optimised as shown in aFinger which has phalanges of 2:3:5 ratio.

From the experiments, the fingers were able to demonstrate stable grasping, forming three to six contact points across all the object types which consist of the typical boxes and irregularly shaped objects. From Figure 4.10, Figure 4.11 and Figure 4.12, the results show that the number of contacts formed was within the predicted range. The prototype fingers and fabricated fingers also show the fingers can be easily scaled in two different sizes.

With the adaptive finger, instead of getting new adaptive gripper, the current parallel gripper can become an adaptive gripper, just by replacing the stiff fingers with aFinger. The author believes that the aFinger will give a new life to all the existing parallel gripper. Besides that, low cost adaptive parallel gripper can be developed to serve the industry that requires automation involve object of many varieties. From the results, it was found that the aFinger can perform adaptive grasping as effective as an existing two-finger adaptive gripper.

The proposed finger formed more contact points on specific object shapes which does help

to manipulate the object better. The extra contact points eliminate some degree of freedom (depending on the location). For instance, in manipulating a cylindrical object, the centre of gravity of the object was changing as the gripper manipulates the position and orientation of the cylinder. A two contact points grasp on the cylinder was compared with a three contact points grasp. It was found that the two-contact point grasp will likely allow the cylinder to rotate as the centre of gravity shift. Thus, with the adaptive finger, that form encompasses grasp (more contact points formed) will help gripper to manipulate objects better.

Currently, the aFinger was being used for an experiment for automated picking in a hospital pharmacy environment, where it was common for the pharmacist to collect the medicine from racks manually. The aFinger was suitable for this application because there was the requirement of having a general picker that can handle boxes, bottles, soft packages, irregularly shaped items such as feeding spoon and syringes and so forth Figure 5.1 shows some of the examples of aFinger adaptive effectiveness.

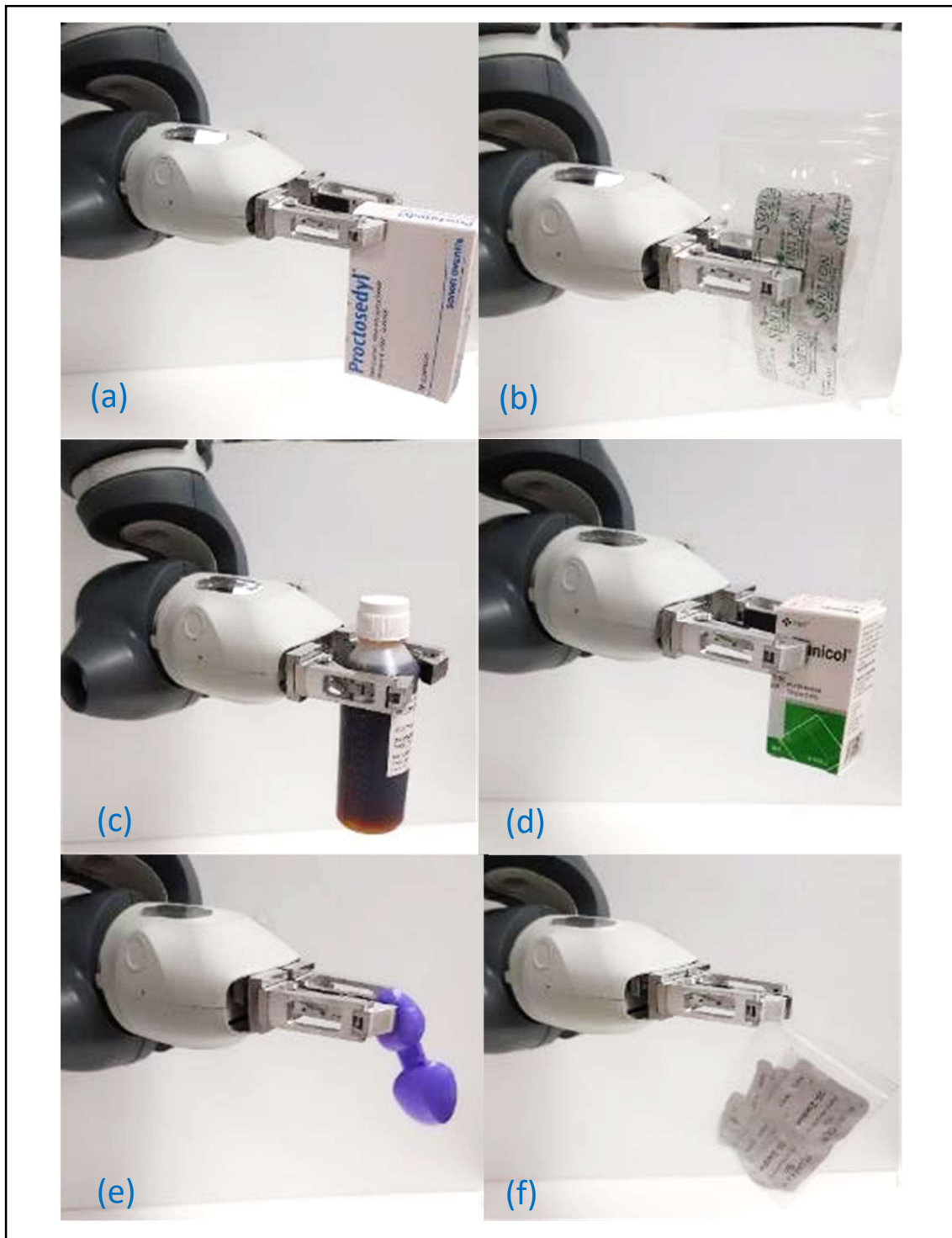


Figure 5.1: The adaptive finger was attached to the servo parallel gripper. From top left to right bottom, observation can be made that the gripper securely: - a) grasps on medium size pill box; b) grasp on the strip of pills; c) cough syrup bottle; d) pinch on the packet of pills; d) eye drops in a box; e) cough syrup feeding spoon; and f) grasp on the bag of pills.

5.2 *Contributed Results*

The author had completed the literature review and studied the state-of-the-art technologies of adaptive grippers such as the cable driven and soft robotics. From the studies, the summary of the adaptive grasping method includes encompassing grasp and pinches grasp to enable the adaptive gripper to grasp a wide range of items.

The author had designed a new adaptive finger for this application. Using 3D modelling and linkage design application the design of the finger was being optimised. By using the additive technology 3D printing, the prototype was made quickly and evaluated. This allows fast design iterations thus further improvised on the adaptive finger design. Lastly, a scaled down version was made to test out the scalability of the adaptive fingers.

The author also filed a Technology Disclosure, and they had been granted a patent for the adaptive finger [48]. The product came from the project had generated interest from several users. Thus, the patent had been extended for the second year. From this work, a paper was published [49].

5.3 *Future Works*

The current achievements of the research work may still have room for improvement and innovative applications to transform the adaptive finger, making it functional and applicable to a different type of parallel grippers. The parallel grippers can be in different sizes or in a different number of fingers. The current work still needs additional validation specifically in usage variation and more tests to affirm grasp quality and scalability. The future work was listed as follows: -

Scalability: The work on the scalability can be done by leveraging on the mechanical advantages found in this design. The possible application that could be explored including; in microscale for performing surgery; or large-scale gripper for handling construction parts such as building pillars. Other than just considering the scale of the adaptive fingers, the application of the gripper was also essential. For instance, mechanical design challenges for a microsurgery application which requires high precision and almost zero backlash mechanisms. The fingers were mainly an extension of the manipulator and the parallel gripper. The precision and backlash control of the overall robotic arm were depending on the manipulator and the parallel gripper. Thus, the adaptive finger with good tolerance control should be able to do the job. Other than that, it was also possible to scale in terms of some fingers used per gripper. Current experiments only conducted with only two fingers per gripper. For future work, it was possible to make it work on three-finger or four-finger parallel gripper [9].

Industrial Validation: The author was making an effort to get the industry to try and adapt the invented adaptive finger; by writing to companies and speak to companies at conferences, as the patent had been filed for the two years [50]. The adaptive finger was getting attention and interest;

thus, the patent was getting extended. On the other hand, the downside of this was that the patent does not allow us to do any publication regards to the adaptive finger mechanism. Even after the completion of this project, the author will still work hard to ensure the adaptive finger was pushed out to the market to benefit the various industry.

Autonomous Grasp Planning: The design of the finger allows centre justified, left or right justified grasping. This means the adaptive fingers allow flexibility in grasp planning. The grasp planning software can do the grasping with more offsets; it does not constrain to just grasping from the centre. This feature was especially useful for grasping objects in the clustered environment. Also, the distinct grasp region that differentiates encompassing and pinch grasp helps in classification of grasp planning. Future work could be implementing mentioned classification to show the ease of programming and consistency in using adaptive parallel gripper.

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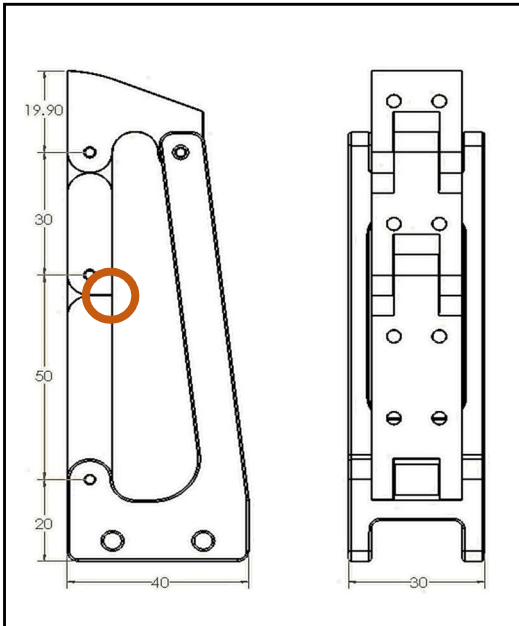
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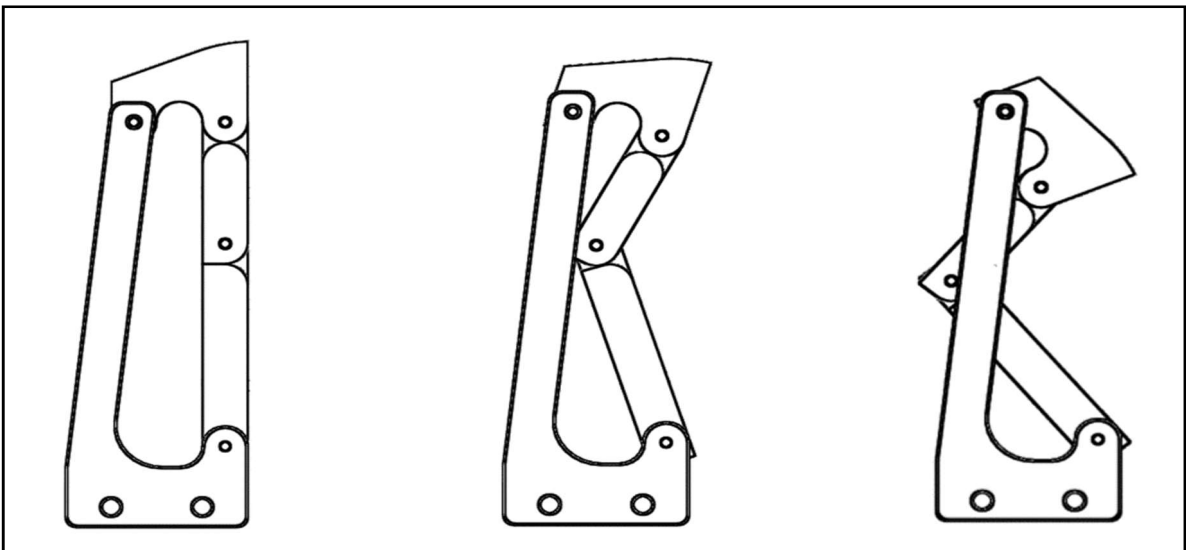
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APPENDIX

Appendix A.1 - Dimensions and characteristic of the aFinger

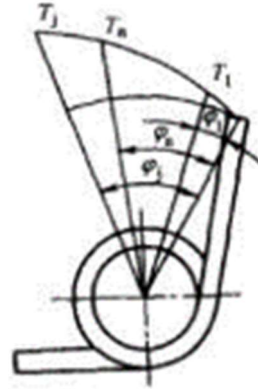
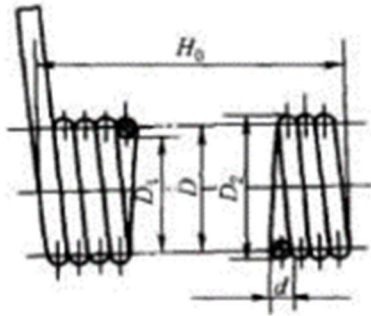


1. The general dimension of the aFinger, where the ratio of the three phalanges were 2:3:5.
2. The length of the finger should always be minimised to prevent deflection at the end of the finger. The finger length of each phalanx would be 2:3:5 of total length.
3. The width of the finger can be scale depending on the application.
4. The circled area on between the second and third phalanx was a feature to ensure when returned to original position, the finger was always straight.



- These images show the dimension of an aFinger and the simulated movement of the aFinger. From left to right, the aFinger was at the idle position and progressively reaching the

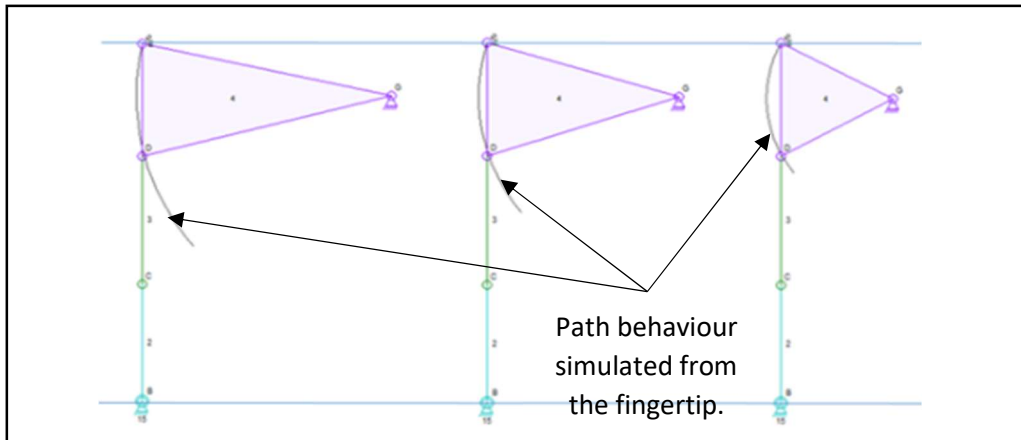
Appendix A.2 - Parameters of spring design



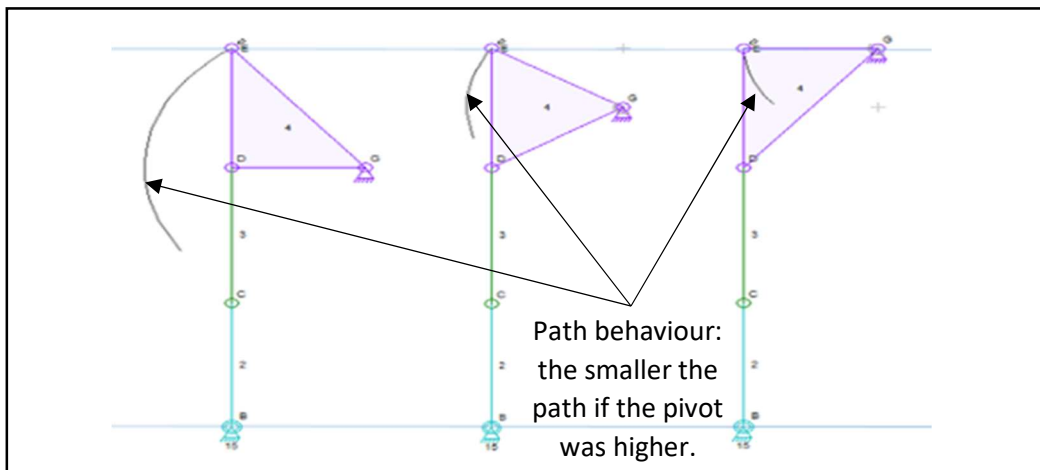
Parameters of spring design

Item	Unit	Formulas
Diameter, d	mm	$d \geq \sqrt[3]{\frac{32T_n K_1}{\pi \alpha_{Bp}}}$
number of active coils, n		$n = \frac{Ed^4 \phi}{3667D(T_n - T_1)}$
Rigidity, T'	$N \cdot mm / (^\circ)$	$T' = \frac{Ed^4}{3667Dn}$
Minimum working torque, T_1	$N \cdot mm$	$T_1 = T' \phi_1$
Torsion angle when with the maximum torque, ϕ_n	$(^\circ)$	$\phi_n = \frac{T_n}{T'}$
Limiting torque for operation	$N \cdot mm$	$T_j = \frac{\pi d^3 \alpha_j}{32K_1}$
Limiting torsion angle for operation	$(^\circ)$	$\phi_j = \frac{T_j}{T'}$
Spacing, δ	mm	$\delta = 0.5 \text{ mm}$ (without special requirements)
Pitch, t	mm	$t = d + \delta$
Free length, H_0	mm	$H_0 = nt + d$
helix angle, α	$(^\circ)$	$\alpha = \arctan \frac{t}{\pi D}$

Appendix A.3 – Linkage simulation: Varying the linkages parameter to study the performance and behaviour of the finger.



It was when varying the distance from the pivot point; the author was able to study the resultant finger path. The further the pivot, the smaller the path that crosses the parallel line.



Varying the high of the pivot point, and found that with the same distance, the higher the pivot point, the smaller the path that crosses the parallel line.

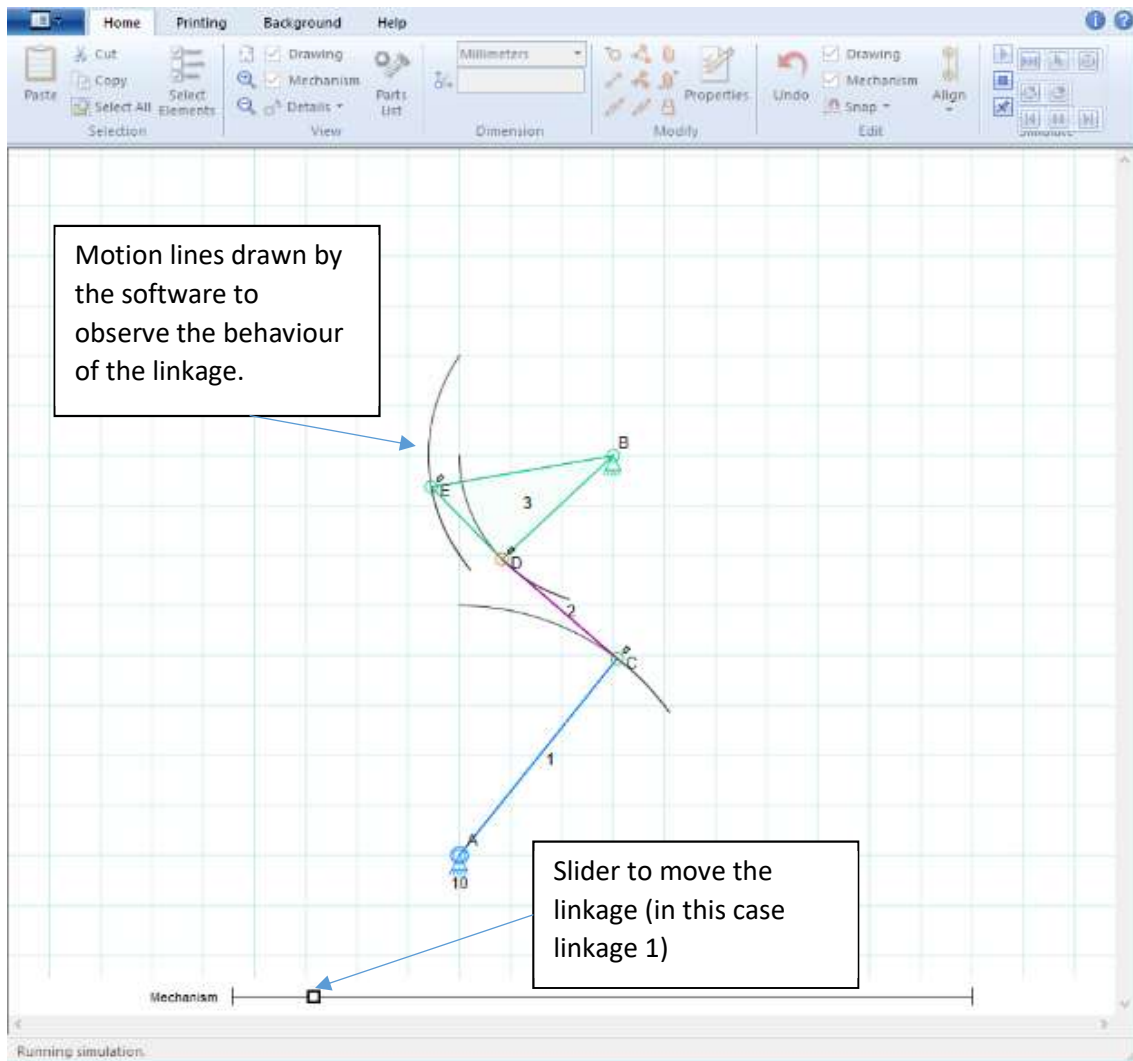
- These images show that the linkage points and length were being varied and the path of the fingertip was studied. The final aFinger prototype was the product of the first iteration forms the simulation.

Appendix A.4 – Images of prototype performing grasping.



- Appendix A.4 shows the collection of images of the prototype finger grasping the target objects. The selected photos were the one the author thinks were unique.
- From the images, observations can be made on the contact formed; 2 to 6 contact points formed on the target object.

Appendix A.5 – Linkage: The software for the linkage simulation study.



- The linkage simulation software can be found online [40]. Alternatively, a paid version SAM Mechanism design software also available if more options such as graph and analysis results needed [52].