Design of a gripper for bunches of bananas

Design and evaluation of a gripper for bunches of bananas in a supermarket environment

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by

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Preface

This report is my final work as a student Mechanical Engineering at the TU Delft. For my minor Robotics I built a cucumber picking robot and since then my interest for agricultural technology has only increased. Therefore I was very happy with this assignment where I could combine working as a design engineer and my interests for the AgTech sector.

I want to thank my supervisors prof.dr.ir. J.L. (Just) Herder and Ad Huisjes for their support and supervision during my research, they have been helpful, optimistic and enthusiastic through the whole process. Furthermore I want to thank AIRLab for their inspiration for the assignment. Lastly, I want to thank my friends and family for their support, not only during the research for my thesis, but through the whole study. I'm very happy about all the people I've met and friends I've made during my time in Delft.

Anne van der Star
Den Haag, October 2022

Contents

Chapter 1

Introduction

In this research a gripper for bunches of bananas is designed and evaluated. Until now, there existed no gripper that can grasp whole bunches. The technology in the agricultural sector is upcoming as a result of growing population and decreasing amount of people who want to work in the sector. Automation in the sector comes with new challenges that were not found in other environments. The randomness in shape and size of products, but also environments makes it hard to implement robotics which excels in repetitive tasks. However, these challenges test engineers again on their creativity to cope with these environments. The fast development of software of the last century helps massively to overcome them, but cannot solve all the problems. Therefore, smart mechanical solutions can improve the system and decrease its limitations.

In this research the mechanical design of a gripper will be presented and evaluated in 7 chapters. In these chapters the design and evaluation of a gripper for bunches of bananas will be discussed. In chapter 2 can be read about the scope of this design assignment. Chapter 3 is a separate research paper on the sensitivity of fruit and how to take that into account when designing a gripper. Chapter 4 is about the location where to grasp the bunch of bananas on the bunch itself, using the assignment and knowledge about fruit bruising. Chapter 5 is about the design method, the several prototypes are presented and discussed. Chapter 6 exist out of a paper on the features and the evaluation of the chosen prototype and finally, in chapter 7 the conclusion of this research can be read.

Chapter 2

Assignment and scope of this research

The use case of this research is how to grasp a bunch of bananas out of their box with a robot arm, move them and put them in a basket or on a shelf (Figure 2.1). The boxes the bananas come in are always filled in the same manner, the bananas orientated with the top to the same direction. The bunches are rotated around their z-axis. The box can be opened in both directions, either with the peduncles upwards or downwards.

Figure 2.1: *Goal of the gripper*

The scope of this assignment includes only the gripper and the actuation of the gripper. The functioning of the robotic system is outside the scope of this research. That means the vision and motion planning of the robotic arm is disregarded. However, the limitations of current robotic systems will be taken into account.

In this research certain parts of the bunch of bananas will be described using the terms depicted in Figure 2.2.

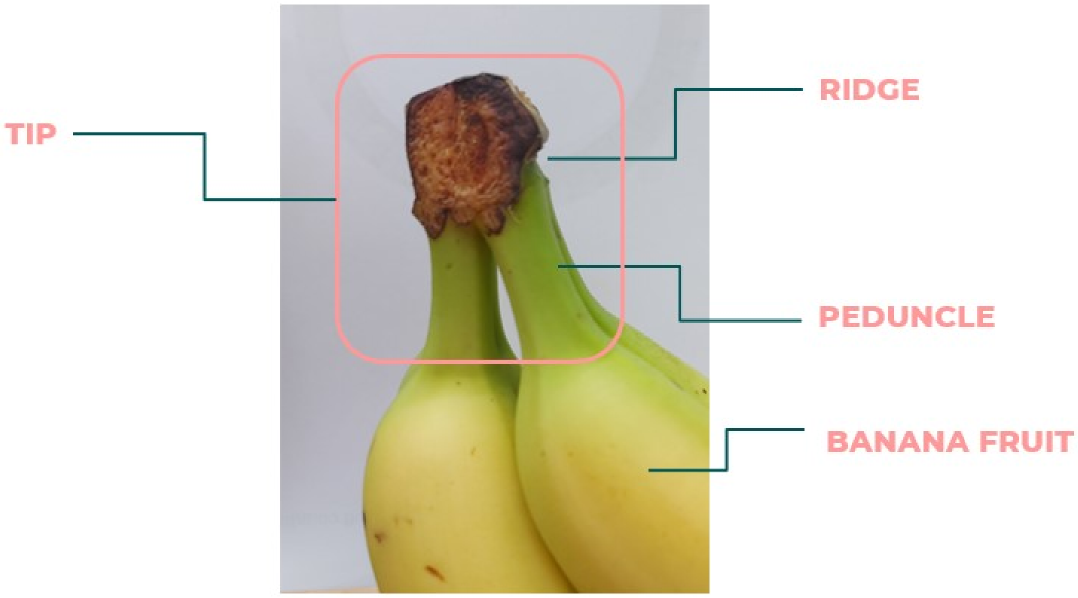

Figure 2.2: *Names of certain parts of the bunch of bananas*

Chapter 3

Fruit bruise assessment methods to improve gripper design in the agri-food sector

Fruit is tender and easily bruised. When bruised, it does not sell anymore and will go to waste. In the following research paper it is presented how to assess the mechanical properties of fruits and to how use that information to better grasp fruit without inflicting any damage.

Fruit bruise assessment methods to improve gripper design in the agri-food sector

Anne van der Star TU Delft

Abstract

Through the whole food production chain from orchard to shelve, robots are interacting with fruits through grippers. There appear to be two challenges in designing grippers for the agrifood sector. The first challenge is to make sure the gripper does not bruise the sensitive fruits and secondly, the gripper has to deal with the variety in size and shape of the objects. The grippers apply forces to grasp the fruit, but these can damage the fruits. To make sure the fruits are able to be sold, it may not contain any damage. Damage to the fruit can be external or internal. External damage refers damage to the skin. Internal damage consists of broken cells which cause the softening and browning of the flesh. With the use of experiments, the damage thresholds of fruit can be determined. After putting loads on the fruit, the severity of the damage can be determined by measuring the bruise volume. However, due to many factors influencing the bruise susceptibility these experiments do not give conclusive results to generalize the situation in the form of analytical formulas. The experimental setup used in most papers can be used to setup new experiments to find specific information of a type of fruit, e.g. the best location to apply the force. Furthermore there are five trends in gripper technology to deal with the inconsistency in shape and size of fruits. When designing a gripper for fruit it is advised to look into these five trends, namely soft shape adaptive grippers, biological inspired grippers, hybrid grippers, dexterous hands, and smart sensor AI based grippers. In general they are soft, to provide the flexibility to handle product variations and grasp in a gently manner.

1 Introduction

With the upcoming dilemmas in the demand for food, robots seem to be an indispensable part of the solution. The growing population needs more food, while workers in the sector are becoming scarce. Farmers can not find enough employees to pick all the fruits and vegetables. In the UK the "Pick for Britain" campaign was organised to find people to work in the fields, however this was not a success (*Flop 'Pick for Britain' Scheme* 2021). Picking robots can be a solution for this problem. In various parts of the agrifood supply chain robots are already operating. Starting in vegetable breeding, robots take over tasks like planting, identifying and sorting seedlings. In the orchard robots take over watering, weed- & pest control and cautiously harvesting as well (*The robots that can pick kiwi-fruit* n.d.). Further down the chain robots do the cleaning, sorting and quality checking of products. At the end of the chain robots are used for packing as well.

This means that in the whole chain the grippers of the robots are interacting with organic material. It is challenging to grip materials that differ in material properties. Fruits are variable in size and shape. Additionally, they are fragile. Robot grippers do better with industrial products. The robots are currently not yet equipped with the haptic feedback that humans have. Additionally, human hands are very versatile, among others due to the under-actuation they are very good with irregular objects.

Even when humans are handling the fruits, the picker is usually the greatest threat for damage to fruit (Martinez-Romero et al. 2004). These damages may cause fruit to decrease too much in quality to sell. The banana is the most spilled fruit in shops because of small bruises and in total 1.4 million bananas are thrown away daily in the UK (*Britons throw away 1.4m edible bananas each day* 2017; Mattsson, Williams, and Berghel 2018).

Two challenges will come up when designing a gripper for fruit and vegetable handling:

1. grasping items that may bruise when being grasped too forcefully
2. grasping items that are variable in size and shape

This first challenge is something that is not being regarded currently when designing a gripper. In Bac et al. 2014, an overview is presented of harvesting robots and their performance evaluation. Out of the 50 robots, 44 have a custom made end-effector, interacting with the fruit, where only 8 of the papers report on the damage rate. In the author's literature research only 1 paper was encountered in which the fruit was tested before designing the gripper (Hayashi et al. 2010). The focus of most research papers is on the inconsistency of the fruits.

This review will be focused on the following research questions:

1. How does fruit bruise?
2. How to find the force limits to prevent bruising fruits?
3. How to grasp irregular shapes like fruits?

To answer these questions this paper will be set up as followed: Firstly, it will describe how fruit can become damaged. It will look into the structural mechanics of fruit to understand the underlying reactions. Secondly, an overview of experimental setups to assess the bruise susceptibility of fruits will be given for different damage types. Thirdly, the paper will regard the state of art in gripping fruit. It will focus on current solutions in gripper technology that exist to cope with the inconsistency in size and shape.

2 Damage in fruits

Fruit can damage post-harvest because of several causes. As can be seen in Figure 1 temperature or relative humidity, biological threats, the composition of the atmosphere and mechanical loading can cause fruit to lose quality (Martinez-Romero et al. 2004). Post-harvest conditions during storage and transportation, like temperature and humidity, must be optimal to guarantee the fruits' longest life. For example, the atmosphere in the storage can contain a higher CO_2 level to slow down the ripening of the fruit. In cases where the levels are too high, the fruit can become victim to CO_2 toxicity. This causes the fruit to soften and acquire undesirable texture and flavour (Thompson et al. 2018).

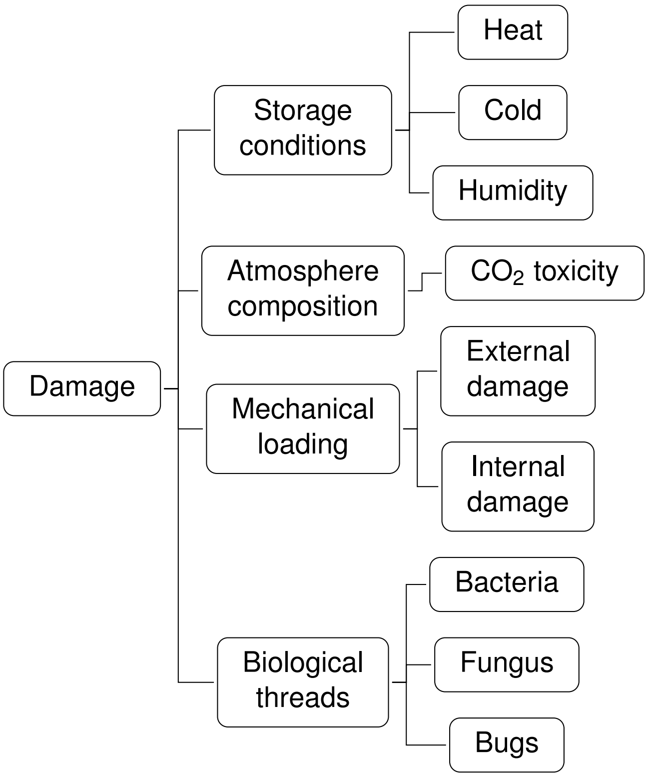

Figure 1: Post-harvest causes of damage to fruits

For this paper, the focus will be on damage caused by one or more mechanical loadings, as these can be induced by the contact between the fruit and a gripper. In Figure 2 the different mechanical loadings are depicted. External damage is damage to the skin of the fruit. This damage is externally visible and therefore easily detectable. Internal damage is damage to the flesh of the fruit. Mostly this is browning or softening of the flesh. This damage can be masked by the skin and is therefore hard to detect.

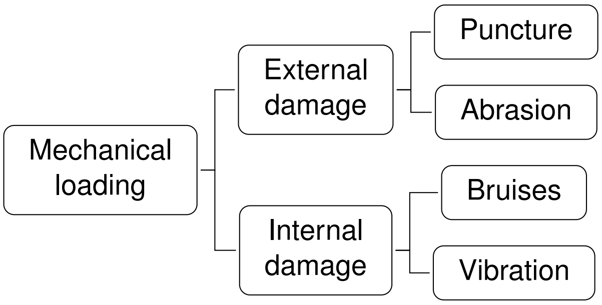

Figure 2: Damage to fruits due to mechanical interaction

After fruits are harvested, they are often thrown in a bin. From the orchard to the shelf, they encounter many more potential loading situations as can be seen in Table 1.

Location	Process stage
Orchard	Harvest into: - Buckets - Field-boxes - Pallet boxes
Packing house	Dumping dry/ into water Sorting Grading Repacking Transportation to retail markets/ chain store distributors/shelf storage
Distributor	Sorting(Conveyors etc.)
Retailer	Putting on display

Table 1: Potential loading situations in post-harvest chain (Hussein, Fawole, and Opara 2020)

2.1 Cellular fruit mechanics

Why fruit becomes soft and brown after damage, can be explained by cellular mechanics. Mechanical damage influences the physiological state of the fruit. Wounds in the peel can give way to bacterial and fungal contamination (Li and Thomas 2014). Bruising causes respiration and dehydration (Elshiekh and Abu-Goukh 2008). The cellular structure of fruits defines what happens when fruits bruise. The shape and size of the cells of both the hypodermis(skin) and flesh, and the intercellular spaces (Altisent 1991) are important for the bruise resistance. Li and Thomas 2014 describes at the fruit at different scales, see Figure 3; the macro-scale, which is the fruit as a whole; the meso-scale, which is the different types of tissue within the fruit and finally the micro-scale which is on the cellular level. "The greater the amount of intercellular space present in the tissue, the more tissue damage from bruising occurred." (Li and Thomas 2014 p. 140) These intercellular spaces creates weak spots in the tissue. In Li and Thomas 2014's paper, the browning process is described in a three step manner.

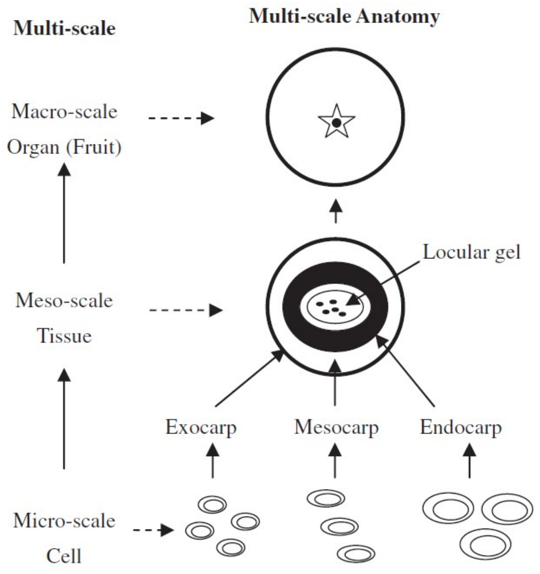

Figure 3: Cellular structure of a fruit

Firstly, the external force on the surface of the fruit on macro-scale will injure the cells at the micro-scale. The membranes may fail or cell structures may break. The tissues of a fruit differ at meso-scale, which explains the differences in magnitude of damage throughout the depth of the fruit. The differences exist out of various chemical components in the tissue and various structures of the cell wall. The second step is enzymatic oxidation. After the cells break, their contents reach

each other and possibly oxygen. Oxygen is necessary to start the process of browning. Because contents of cells can also reach each other, the oxidation that starts at the surface can pass on to other cells like a chain reaction. Lastly, the process of browning and softening starts. The oxidation process finally results in the forming of brown pigment. For different fruits different types of phenolics are part of the transformation. Phenolics are molecules that react with the oxygen. The transformation is also the cause for the softening of the tissue. The concentrations of phenolics vary within the fruit per tissue, they may be higher or lower in the peel (exocarp tissue) than in the flesh (endocarp). This results in more bruising in the peel or flesh.

2.2 External damage

The skin of the fruit protect the fruits against pests. When the skin is damaged, biological threats have easier access to the fruit. This may result in insects laying their eggs in the fruits, or bacteria or fungi entering the fruit. Another effect is that the ripening of the fruit will accelerate(Santana Llado and Marrero Dominguez 1997). Two types of external damage exist: puncture and abrasion. Puncture occurs when a sharp object penetrates the skin of the fruit. This can happen through the whole post-harvest chain, for example by the peduncle of another fruit or sharp edge on a fruit handling equipment. Abrasion is caused by friction on the skin. The friction occurs possibly in containers, with fruit to fruit contact or in contact with the container itself.

2.3 Internal damage

Internal damage can be caused by impacts or compression. Research has shown that the bruises due to impact differ from those due to compression. When cutting the fruit through the bruise, it is visible that the two loadings have a different effect. The cross section of a bruise of an impact and a compression differs. A bruise is defined as where the tissue of the fruit has softened. An impact causes a bruise with spikes, where a compression causes a smooth parabolic shaped bruise, see Figure 4 (Chen et al. 1987).

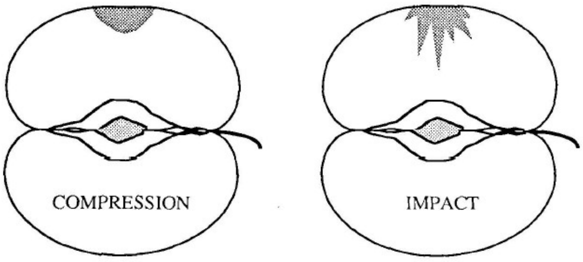

Figure 4: Difference between compression and impact bruise patterns in Asian pears (Chen et al. 1987)

Impact happens when fruits fall or are hit by an object, for instance another fruit. This causes dynamic loading on the fruit. Compression causes static loading on the fruit. This can happen when fruits are on top of each other in packaging or by grasping the fruit too forcefully. Prolonged vibrations can damage the fruits as well. These can occur when transporting the fruits on a truck.

2.4 Which fruit is susceptible for which damage

Looking at the different kind of grippers, certain grippers are more likely to cause a specific kind of damage to fruit than others (Blanes et al. 2011). Grippers that use pneumatics for actuation have a smaller chance on inflicting deformation or damage to the fruit than a hydraulic driven grippers. On the other hand, certain fruits are more susceptible to certain damage than others. Altisent 1991 sums up 5 different characteristics which influence the fruit's susceptibility for bruises.

1. A distinction between fruits can be made on their physiological structure. Fruit either are 'rigid' fruits. These are fruits whose strength is based on their structure with a thin surrounding skin, like apples, pears, peaches, avocados. Otherwise fruits belong with the 'liquid' fruits. These fruits have a liquid mass contained in a elastic skin, examples are tomatoes, grapes and cherries. A side note is that rigid fruits may mature into liquid fruits.

2. The mass of the fruit is crucial in bruise susceptibility. The impact energy of heavier fruits is higher, thus a drop is more harmful.

3. The thickness of the skin, a thicker skin protects the fruit against impacts, but is more susceptible for skin rupture. Examples are bananas and melons.

4. Fibrous fruits like pineapples react in a different way that has not been studied thoroughly.

5. Stone fruits can have an extra impact from within. The stone inside them causes an extra impact.

In literature several more examples can be found for specific fruits. Kiwi's suffer more from impact damage than abrasion(Mencarelli, Massantini, and Botondi 1996). Strawberries suffer more from compression than from impact(Ferreira et al. 2008). Papaya, apples and tomatoes are sensitive to puncture(Li and Thomas 2014). This means the hand rules can be as indication, but for specific knowledge about the sensitivity of a specific fruit, further research is needed.

3 Testing for thresholds

Fruit mechanics is a subject that has been researched for several decades. The research questions differ per research, but all test the bruise susceptibility of fruit. Mostly the incentive of the research is to find the optimal post-harvest storage conditions for the fruits. Another incentive is to find the difference in bruise susceptibility between cultivars. Finally fruits have been tested on where the location of impact will cause the most severe bruising. For all causes that means the following experimental setup; several fruits will be bruised with the same force or energy, then conserved in different conditions and finally assessed on the severity of the bruises.

In research, after the loading is inflicted on the fruit, several ways are used to judge the internal damage. The most common one is 'Bruise Volume' (Kajuna, Bilanski, and Mittal 1997; Komarnicki et al. 2016; Ferreira et al. 2008. The researcher will mark the spot of the loading on the fruit. After several days, the soft tissue will be examined. The volume of the softened tissue is the Bruise Volume(BV), indicating the severity of the damage. By cutting the fruit on the location of the loading, like in Figure 5, the volume of the softened tissue can be found. Other methods to assess the damage caused by loadings are among others a puncture test, the relative loss of mass or surface discoloration (Pang et al. 1996; Gamea, Aboamera, and Mohmed 2011; Menesatti et al. 2002).

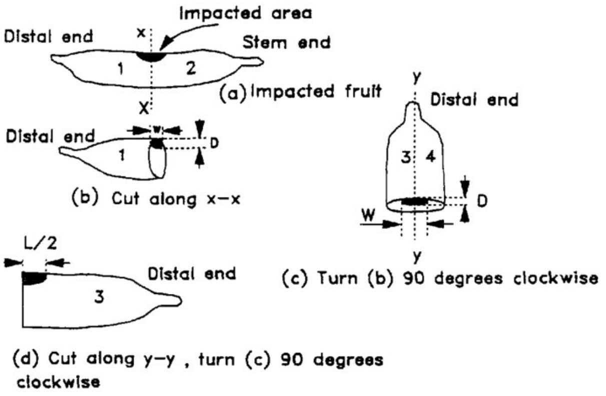

Figure 5: Method to measure bruise volume (Kajuna, Bilanski, and Mittal 1997)

To inflict damage on the fruits different testing setups exist for each damage type. The following damage types will be discussed:

- Compression
- Impact
- Abrasion
- Puncture

Research has been done in vibration experiments, however as this is not damage that can be inflicted by a gripper, this will not be discussed.

3.1 Experimental setups for compression

In compression tests fruit is put under constant pressure. This is inflicted in several ways as can be seen by the different experiments. In all experiments conditions during the storage of the fruits are noted down. An overview of the testing conditions, if known, can be found in Table A1 in the Appendix. Extra information about the specific studies are noted down; the specific compression machine used, the conditions of the fruit storage before and after the test, the test conditions and extra information about the fruit that the author gathered. The size and the shape of the probe are important to analyse the outcomes of a compression experiment.

In their earliest paper about bruising of fruits Banks and Joseph 1991 used a motorised platform to press a rounded-end probe on a force gauge into the banana. The use of a motorised platforms however inflicts difficulties and gives dissatisfactory results. Therefore an experimental setup is designed for a successive paper. There bananas are subjected to compression- and impact force tests(Banks, Borton, and Joseph 1991). The main results are the bruising thresholds for different (post)harvest conditions. To do the compression test, Banks develops an compression machine, see Figure 6. Block **D** has a mass, by putting the fruit **G** somewhere along the line **C - F**, the force on the fruit can be adjusted.

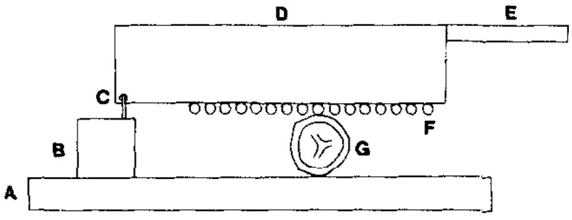

Figure 6: Banks, Borton, and Joseph 1991 design for fruit compressing

In a study different varieties of Asian pears were compared, as well as different circumstances like storage time and storage temperature(Chen et al. 1987). To test the compression resistance of the pears, a spherical indenter on a testing machine was used to press into a pear with a constant velocity. Each pear was compressed twice, once until 1.5 mm deformation and once until 3 mm. During the deformation the force-deformation curve was recorded. The study found that one variety of pears is significantly less susceptible for bruising than the other three varieties.

Ferreira et al. 2008 used "the IFAS Firmnes Tester developed at the Horticultural Science Department, University of Florida, Gull 1987" to subject strawberries to compression forces. This tester exists out of a probe with a convex tip and exerts a constant force on the fruit. "Considerable effort was made in the design of these experiments to simulate impact and compression bruises such as are encountered during commercial strawberry handling" (Ferreira et al. 2008 p. 492). In their research, they found that bruise volume increases when strawberry are subjected to compression forces for a longer time.

Akbarnejad, Azadbakht, and Asghari 2017 used a different approach. The mechanical and physical properties of bananas can be used to design machinery to process the fruits. In this research, tests were conducted on bananas to find relations between the moisture content and the mechanical properties of the fruit. They found that bananas have a higher risk of failure when the moisture content is at a higher level. To come to these findings, the bananas have been placed in a pressure-stress device, see Figure 7.

Figure 7: Akbarnejad, Azadbakht, and Asghari 2017 banana under the pressure-stress device

Jahanbakhshi, Yeganeh, and Shahgoli 2020 used a

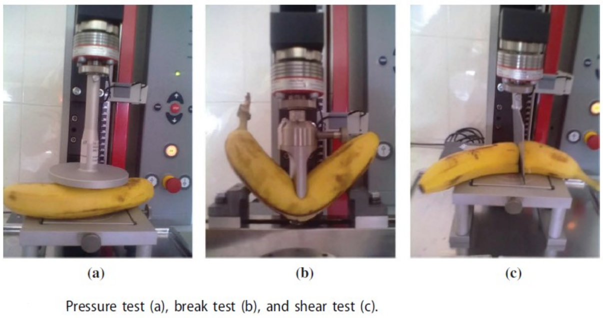

Figure 8: Jahanbakhshi, Yeganeh, and Shahgoli 2020 banana under the pressure-stress device

pressure-stress device as well, see figure Figure 8. The purpose of this study is the same as the Akbarnejad, Azadbakht, and Asghari 2017, namely knowing the mechanical limits of this fruit to optimise the processing of it. In the study a Zwick/Roell Instron testing machine was used, based on the recommended standards. It found maximum forces for bruising, bending and shearing of the banana fruit.

An unique approach is to use a Finite Element Method(FEM) to model the compressed fruit (Lewis et al. 2008). The differences in material characteristics in exocarp, mesocarp and endocarp tissue (subsection 2.1) were used in the modeling of an apple. To find the geometry of the apple, a laser scan of the apple was obtained. In order to compare the results, a real apple was compressed and afterwards scanned with a novel ultrasonic technique. The FEM technique appeared to be a promising method to help reduce the likelihood of damage due to packaging material to fruits.

3.2 Experimental setups for impact

Impact is the most studied damage in research. The impact is applied on the fruit in several ways. Either an object is dropped on or against the fruit or the fruit is being dropped. An overview with the conditions of the experiments can be found in Table A2 in the Appendix. Extra information about the specific studies are noted down; the conditions of the fruit storage before and after the test, the different energy levels inflicted by a force on the fruit, the test conditions and extra information about the fruit that the author gathered.

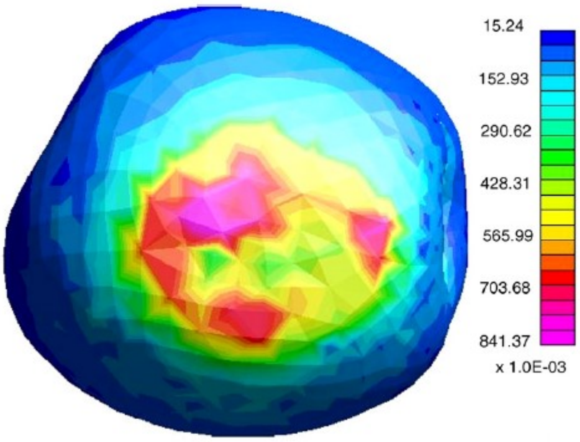

Figure 9: Pressure distribution in a compressed apple with the FEM analysis(Lewis et al. 2008)

To test the response of Asian pears on impact forces, Chen, Tang, and Chen 1985 developed an instrument to drop a steel rod with a spherical tip on the fruit. The height was predetermined. The instrument recorded the acceleration of the rod and calculated the maximum force, maximum deformation, absorbed energy and duration of the impact. Finally the study tried to find a correlation between mechanical damage and physical variables like flesh-firmness, compression force, maximum force and deformation during impact.

Banks and Joseph 1991 dropped a ball through a guiding tube on four sides of a banana. The ball is dropped from 16 different heights with increments of 0.5 cm. There was assumed that the banana absorbed all energy using $E = mgh$. The same method was used by Opara 2007 to compare the bruise susceptibility of apples grown with different orchard practices, such as irrigation frequency and harvest timing.

In a following study this experiment was repeated, but this time recorded on video to gain extra information of the impact(Opara et al. 2007). Furthermore, a second experiment was added to this research by attaching the fruit to the drop arm of a pendulum. By analyzing the video recording, the rebound height of the ball or fruit can be determined, in order to calculate the difference in kinetic energy. This setup is also used to test the bruise susceptibility of pears (Komarnicki et al. 2016). Here, the fruit is attached to the pendulum instead of a ball and will hit a bumper plate with a pressure sensor, see Figure 11. With the pressure sensor the contact area can be determined. Another use of this setup is to determine the differences in reaction forces of different packaging materials. Öztekin and Güngör 2020 used an electronic sensor instead of a fruit on the end of the pendulum and changed the backstop material.

The difference between how bananas and plantains react on impact forces is the main research question in Kajuna, Bilanski, and Mittal 1997. A model is made for both fruits, where the bruise volume depends on impact energy and storage time. The data for these models comes from tests. The impact was done by a ball on a rigid-arm pendulum, see Figure 10. The rigid rod was connected to the axis of rotation 'AR' and the fruit was put on the stage in a way it couldn't move. The potentiometer 'P' recorded the rebound height of the ball. Before dropping the pendulum, the ball was rubbed with ink to know where the bruise would form.

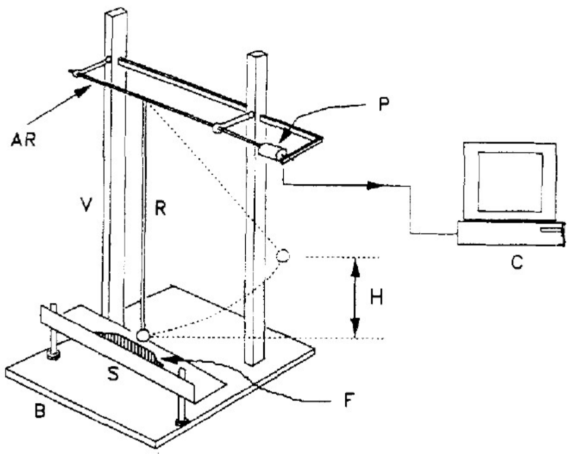

FIG. 1. SCHEMATIC OF THE PENDULUM IMPACTER
AR = Axis of rotation, V = Vertical post, R = Rigid rod, S = Adjustable stage, B = Solid base, F = Fruit, H = Deflection height, P = Potentiometer, C = Computer

Figure 10: Pendulum designed for impact simulation (Kajuna, Bilanski, and Mittal 1997)

To test the resistance of strawberries against impacts, two tests were conducted; a pendulum impactor and a drop test(Ferreira et al. 2008). The pendulum impactor was used to inflict specific impact energies on the strawberries. The strawberry was fixed in a cheesecloth with a solid backstop, then a chrome ball attached to a line would fall against the strawberry. The energy levels were chosen after a preliminary study to field conditions. Additionally, strawberries were dropped from a certain height onto an aluminium plate. To avoid a second impact, the strawberry was caught after it bounced from the plate.

"In contrast to apples no browning of damaged tomato tissue occurs, making objective measurement of tomato bruise damage very difficult" (Van Zeebroeck et al. 2007). This study aims to find a relation between the absorbed energy by the tomato and the bruise damage, regardless of variants like cultivar or ripeness. To imply the impact a designed pendulum from Van Zeebroeck et al. 2003 is used. This pendulum exists out of a rigid arm and a spherical impactor, Figure 12.

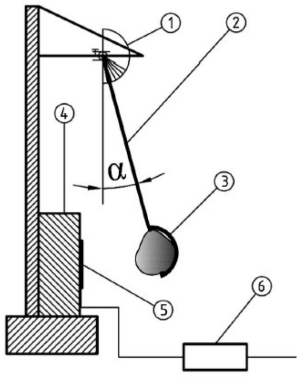

Figure 11: Pendulum with pear (Komarnicki et al. 2016)

Figure 12: Mechanical impactor for tomatoes (Van Zeebroeck et al. 2007)

3.3 Experimental setups for abrasion

Fruits are less likely to be severely damaged by abrasion than by causes that inflict internal damage. Therefore the research on abrasion could be more limited than the research on bruises caused by impact or compression. In literature various methods have been used to apply abrasion to fruits. Santana Llado and Marrero Dominguez 1997 checks what the physiological consequences are for the allowed surface damages on bananas for certain quality grades. The 1 and 4 cm^2 of surface damage are manually applied using sandpaper. Timm, Brown, and Armstrong 1996 researched the abrasion as a result of vibrating containers during transport. Apples were inspected after being transported 55 or 110 km in 5 types of containers on trucks with either steel-spring or air-cushion suspension. The test method in this research is an imitation of the real world. The fruits were afterwards checked for impact and abrasion damage. Additionally, a simulation was done on a vibration-table, which gave comparable abrasion results to the real truck tests. Mencarelli, Massantini, and Botondi 1996 tested the sensitive kiwifruits on the consequences of impact damage and abrasion. To inflict abrasion during the impact tests, the kiwis where dropped on sandpaper. The sandpaper simulated the wooden boxes. The abrasion test consisted out of a kiwi being pressed on wood with a constant force. Then the kiwi was pulled out while keeping the wood stationary. Puchalski and Brusewitz 1996a build a machine to determine the resistance of the skin of a watermelon, see Figure 13. The counter weight presses the watermelon against an abrasive surface, which moves with a constant speed tangent to the surface. Because of the sandbag base, the watermelon will stay in place. The goal of the study was to predict the area of the surface damage on the basis of variables like tangential force.

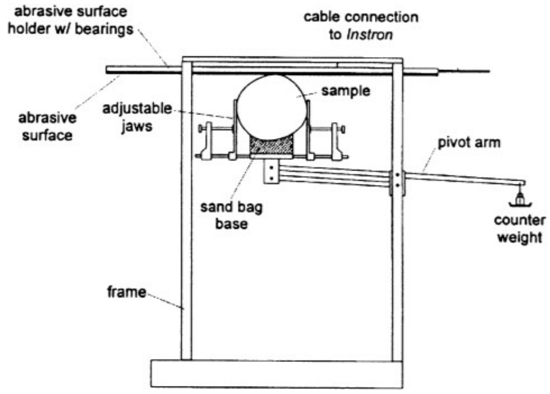

Figure 13: Machine to apply surface damage to watermelon, Puchalski and Brusewitz 1996b

3.4 Experimental setups for puncture

When a fruit is pressed on a sharp object, puncture of the skin may occur. To research the differences in puncture susceptibility between tomato cultivars and differences over storage time, Desmet et al. 2003 designed a pendulum. The end of the arm of the pendulum contained a impact probe, see Figure 14. The setup was designed is such a manner that the probe would hit all tomatoes in the same place. *Fruit Texture: How to assess skin strength and flesh firmness of whole fruits* 2018 writes about penetrating fruits with a needle probe to test the ripeness of the fruits. This test setup gives a force-displacement revealing the bioyield point. The bioyield point corresponds to a failure in the microstructure of the fruit, resulting in irreversable damage(Kubík and Kažimírová 2015). The information of the bioyield point can be used to know how much force can be put on a fruit while staying in the elastic zone, avoiding plastic deformation.

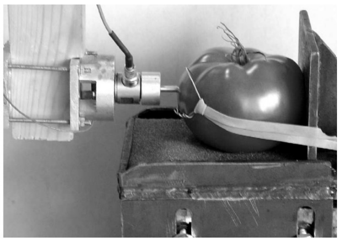

Figure 14: Pendulum for puncturing tomatoes (Desmet et al. 2003)

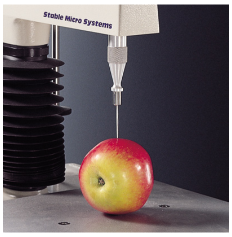

Figure 15: Needle probe puncturing apple

3.5 Discussion of different threshold methods

The experiments resulted in several conclusions. The comparison of storage conditions and the comparison of the bruise susceptibility of cultivars gave statistically relevant results. Often the probability on damage, or the probability on severe damage is linked to factors like picking date, firmness, drop height, impact location and/or storage temperature(for more results see

Figure A1). However, when trying to model the bruise volume related to parameters, this results in very convoluted formulas, see Figure 19. "Despite these reports, it seems optimistic to hope that susceptibility to bruising could be characterised by a single mechanical parameter and most researchers have therefore used multivariable regression analysis to relate mechanical damage (bruising, probability of bruising on impact, probability of puncture injury) to a range of mechanical, geometrical, harvesting and cultivar parameters" said Li and Thomas 2014 p. 147. Research into damage thresholds of bananas found values for which forces the banana started develop a bruise(Banks and Joseph 1991). The values however depend on several parameters such as relative humidity and temperature. Another side note is that there is more research needed to verify if the experiments are comparable with the forces to which bananas are normally exposed. There are many parameters that influence the structural mechanics, because of the fact that fruits are biological objects. This makes it hard to predict how they will respond to certain loadings.

4 Grippers in the agricultural sector

In literature two types of gripper design methods can be found. Either universal designed grippers are capable of grasping various objects including fruit, like this granular gripper in Figure 16. Other times grippers are specially designed to grasp a specific fruit, like this gripper designed for strawberries, see Figure 17.

Zhang et al. 2020 presents a comprehensive overview of the state-of-art of grippers in the agrifood sector. Grippers in this sector need to be less aggressive, more flexible and more controllable than grippers in industrial sectors. Many grippers have been chosen or designed for various tasks in the sector, like harvesting or sorting (Bac et al. 2014). Zhang et al. 2020 finds five potential future trends in gripper technology for agricultural applications.

Figure 16: Granular gripper grasping several objects (Krahn, Fabbro, and Menon 2017)

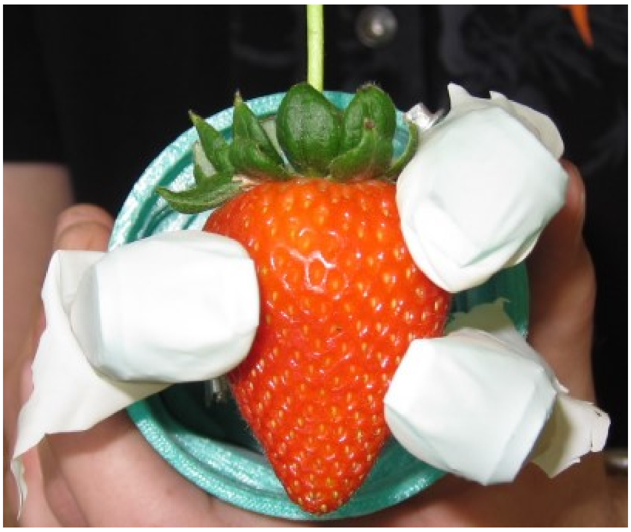

Figure 17: Gripper specially designed to grasp strawberries (Dimeas et al. 2013)

Soft shape-adaptive grippers

An solution that is upcoming is soft grippers. These grippers have no rigid parts, therefor it is hard to inflict damage to a fruit. Another advantage of the soft fingers is the increase in surface contact, this decreases the chances on puncture even further. Soft grippers are also capable of dealing with inconsistent shapes as they form to the object (Hughes et al. 2016). "However, their inherent lack of repeatability, precision, and lower grasping force can be seen as a limiting factor for their applications".

Biological inspired grippers

Bio-inspired design is an upcoming trend in robotics. The company Festo has been investing animals for inspiration since 2006 (*Bionic Learning Network* n.d.). This has resulted in biomimicred robots and grippers inspired by various animal body parts like the tongue of a chameleon, the human hand, and octopus arm and the beak of a crow. The advantages of the different grippers differ from versatile to strength. Lastly Festo also developed the Fin Ray®, see Figure 18. This gripper is inspired on the fin of a fish and it structure is soft and compliant. When a force is on the side of the gripper, it is not pushed away, but arches around the contact point. This gripper is already being used in the agrifood sector (*Bionic Learning Network* n.d.).

Figure 18: Fin gripper developed by Festo (Morar et al. 2020)

Hybrid grippers

Hybrid grippers use multiple strategies in one gripper to combine both advantages. For example rigid fingers and a suction cup can be combined (Park et al. 2012), or another example is that fingers contain rigid and flexible materials (Park, Seo, and Bae 2018).

Dexterous hands

Dexterous hands are robotic grippers that are inspired on human hands. These do not necessarily need to be the anthropomorphic hands that look like human hands. These kind of grippers come with multi-sensors, high degree of freedoms, and intelligent control strategies. Therefore they are capable of dealing with variation in both external shape and the range of movement.

Smart sensor and AI based intelligent grippers

Finally, next to mechanical solutions, interactive grippers are needed as well. Grippers with sensors that can provide haptic feedback to the system. The robot can be programmed with Artificial Intelligence to learn to use the sensory feedback. "A smart sensor network could make the grippers more intelligent and precise, and to perform a wide range of intelligent manipulations as human hands. Meanwhile, the information of targets could also be measured during the grasping operations" (Zhang et al. 2020 p. 16).

Eventually Zhang et al. 2020 draws two conclusions about future design for robot grippers in the agrifood sector. "Firstly special attention should be paid to the physical, chemical, and biological characteristics of the agricultural products for gripper design and control. Secondly, specific grippers applied to pruning,thinning, bagging, packaging, chemical application and pollination will be increasingly needed for agricultural automation" (Zhang et al. 2020 p. 16).

5 Discussion

It is fairly well known how the internal structure of fruit responds to loadings. Some of that knowledge can be used in an advantage to reduce the chance of bruising a fruit grasping it with a robotic gripper. The sensitivity of specific sorts of fruits for certain damage types is something to take into consideration for gripper design. There are some hand rules for groups of fruit types, but when focusing on one type of fruit, it is advised to concentrate researching the sensitivity of that specific type. The information can be used to prefer one type of loading over another and result in design choices for the gripper. For example for fruit that is sensitive for puncture, it is important to make sure the fruit does not come in contact with sharp parts of a gripper. To counter abrasion it is important that the fruit can not move against the fingers resulting in friction. Bac et al. 2014 investigated gripper types and the type of damage they may cause. This research focuses on actuation of the grippers. To be of more value this should be expanded by looking into the type of mechanical interaction the gripper has with the fruit, e.g. the shape of the finger.

The predictability of bruising is not resulting in conclusive thresholds. Consequently, it is recommended to minimise forces on the fruit. However, to grasp a fruit one has to inherently apply forces. To minimise the chance of bruises, the experimental setup used in many studies can be used to find more specific information about the fruit. The listed experimental setups can be used as inspiration for similar experiment with a different research objective. A possible outcome could be to find the least sensitive part of the fruit, which would be a good location to apply the forces. Another outcome could be to find the amount of force that the weakest fruit can handle without causing a bruise.

Current robotic solutions cause more damage to fruit than handling by human hands (Hussein, Fawole, and Opara 2020). This means that current solutions are not

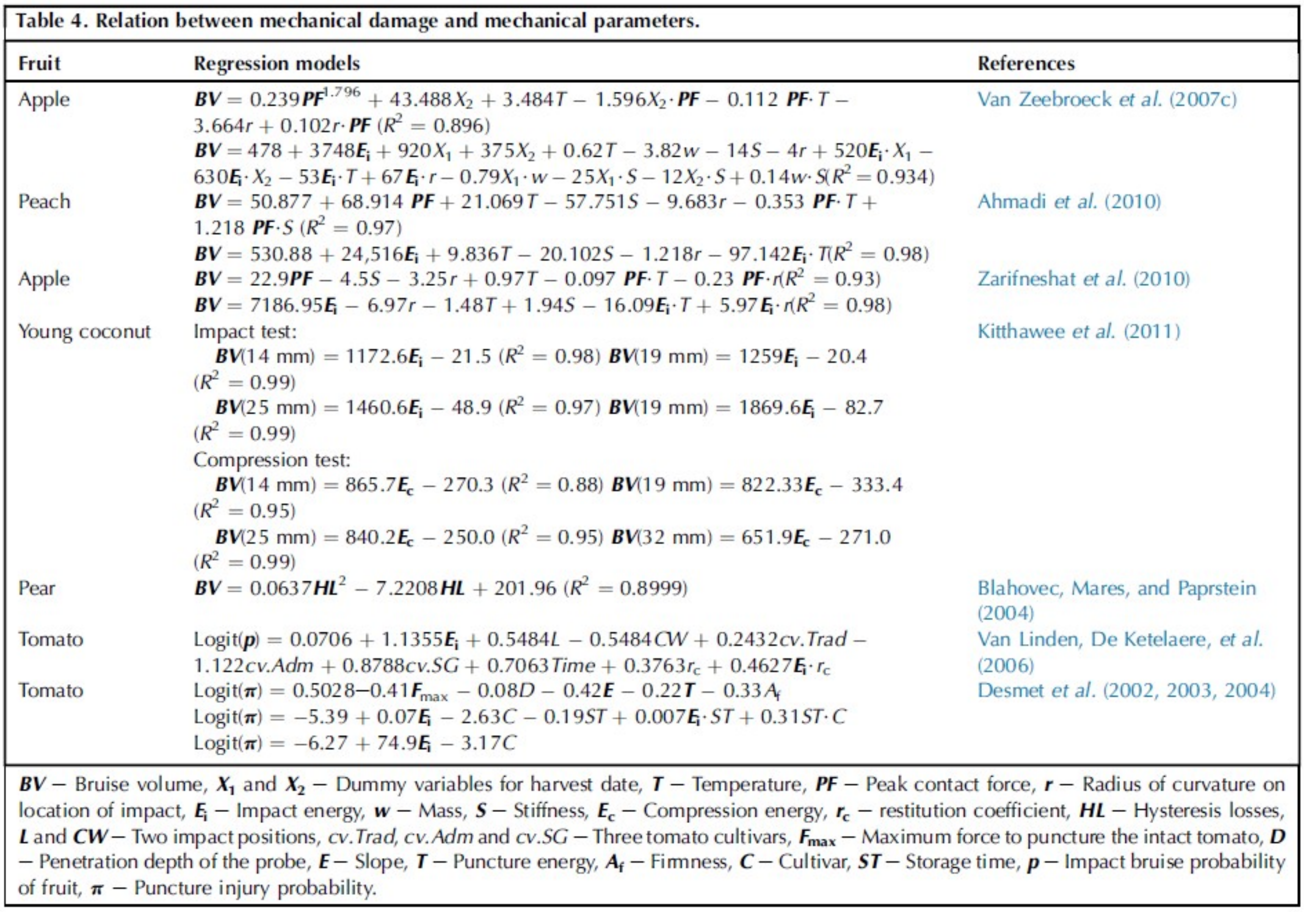

Table 4. Relation between mechanical damage and mechanical parameters.

Fruit	Regression models	References
Apple	$\boldsymbol{BV} = 0.239\boldsymbol{PF}^{1.796} + 43.488X_2 + 3.484T - 1.596X_2 \cdot \boldsymbol{PF} - 0.112\,\boldsymbol{PF} \cdot T - 3.664r + 0.102r \cdot \boldsymbol{PF}\ (R^2 = 0.896)$ $\boldsymbol{BV} = 478 + 3748\boldsymbol{E}_i + 920X_1 + 375X_2 + 0.62T - 3.82w - 14S - 4r + 520\boldsymbol{E}_i \cdot X_1 - 630\boldsymbol{E}_i \cdot X_2 - 53\boldsymbol{E}_i \cdot T + 67\boldsymbol{E}_i \cdot r - 0.79X_1 \cdot w - 25X_1 \cdot S - 12X_2 \cdot S + 0.14w \cdot S(R^2 = 0.934)$	Van Zeebroeck *et al.* (2007c)
Peach	$\boldsymbol{BV} = 50.877 + 68.914\,\boldsymbol{PF} + 21.069T - 57.751S - 9.683r - 0.353\,\boldsymbol{PF} \cdot T + 1.218\,\boldsymbol{PF} \cdot S\ (R^2 = 0.97)$ $\boldsymbol{BV} = 530.88 + 24{,}516\boldsymbol{E}_i + 9.836T - 20.102S - 1.218r - 97.142\boldsymbol{E}_i \cdot T(R^2 = 0.98)$	Ahmadi *et al.* (2010)
Apple	$\boldsymbol{BV} = 22.9\boldsymbol{PF} - 4.5S - 3.25r + 0.97T - 0.097\,\boldsymbol{PF} \cdot T - 0.23\,\boldsymbol{PF} \cdot r(R^2 = 0.93)$ $\boldsymbol{BV} = 7186.95\boldsymbol{E}_i - 6.97r - 1.48T + 1.94S - 16.09\boldsymbol{E}_i \cdot T + 5.97\boldsymbol{E}_i \cdot r(R^2 = 0.98)$	Zarifneshat *et al.* (2010)
Young coconut	Impact test: $\boldsymbol{BV}(14\text{ mm}) = 1172.6\boldsymbol{E}_i - 21.5\ (R^2 = 0.98)\ \boldsymbol{BV}(19\text{ mm}) = 1259\boldsymbol{E}_i - 20.4\ (R^2 = 0.99)$ $\boldsymbol{BV}(25\text{ mm}) = 1460.6\boldsymbol{E}_i - 48.9\ (R^2 = 0.97)\ \boldsymbol{BV}(19\text{ mm}) = 1869.6\boldsymbol{E}_i - 82.7\ (R^2 = 0.99)$ Compression test: $\boldsymbol{BV}(14\text{ mm}) = 865.7\boldsymbol{E}_c - 270.3\ (R^2 = 0.88)\ \boldsymbol{BV}(19\text{ mm}) = 822.33\boldsymbol{E}_c - 333.4\ (R^2 = 0.95)$ $\boldsymbol{BV}(25\text{ mm}) = 840.2\boldsymbol{E}_c - 250.0\ (R^2 = 0.95)\ \boldsymbol{BV}(32\text{ mm}) = 651.9\boldsymbol{E}_c - 271.0\ (R^2 = 0.99)$	Kitthawee *et al.* (2011)
Pear	$\boldsymbol{BV} = 0.0637\boldsymbol{HL}^2 - 7.2208\boldsymbol{HL} + 201.96\ (R^2 = 0.8999)$	Blahovec, Mares, and Paprstein (2004)
Tomato	$\text{Logit}(\boldsymbol{p}) = 0.0706 + 1.1355\boldsymbol{E}_i + 0.5484L - 0.5484CW + 0.2432cv.Trad - 1.122cv.Adm + 0.8788cv.SG + 0.7063Time + 0.3763r_c + 0.4627\boldsymbol{E}_i \cdot r_c$	Van Linden, De Ketelaere, *et al.* (2006)
Tomato	$\text{Logit}(\boldsymbol{\pi}) = 0.5028 - 0.41\boldsymbol{F}_{max} - 0.08D - 0.42\boldsymbol{E} - 0.22\boldsymbol{T} - 0.33A_f$ $\text{Logit}(\boldsymbol{\pi}) = -5.39 + 0.07\boldsymbol{E}_i - 2.63C - 0.19ST + 0.007\boldsymbol{E}_i \cdot ST + 0.31ST \cdot C$ $\text{Logit}(\boldsymbol{\pi}) = -6.27 + 74.9\boldsymbol{E}_i - 3.17C$	Desmet *et al.* (2002, 2003, 2004)

$\boldsymbol{BV}$ – Bruise volume, $\boldsymbol{X_1}$ and $\boldsymbol{X_2}$ – Dummy variables for harvest date, $\boldsymbol{T}$ – Temperature, $\boldsymbol{PF}$ – Peak contact force, $\boldsymbol{r}$ – Radius of curvature on location of impact, $\boldsymbol{E}_i$ – Impact energy, $\boldsymbol{w}$ – Mass, $\boldsymbol{S}$ – Stiffness, $\boldsymbol{E_c}$ – Compression energy, $\boldsymbol{r_c}$ – restitution coefficient, $\boldsymbol{HL}$ – Hysteresis losses, $\boldsymbol{L}$ and $\boldsymbol{CW}$ – Two impact positions, *cv.Trad*, *cv.Adm* and *cv.SG* – Three tomato cultivars, $\boldsymbol{F_{max}}$ – Maximum force to puncture the intact tomato, $\boldsymbol{D}$ – Penetration depth of the probe, $\boldsymbol{E}$ – Slope, $\boldsymbol{T}$ – Puncture energy, $\boldsymbol{A_f}$ – Firmness, $\boldsymbol{C}$ – Cultivar, $\boldsymbol{ST}$ – Storage time, $\boldsymbol{p}$ – Impact bruise probability of fruit, $\boldsymbol{\pi}$ – Puncture injury probability.

Figure 19: Hierarchical structure of the grasping mechanism based on the gripping approach(Marwan, Chua, and Kwek 2021)

likely to be replacing human labor. The trends presented could possibly decrease the bruising done by grippers. Soft robotics has less chance of inflicting damage because of the lack of rigid parts. However, the lack of precision and grasping force can cause fruits to slip lose and fall. This could be compensated by a bigger contact surface and materials with higher friction coefficients. Overall the proposed trends are using more flexible and softer structures. The smart sensors can either help the robot to know if the applied force is enough, to avoid dropping fruits, or not too much, to avoid bruising the fruit.

6 Conclusion

In this article the causes of fruit damage are discussed. Fruit damage by mechanical interaction is explicitly elaborated in more depth as these are of upmost important for designing grippers. Mechanical damage can be distinguished in external and internal damage. In general compression and impact have the same result; the cell walls will break and the content spread out through the fruit and its compound start to deteriorate and cause browning and soft spots: called bruises.

To measure by how much force a fruit will bruise, experiments can be done. Overall these experiments have the same setup; apply a force to a fruit, wait for a while and access the damage. The instruments used for compression experiments are mostly(83%) off-the-shelve machines. Only Banks, Borton, and Joseph 1991 designs an own instrument. There have been found four possibilities for experimental setups that inflict an impact force to a fruit; hit the fruit with a falling ball(23%), hit the fruit with a pendulum(31%), drop the fruit itself(23%) or attach the fruit to the pendulum hitting a wall(23%). To access the damage to a fruit, bruise volumes are the most used method. However, there has not been found a conclusive manner to predict the the bruise volume, thus to predict the damage. This is because of the numerous factors influencing the bruise susceptibility of fruit.

Finally, grippers in the agrifood sector will be increasingly needed, but they need to be carefully designed. This is because the special characteristics of fruits have to be taken into consideration; the sensitive material and the variability of the size and shape. Five upcoming trends in the gripper technology may provide promising solutions to these challenges, namely soft shape-adaptive grippers, biological inspired grippers, hybrid grippers, dexterous hands, and smart sensor AI based intelligent grippers.

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Appendix

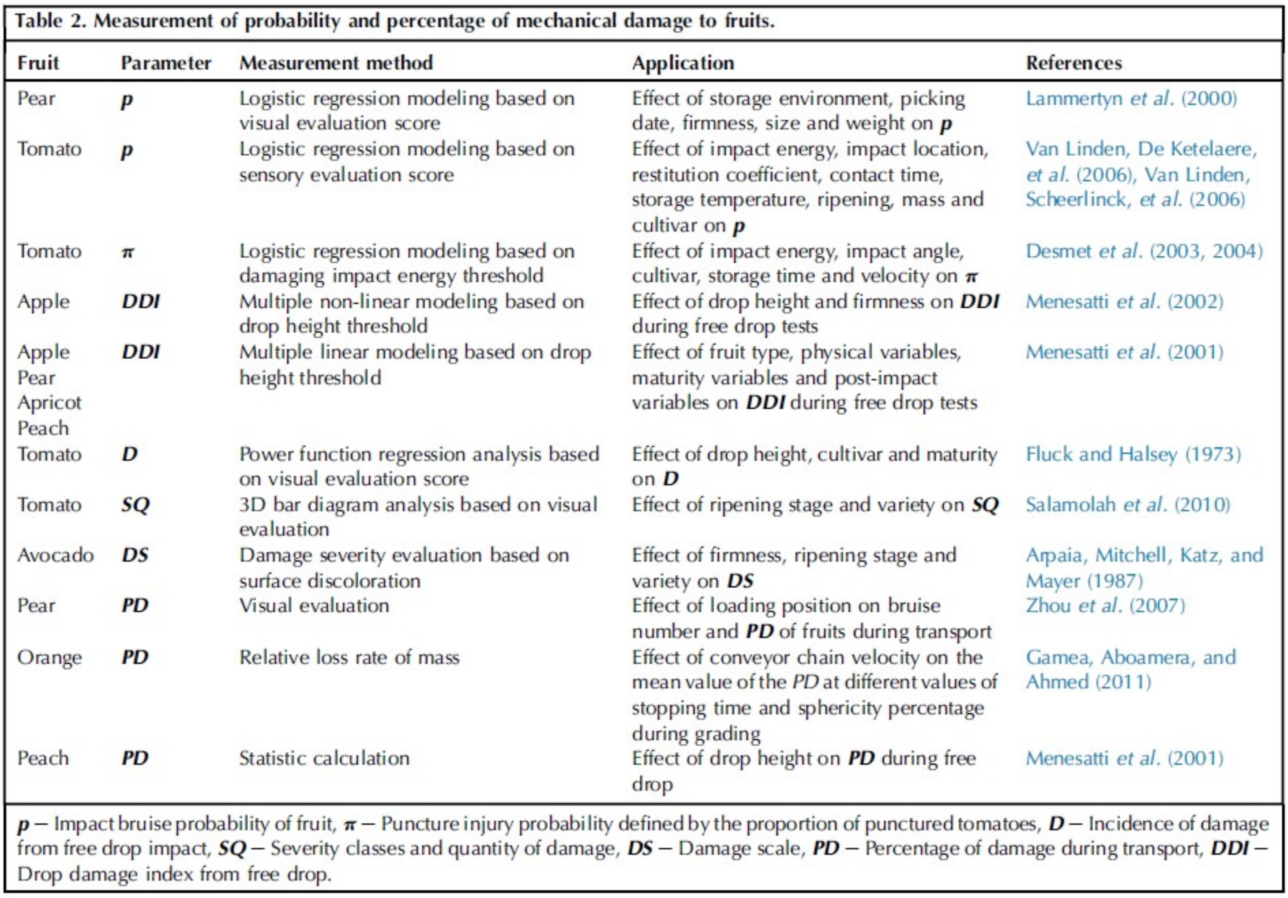


Table 2. Measurement of probability and percentage of mechanical damage to fruits.

Fruit	Parameter	Measurement method	Application	References
Pear	***p***	Logistic regression modeling based on visual evaluation score	Effect of storage environment, picking date, firmness, size and weight on ***p***	Lammertyn *et al.* (2000)
Tomato	***p***	Logistic regression modeling based on sensory evaluation score	Effect of impact energy, impact location, restitution coefficient, contact time, storage temperature, ripening, mass and cultivar on ***p***	Van Linden, De Ketelaere, *et al.* (2006), Van Linden, Scheerlinck, *et al.* (2006)
Tomato	π	Logistic regression modeling based on damaging impact energy threshold	Effect of impact energy, impact angle, cultivar, storage time and velocity on π	Desmet *et al.* (2003, 2004)
Apple	***DDI***	Multiple non-linear modeling based on drop height threshold	Effect of drop height and firmness on ***DDI*** during free drop tests	Menesatti *et al.* (2002)
Apple Pear Apricot Peach	***DDI***	Multiple linear modeling based on drop height threshold	Effect of fruit type, physical variables, maturity variables and post-impact variables on ***DDI*** during free drop tests	Menesatti *et al.* (2001)
Tomato	***D***	Power function regression analysis based on visual evaluation score	Effect of drop height, cultivar and maturity on ***D***	Fluck and Halsey (1973)
Tomato	***SQ***	3D bar diagram analysis based on visual evaluation	Effect of ripening stage and variety on ***SQ***	Salamolah *et al.* (2010)
Avocado	***DS***	Damage severity evaluation based on surface discoloration	Effect of firmness, ripening stage and variety on ***DS***	Arpaia, Mitchell, Katz, and Mayer (1987)
Pear	***PD***	Visual evaluation	Effect of loading position on bruise number and ***PD*** of fruits during transport	Zhou *et al.* (2007)
Orange	***PD***	Relative loss rate of mass	Effect of conveyor chain velocity on the mean value of the *PD* at different values of stopping time and sphericity percentage during grading	Gamea, Aboamera, and Ahmed (2011)
Peach	***PD***	Statistic calculation	Effect of drop height on ***PD*** during free drop	Menesatti *et al.* (2001)

p – Impact bruise probability of fruit, π – Puncture injury probability defined by the proportion of punctured tomatoes, ***D*** – Incidence of damage from free drop impact, ***SQ*** – Severity classes and quantity of damage, ***DS*** – Damage scale, ***PD*** – Percentage of damage during transport, ***DDI*** – Drop damage index from free drop.

Figure A1: Hierarchical structure of the grasping mechanism based on the gripping approach(Marwan, Chua, and Kwek 2021)

Table A1: Table with compression test conditions

Author	**Fruit**	**Compression machine**	**Velocity of the probe**	**Time between harvest & test**	**Conditions before test**	**Time between test & damage evaluation**	**Conditions after test**	**Stop condition**	**Test conditions**	**Information about fuit**
Afsharnia et al. 2017	Mulberries	TA-XT Plus Texture analyzer	1.7mm/s		3 degC	1, 3, 7 days		Strain = 40%	25mm plate probe	
Akbarnejad, Azadbakht, and Asghari 2017	Bananas	Model STM-5, Santam							10cm plate probe	Moisture content
Banks, Borton, and Joseph 1991	Bananas	Salter Electronic Force Gauge	2.5 mm/s	30 min/1-2 days	24-31 degC	until stage 4/5(Von Loesecke)	25degC	10s	11 forces: 0.98-13.53N, 6 mm rounded probe	
Banks and Joseph 1991	Bananas	Self designed apparatus	2.5 mm/s			22 degC, acetylene threatment, until stage 4/5(Von Loesecke)		2.5, 5, 10, 20s	a series of 8-mm stainless steel balls mounted at 10-mm intervals, F = 3.91, 3.31, 2.87, 2.70 N	
Chen, Tang, and Chen 1985	Pears	Instron universal testing machine(model 1122)	10 mm/min	1,2, 4 days wait	0, 20 degC	2 h		1.5 or 3 mm deformation	spherical tip	Flesh-firmness reading with UC fruit firmness tester
Ferreira et al. 2008	Strawberries	IFAS Firmness tester			20-24 degC	1-2 days	20-24 degC	2-5 sec	convex tip probe 15 mm	

Table A2: Table with impact test conditions

Author	Fruit	Pendulum /pipe/drop	Time harvest - test	conditions before test	Time test - damage evaluation	conditions after test	Levels	Test conditions	Information about fuit
Chen, Tang, and Chen 1985	Pears	Steel rod with sphere tip	1, 2 or 4 days	0&20 deg	2h		Dh = 6, 10 cm	43.2g steelrod, 19mm sphere tip	Flesh firming reading
Banks and Joseph 1991	Bananas	Ball through tube drop			Until stage 4/5(von Loesecke)	25 degC	Dh = 0.4-8.0 cm	Steel ball 2.04g	
Kajuna, Bilanski, and Mittal 1997	Bananas	Rigid arm pendulum	1-11 days	20 degC		24 h	E = 0.21, 0.51, 0.83 J	Spherical impacter, r = 1.9 cm	
Van Zeebroeck et al. 2007	Tomatoes	Pendulum against fruit		15 or 20 deg			F = 15, 30, 60 N	Spherical impacter, r = 25mm	Acoustic stiffness
Opara 2007	Apples	Ball through tube drop			20-24h	20-22 degc		Ball 110 g, apple on double layered paperboard	
Opara et al. 2007	Apples	Ball through tube drop					Dh = 18.5-49.5 cm		
	Tomatoes	Fruit on pendulum					Dh = 9-39.5 cm		
Ferreira et al. 2008	Strawberries	Pendulum against fruit		20-24 deg	1-2 days	20-24 deg	E= 0.040, 0.024, 0.008 J	Ball 32.16g, 20 mm, berry in cheesecloth pouch and solid backstop	
		Fruit drop					E = (7.5, 4.0, 2.5) * 10^{-2} J	On aluminium plate	
Komarnicki et al. 2016	Pears	Pendulum with fruit				1 deg	2-328 mm	Against bumper with pressure sensor	Firmness index of fruit
Stopa et al. 2018	Apples	Fruit drop			4 days	25 degC	15 heights	Surface: concrete, five layer corrugated cardboard, polyethylene foam	Surface pressure
Öztekin and Güngör 2020	Peaches	Pendulum with fruit	6 h	21 degC	24h		Dh = 100-500 mm in steps of 100	Steel surface, 4mm rubber foam or 3.17mm Poron	Weight
Mencarelli, Massantini, and Botondi 1996	Kiwi	drop by hand		18degC		4/18degC	30 cm		

Chapter 4

Selecting a grasp location on the object

It can be concluded from the literature study that it is hard to determine how much force a fruit can handle without becoming damaged. Therefore it is recommended to avoid normal or friction force on the fruit itself to avoid bruising or abrasion. The peduncle of the banana seems a safe place to grasp. Damage to the peduncle does not have any influence on the flesh of the fruit.

A second argument in favour of grasping the top of the bunch is the way boxes of bananas can be opened. As you can see in Figure 4.1 it is hard for a robot to recognize which bananas are together in a bunch. Humans can not do it either. However, in the supermarket the boxes are opened this way. There has been observed how the greengrocer grasps a bunch of bananas out of its box in the supermarket. He grasps one banana, pulls it slightly out of the box, watches which other bananas move along. Then he grasps up to three bananas simultaneously and gently, pulls them out of the box and rotates the bunch as soon as possible, so that it lays on his hand. He uses his other hand to grasp the bunch at its tip and puts them on the shelf. For a robot this way of handling would not only require two arms and end effectors, it would also require a level of intelligence that robotic system do not have at the moment. When opening the box as in Figure 4.2 and grasping the tips of the bananas, it is easy recognizable where the robot needs to aim for the grasp.

Figure 4.1: *Box of bananas opened with the peduncles downwards*

Figure 4.2: *Box of bananas opened with the peduncles upwards*

Thirdly, empirical research has been done to find out how humans grasp a bunch of bananas. In Figure 4.3 and Figure 4.4 the bunch is grasped by one or two single bananas and lifted. The load, especially for the single banana, creates a bending at the end of the peduncle and the top of the banana fruit it self. This causes the banana fruit tip to become soggy. Additionally, when the gripper has to grasp multiple bananas, it is hard for a robotic system to figure out which banana belongs to

which bunch. In Figure 4.5 is visible how the bunch is scooped up and lifted. This however, requires space around the object and a fairly big gripper. Again, the best way to pick up the bunch is to grasp the tip where the peduncles meet, like in Figure 4.6.
With these three arguments there can be concluded that the best way for a robot to grasp a bunch of bananas is at the tip, where the peduncles connect.

Figure 4.3: *Grasping a couple bananas*

Figure 4.4: *One banana grasped*

Figure 4.5: *Bananas scooped*

Figure 4.6: *Bananas grasped at the tip*

Chapter 5

Method

In this chapter is the design method described. First the use case is regarded and used to define the functions of the gripper. These functions were used to make decisions in the design phase. The design phase existed out of two design circles. First, several prototypes were designed based on three different grasping principles. Out of those three prototypes, one was selected to continue using for the research. Secondly, the selected prototype was improved.

5.1 Design requirements

The goal of this study is to develop a gripper, select the actuator etc. The control of the robot arm and vision recognition is not in of the scope of this research. The goal of this gripper is to be able to grasp bunches of bananas out of the box and to lay them in a crate or on the shelf, in this case a banana wave. This has to be done without damaging the bananas in any way, as described in chapter 3. Lastly, robotic systems are not accurate. They have positioning errors up to 17.2 mm in the perpendicular plane(Zou et al., 2016, Cao et al., 2019). The gripper should be able to compensate for these misalignments. This results in several design requirements for the gripper:

1. Grasp a bunch of bananas, hold it while the robot arm lifts and moves the bunch and finally release the bunch
    (a) Move towards the bunch of bananas
    (b) Grasp the bunch of bananas
    (c) Hold on to the bunch of bananas while moving
    (d) Release the bunch of bananas
2. Minimize damage inflicted to the banana
    - No damage can be inflicted to the edible part (the fruit itself)
3. Compensate for the positioning errors of the robot
    - Compensate for misalignment of 17.2 mm in the plane perpendicular to the robots line of vision
    - Compensate for misalignment of 60 mm parallel to the line robots line of vision

5.1.1 Selection criteria of the gripper

To select the best prototype, hard and soft selection criteria are defined. The hard selection criteria are must-haves, the soft selection criteria are nice-to-haves.

Hard selection criteria

1. Fits inside a box of 50x100x200 mm
2. Strong enough to carry the weight of one bunch of bananas, 1kg on average with a maximum of 2 kg
3. Is able to grasp a bunch of bananas with 4-10 bananas with differently formed tips
4. Does not inflict any damage to the fruit of the bananas (the edible part of the banana)

Soft selection criteria

1. Minimize chances on damage inflicted to the peduncles of the bananas
2. Maximize the misalignment of the robot it can compensate
3. Easy to prototype
4. Durable

5.2 Design circle 1

In this section the description of the development of three prototypes is stated. Conclusively, one of the prototypes is selected for further development.

5.2.1 How to grasp the tip

A bunch of bananas is a complicated object to grasp. Until now there have been no robots in literature able to pick up a bunch. They only have been able to grasp a single banana. A bunch of bananas exists out of approximately 4-10 rigid, but vulnerable objects that are connected at the top by flexible links. There is concluded in chapter 4 that the best part to grasp a bunch is the tip. To find ways to lift the bananas by the tip empirical research was conducted by handling the bunch itself manually. The lifting could be done by hooking something between the peduncles(Figure 5.1), pinching the tip(**??**), or hooking something behind the ridge on the tip(Figure 5.3).

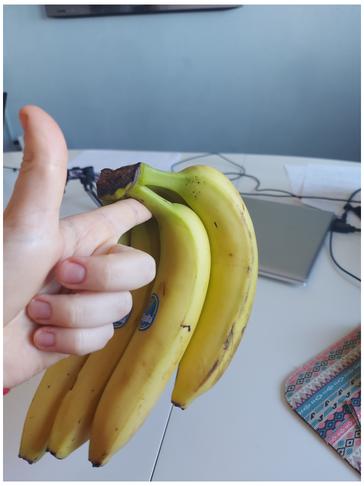


Figure 5.1: ***Method 1:*** *Lifting the bunch by hooking between the peduncles*

Figure 5.2: ***Method 2:*** *Lifting the bunch by pinching the tip of the bunch*

Figure 5.3: ***Method 3:*** *Lifting the bunch by hooking the ridge on the tip*

5.2.2 Banana replicas

Initially, testing the prototypes was done with real bananas. However, the bananas were only usable for a maximum of three days. Therefore there was looked into bunch replicas to test the prototypes on. Two options were found.

Foam bunches of bananas To start a foam bunch of bananas was used. The shape of this bunch is representative. However, the shape of the tip is not, and the weight is very low compared to a real bunch(Figure 5.4).

3D-scanned & 3D-printed bunches of bananas
Another way to create artificial bananas is 3D-printed bunches of bananas. To acquire the 3D-models of banana bunches, three different bunches were scanned using a 3D-scanner(Figure 5.5). Next to that a single banana was scanned as well. The results of the scans are 3D-models, examples can be seen in Figure 5.6 & Figure 5.7. Eventually in the printed 3D-model of the bunch, the bananas were cut off because it would cost too much material and did not contribute enough. The goal was to test the grip on the tip of the bananas(Figure 5.8). The disadvantage of the scanned tip, is that there is no space between the peduncles of the bananas. Therefore the tip was recreated by using a combination of the models of a bunch and the single banana(Figure 5.9).
Eventually, a combination of the three options was used. The foam bunches were used to easily show the working of the gripper, the 3D-printed tips were used for initial testing of the prototypes, but for the final testing real bananas were used.

5.2.3 Prototypes

Three prototypes were designed and prototyped. All have several iterations. After production, improvements have been made based on observed shortcomings of the design. Thereby a fourth prototype, which is a combination of two other prototypes, was developed.

Prototype 1 "Multiple small fingers" The first prototype inspired on grasping method 1, Figure 5.1. It exists out of an oval base with small fingers that need to wedge themselves between the peduncles of the bananas. The finger can rotate around an axis that is wedged between the upper and lower half of the base. The actuators are two half rings that are connected to the fingers. The fingers rotate inwards when the actuators are pulled outwards. The connection is elastic. Because it is elastic, the fingers can stop rotating inwards when they hit a peduncle and the ones that align with the gaps between the peduncles rotate further until they are between. When multiple fingers are between the peduncles the bananas can be lifted. The shape of the fingers made hard to get between the peduncles, see Figure 5.12. Therefore the finger was redesigned (Figure 5.13). Next to that, the shape of the ring was redesigned, to better fit around the tip of the bananas. The oval shape was made more rectangular, see Figure 5.14. The gripper is able to pick up a bunch of bananas, see Figure 5.15.

Prototype 2 "Hook gripper" The second prototype is a hook that grasps the bananas like in Figure 5.3. Another finger makes sure that the ridge is pushed on the hook and stays there. The first version exists out of a hook and a sliding finger, Figure 5.16. The prototype is able to grasp a bunch of bananas. However, the rounding of the hook caused the point of the hook not to reach the ridge, because the rounding would push against the peduncles. If the ridge is deep enough, the hook can

Figure 5.4: *Foam bananas*

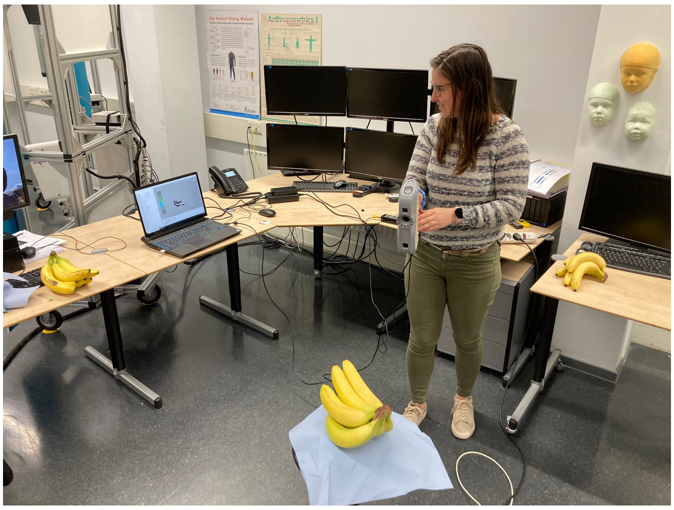


Figure 5.5: *Scanning the bananas with a 3D-scanner*

Figure 5.6: *Render of a single scanned banana*

Figure 5.7: *Render of a scanned bunch of bananas*

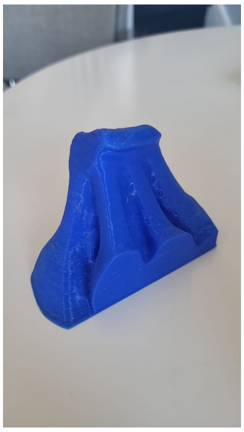


Figure 5.8: *Photo of printed tip of bunch of bananas*

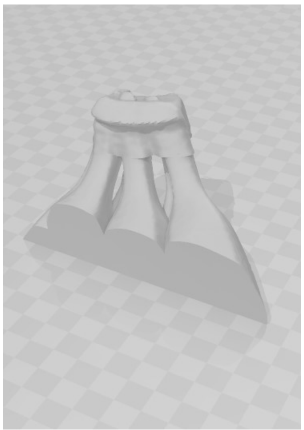


Figure 5.9: *Render of merged tip of bunch of bananas*

grasp the bunch underneath it, the second finger is used to push the ridge on the hook.
The second iteration of the hook gripper exists out of a base with a push finger and a slider for the hook finger, see Figure 5.18. This slider is used for prototyping, so that the distance between the two fingers could be adjusted. The hook finger is attached to the base by a bold, that cannot not move. The finger can rotate around the bold. The hook finger exists out of a bar and a cylinder with multiple hooks. The idea was that a rotational spring would push the cylinder clockwise(as seen in Figure 5.18), while closing the finger. This should assure that there would always be one hook locking itself underneath the ridge.
The third iteration of the hook gripper is a simplification. The point of the hook is protruding, giving it enough clearance to hook itself under the ridge. The joint between the two fingers is made compliant, this was done to make it easier to operate the gripper by hand. When pushing the gripper over the tip of the bananas, the gripper opens automatically because of the funnel shape of the fingers. When the point of the hook is over the ridge, you can squeeze the fingers together and the gripper will lift the bunch.

Prototype 3 "The bellow" The third prototype is inspired by grasping method 2, pinching the tip of

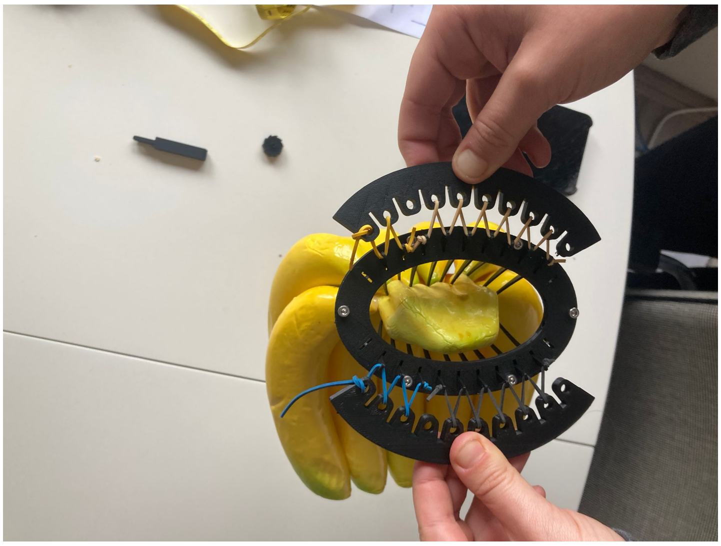


Figure 5.10: ***Prototype 1.1*** *Grasping a the foam bunch of bananas, top view, gripper existing out of one base, multiple fingers and two half rings to actuate the fingers*

Figure 5.11: ***Prototype 1.1*** *Grasping the foam bunch of bananas side view*

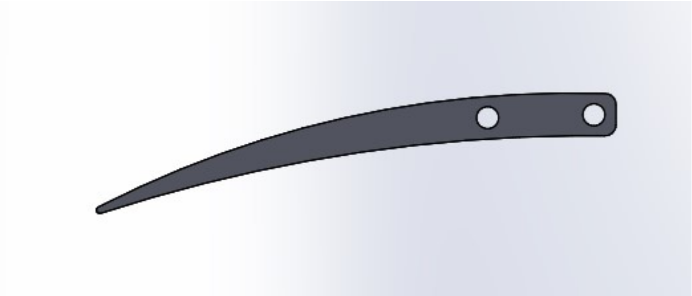


Figure 5.12: ***Prototype 1.1*** *Shape of first iteration of the finger*

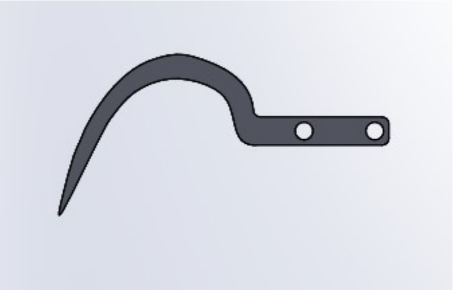


Figure 5.13: ***Prototype 1.1*** *Shape of second iteration of the finger*

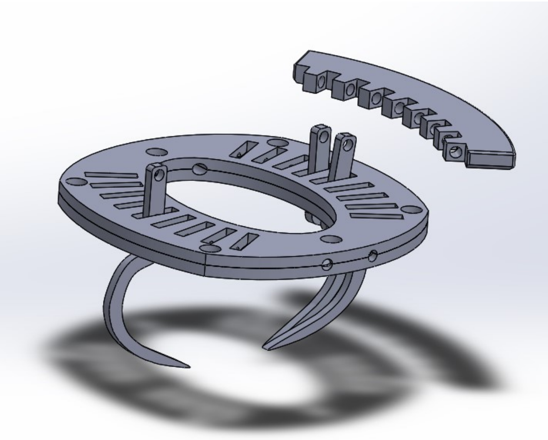


Figure 5.14: ***Prototype 1.2*** *Second version of the fingers prototype, with a rectangular base*

Figure 5.15: ***Prototype 1.2*** *Grasping a real bunch of bananas with the second version of the fingers prototype*

the bananas (Figure 5.2). The area on which force can be applied is small in relation to the weight of the object. Human fingers are quite soft and can apply the high force needed without damaging the bananas. To recreate this soft but sturdy grip, the functioning of the Festo bellow and granular sack

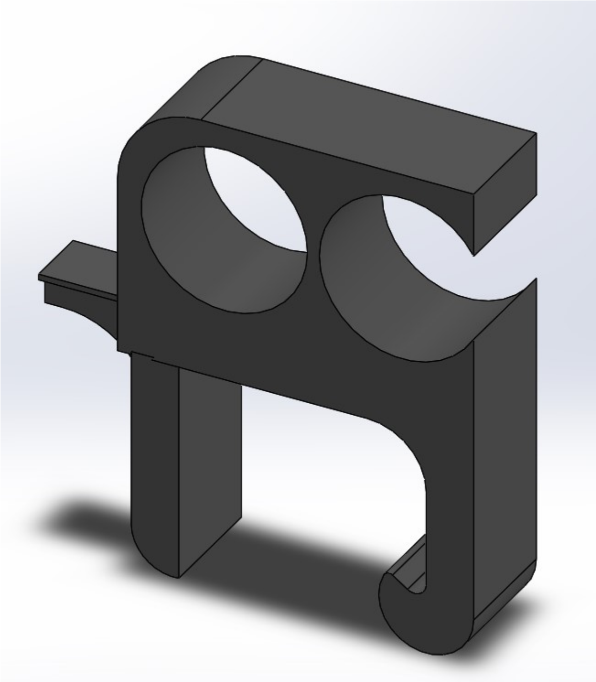


Figure 5.16: ***Prototype 2.0*** *A base with a hook and two holes for fingers. The pushing fingers slides through a slid to push the bunch on the hook.*

Figure 5.17: ***Prototype 2.0*** *Grasping a real bunch of bananas*

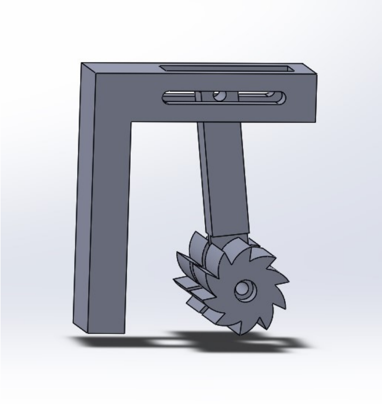


Figure 5.18: ***Prototype 2.1*** *A base with a push finger and a slider for the hook finger. The hook finger exists out of a bar and a cylinder with multiple hooks.*

Figure 5.19: ***Prototype 2.1*** *Grasping a real bunch of bananas*

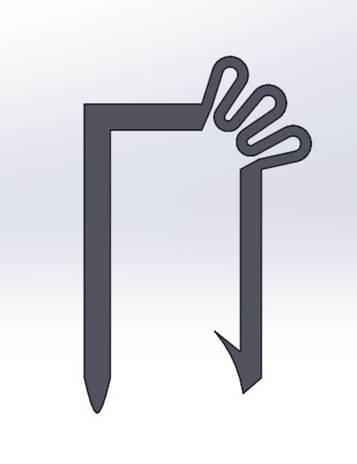


Figure 5.20: ***Prototype 2.2*** *A push finger and hook finger connected by a compliant hinge*

gripper was used as inspiration. The prototype exist out of a rigid oval ring (fig:prot3.0 & 5.22) with on the inside a inflatable ring. In this prototype the inflatable ring is made out of a long balloon. The rigid ring is rounded on the inside to ensure the balloon stays in place. When squeezed around the tip of the bananas, the balloon is sturdy enough to hold the weight of the bunch, see Figure 5.23. However, inflating the balloons when in the rigid ring of the prototype does not work properly.

Hybrid prototype, small fingers combined with push finger from hook finger During the prototyping phase, it was suggested to combine the small fingers with the push finger of the hook principle,

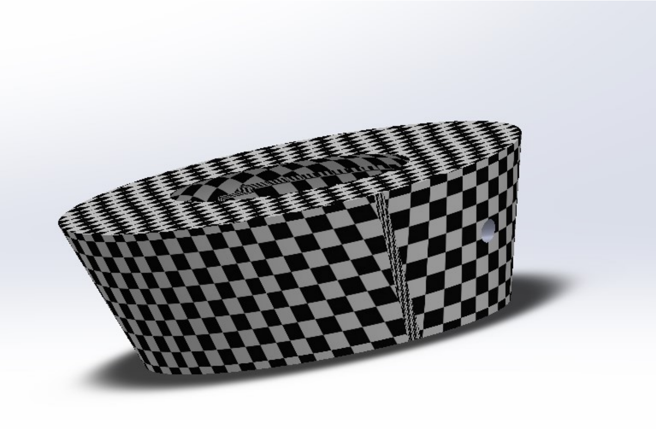


Figure 5.21: ***Prototype 3*** *Outside of the rigid ring, a small hole is visible on the right edge to blow air through to inflate the balloon.*

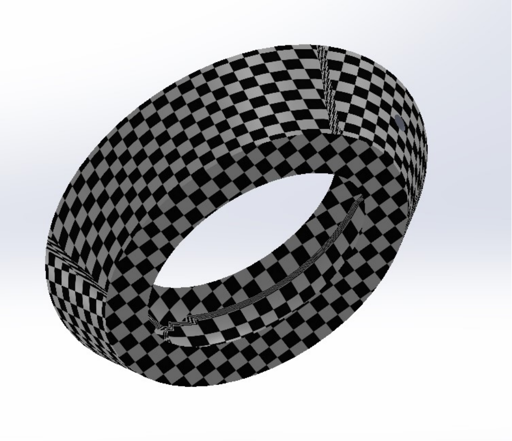


Figure 5.22: ***Prototype 3*** *Rounded inside of the rigid ring*

Figure 5.23: ***Prototype 3*** *Lifting a real bunch of bananas using an inflated balloon around the tip*

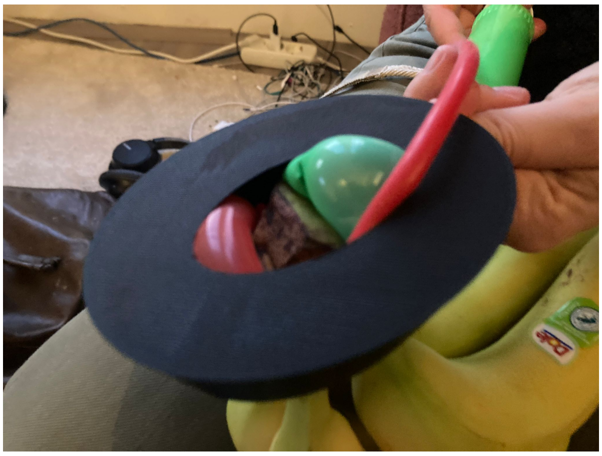


Figure 5.24: ***Prototype 3*** *Balloons inflated inside the rigid ring*

see Figure 5.25.

5.2.4 Production

All prototypes are produced by a 3D-printer using PLA. The assembly is done by M3 bolts and nuts. As small axis in the "small fingers" design the unused filament of the 3D-printer was used.

5.2.5 Selection

The "small fingers" and "hook" prototype fulfill the hard selection criteria. The principle of the "bellow" prototype does work, as it's possible to lift the bunch by squeezing the balloon around its tip. However, the prototype did not work, because it was hard to manufacture it. Thereby the gripper was relatively big compared to the other two prototypes.
The small fingers and the hook gripper both fulfill all hard criteria. However, when looking at the soft criteria the small fingers has some shortcomings. The small fingers have the potential to inflict more damage to the peduncles and are likely to be less reliable due to their complexity and thin geometry. The hybrid version did not reduce any of these issues. Therefore it is decided to move forward with the

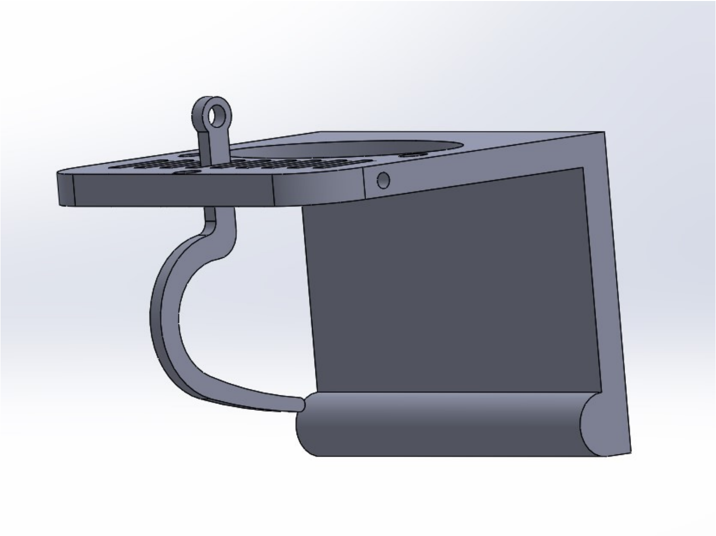


Figure 5.25: ***Hybrid prototype*** *Design of the hybrid prototype, one finger displayed, in every sloth belongs a finger*

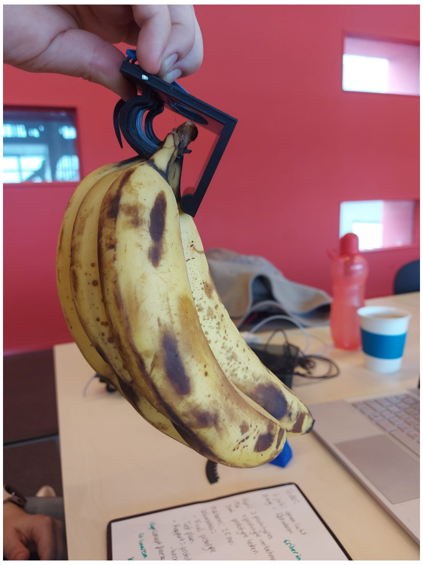


Figure 5.26: ***Hybrid prototype*** *Prototype lifting a real bunch of bananas*

hook gripper prototype.

5.3 Design circle 2

During the second phase of the design method, the gripping principle of hooking the bunch under the ridge is a certainty. To improve this design, parts of the gripper are regarded separately. First the way the fingers move in relation to each other is designed, then an actuator is selected to move the fingers and finally the connection to the robot is designed. The principle started with is the fingers connected by a compliant hinge as in Figure 5.20.

5.3.1 Grasping method

The grasping method has three different setups, a ratchet, a compliant hinge and a revolute joint with springs.
The idea of the ratchet (Figure 5.28) is tho use the fact that the tip of the banana has a thinner part like the waist of a hourglass (Figure 5.27). The gripper is opened and moved over the tip of the banana. It closes where the peduncles meet the fruit, while moving up, the fingers follow the shape of the tip and keep closing, without being able to open any further. That means that when the hook would meet the ridge of the banana, it isn't able to move further up and it will lift the bunch of bananas. The problem with this design is the step size of the ratchet. It could not be prototyped small enough to prevent the gripper from opening over the ridge of the tip.
The second iteration uses a complaint hinge to open or close the fingers(Figure 5.29). The complaint hinge made sure that the fingers are normally closed. After a bit of testing, the compliant hinge broke pretty fast. Because the gripper needs to be long lasting, the hinge was replaced by a revolute joint(Figure 5.30). Springs were added to the prototype to make sure that it was still normally closed. Finally, the hook finger and the nudge finger were switched around, to test if that would improve its functioning. There was found that the gripper has more reach when the hook finger rotates and is not

Figure 5.27: *Waist on the tip of a banana like an hour glass*

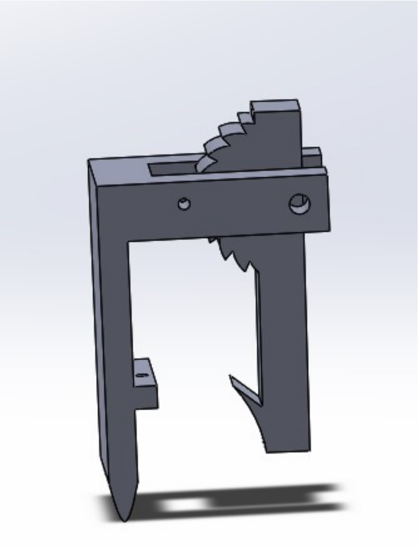


Figure 5.28: ***Ratchet principle** Prototype lifting a real bunch of bananas*

fixed to the system.

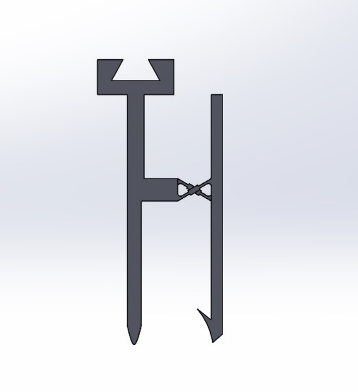


Figure 5.29: *Prototype with a hinge*

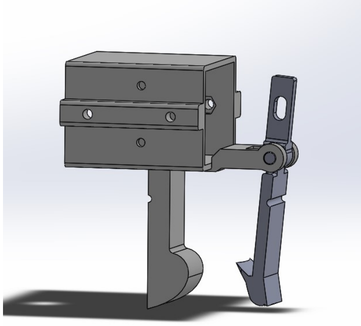


Figure 5.30: *Prototype with a revolute joint*

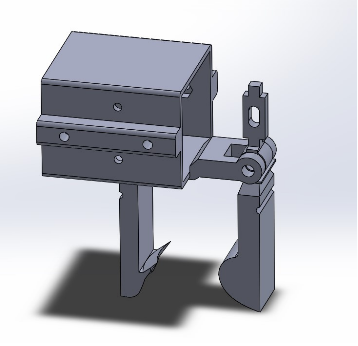


Figure 5.31: *Prototype with a revolute joint, but fingers switched*

5.3.2 Actuation

The gripper has to be normally closed, therefore two tension springs keep the fingers closed together, see Figure 5.32. The gripper either needs to be open, which is a hard stop, or it needs to close. The angle to which it needs to close depends on the size of the tip of the bunch. Thereby it needs to follow the shape of the tip and adjusts its closing accordingly. Therefore solenoid was selected as actuator. When it’s activated it opens the gripper, but when its non-active the finger can move freely. The closing is done by the two tension springs and the compression spring on the solenoid. To counter the forces of the springs, the first chosen 5N solenoid was not enough, therefore a stronger solenoid of 55N was selected. This one did suffice.

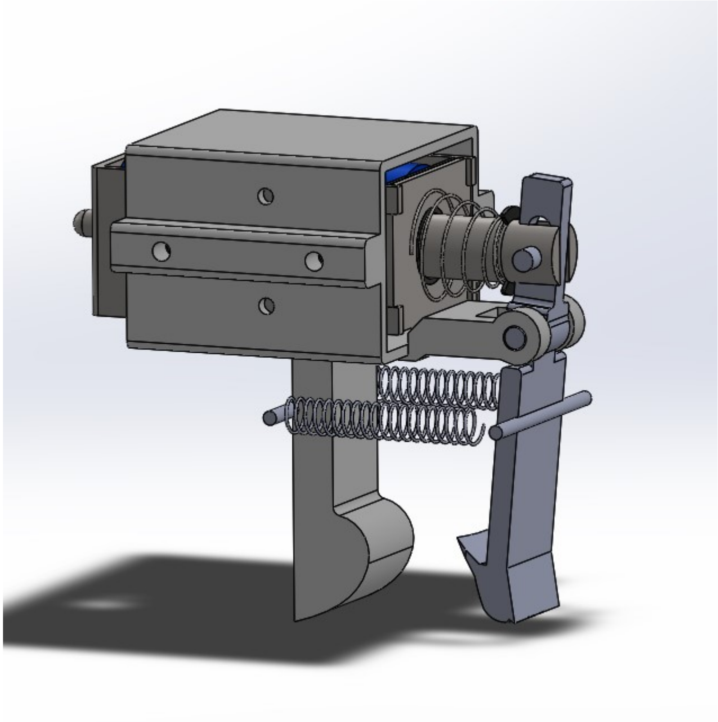


Figure 5.32: *Final gripper design with actuation*

5.3.3 Connection to robot

There are several reasons that the connection to the robot should not be a solid connection as can be read in chapter 6. Therefore several complaint and non-complaint structures were tested. The compliant structures were printed in TPU instead of PLA. The difference in the structures are the axis of rotation and the compliance. First it was thought that it would be beneficial to have the axis of rotation through the point where the gripper makes contact with the bananas. However, because of the heavy solenoid, the gripper could not keep it self upright before picking up the bunch(Figure 5.33). To solve that problem, a compliant V-joint was designed. The axis of rotation of this joint lays where the extensions of the compliant planes cross each other(Figure 5.34). Eventually, it was thought that the joint should work as a wrist joint, operating above the grasping location, so that the system could act like a pendulum underneath the joint. Therefore the V-joint was replaced by an X-joint(Figure 5.35). As an alternative, two tubes replaced the X-joint. In Figure 5.36 two tubes allow rotational freedom in 2 directions. However, production was difficult, as the tubes ripped apart quite easily. Therefore, finally the X-joint was selected and the final design can be seen in Figure 5.37.

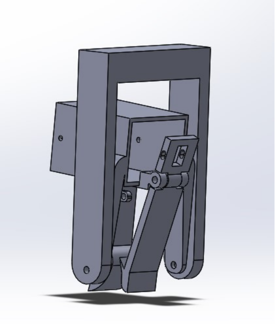


Figure 5.33: *Connection with a revolute joint*

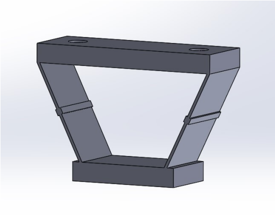


Figure 5.34: *Connection with a compliant V-joint*

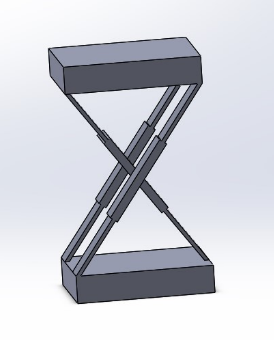


Figure 5.35: *Connection with a compliant X-joint*

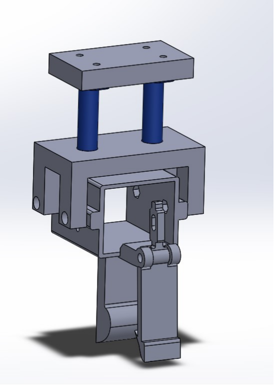


Figure 5.36: *Connection with two compliant tubes*

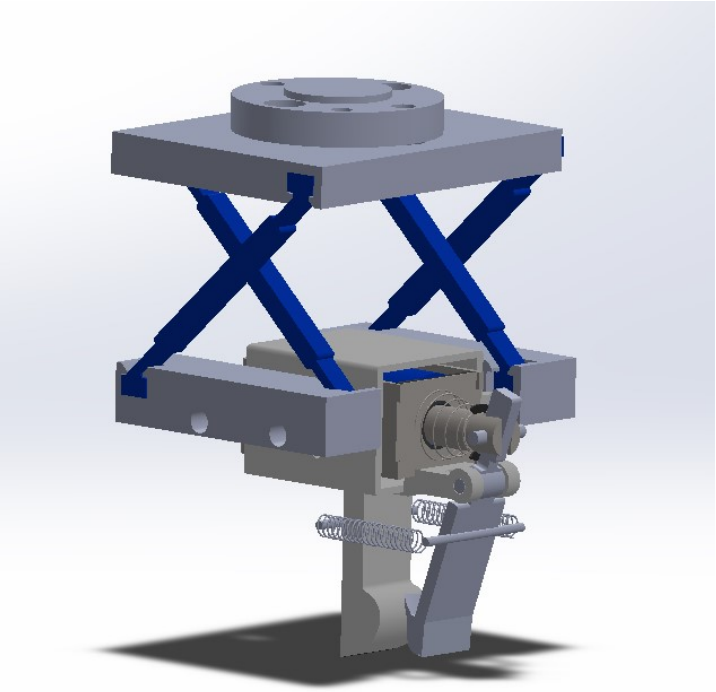


Figure 5.37: *Final gripper design with actuation and the connection to the robot*

Chapter 6

Evaluation of the functioning of the proposed design

In this chapter a research paper about the final gripper and its evaluation is presented.

Design and evaluation of a gripper for bunches of bananas in a supermarket environment

Anne van der Star TU Delft

Abstract

In this paper the first gripper that can grasp bunches of bananas is presented. Bunches of bananas are difficult to grasp by a mechanical gripper, as they vary in size and shape and are sensitive to damage caused by mechanical impact. In former research, single bananas have been grasped with pinching- or granular grippers. The gripper proposed in this paper grasps the bunch at its most sturdy part, namely its tip, and uses a hook finger to minimize the chances on damage. The scissoring fingers allow the gripper to handle the variability of the object. Additionally, the scissoring combined with the funnel shaped finger tips ensure that the gripper compensates the position errors of robotic systems. In the evaluation of its abilities the gripper is able to pick up 19 out of 19 bunches of bananas. It has a tolerance for a maximum positioning error of 4.9 cm and causes only minor damage on the peduncles of the bananas. In practical experiments, the gripper performed adequately and showed to be able to cooperate with the object to guide itself to the right location. The novel strategies of hook gripping and the extra degree of freedom of the compliant X-joint show that bunches of bananas can be grasped mechanically, while compensating for some of the shortcomings of current robotic systems.

1 Introduction

A growing and ageing population is causing challenges for the food sector. With more mouths to feed, but less hands to do the work, a shortage of food could become a problem in the future. Automation is one of the solutions in this sector, but the interaction with biological products is difficult. The challenges are the variety of shape and size, and the fact that these products bruise easily. Post-harvesting mechanical grippers are already being used. However with harvesting and the end of the supply chain, robots need to interact directly with the products instead of their packaging.

In the agricultural sector several solutions have been proposed and designed to cope with these challenges. Grippers have been designed specifically to harvest fruit, with the ability to accommodate differences in size and shape. These grippers are mostly targeting spherical fruits like tomatoes, oranges and apples (Chiu et al. 2013, Setiawan et al. 2004, Zhang et al. 2020). Grippers for i.e. bell peppers (Bac et al. 2014), strawberries (Hayashi et al. 2010) and raspberries (Yang et al. 2021) have also been proposed. In other research, grippers are designed to grasp a variety of objects. For example the granular gripper of Krahn et al. 2017, which proved to be able to pick up, among others, an apple, a tomato, a pear and a banana. Although the granular gripper of Krahn et al. 2017 is able to pickup a single banana, there is no gripper to grasp a bunch of bananas. This paper will delve into this matter.

Besides harvesting, robots could be working in the supermarket as well. Tomizawa et al. 2006 & Cheng et al. 2017 propose a robot that can take groceries from a shelf and put them in a basket. Other use cases could be stocking the shelves or filling the baskets of online grocery orders in distribution centers. Grippers from the agricultural sector could be used in these environments. However, the implementation of such systems may still take a long time. These systems have too many shortcomings, like the fact that certain products cannot be grasped by current solutions. There is no gripper yet that has been able to grasp a bunch of bananas. Existing grippers are not fit for the job, to grasp this heavy, weirdly shaped, sensitive fruit. Currently, bananas are the most spilled fruit (Mattsson et al. 2018). Even light forces on the fruit cause brown spots, which makes it less attractive to eat. However, to lift this heavy object, light forces are not sufficient. To minimize the chances of damage, a novel gripper is proposed which grasps the tip of a bunch of bananas in order to minimize chances of damage, and be able to reliably grasp bunches of bananas considering the abilities of existing robot technology.

1.1 Research objective

The proposed gripper has to be able to grasp bunches of bananas out of their container, hold them during movement of the robot and put them down on a different location, for example on the shelf or in a crate. The chances of damage to any of the bananas in the bunch should be minimized.

1.2 Research structure

In this paper a prototype will be designed and evaluated to show that the proposed gripper is able to successfully grasp bunches of bananas. Firstly, the method section starts with the functional requirements of the gripper. Following the advantages of certain design features will be discussed. Then the setup of the measurements is explained. The method section is finalized with the setup of two practical experiments. In the next section the results are presented and discussed. Finally, in the last section the conclusions of this research are presented.

2 Method

The method section explains the functional requirements and design features of the gripper. Subsequently the test setup for the measurements and practical experiments is described.

2.1 Functional Requirements

The designed gripper has to fulfill several functional requirements to function properly with the challenges stated earlier in the introduction. Firstly, the gripper has to be able to grasp a bunch of bananas, hold it while the robot arm lifts and moves the bunch and finally release the bunch. A bunch of bananas contains 3-10 bananas and the weighs 1 kg on average.

Secondly, the gripper should minimize the chance of inflicting damage upon the object. Fruit waste has to be minimized and it helps if there is less visible damage. “We love bananas but we do not buy them if they have any brown spots," says Lisa Mattsson(Monaco 2018). Bananas can be damaged in several ways, bruising, abrasion and puncture(Li et al. 2014). Bruising is caused by too much pinching force or an impact, abrasion by friction on the skin and puncture by sharp objects penetrating the skin. All of these types of damage should be avoided in case to minimize food waste.

Thirdly, the gripper has to compensate for position errors. Robots have positioning errors (Cao et al. 2019). This means that there is a difference between the aimed location and the real location of the end effector. The errors can be caused by the vision or the sum of the errors in the joints of the robot. Vision based errors can result in a mispositioning of 17.2 mm in the x- or y-direction and up to 60.1 mm in the z-direction (Zou et al. 2016).

2.2 Design features

At the start of this design process, human handling of bunches of bananas (from now on “the object”) was investigated as inspiration for the design. Inspired by that research, the decision on where to grasp the object was made. The prototype (Figure 2) hooks the object under the ridge on the tip of the bunch (Figure 1). The gripper is actuated with a solenoid, which is a linear actuator driven by a coil. When not activated, the solenoid can move freely through its stroke length. The gripper is normally closed because of the springs. A compliant x-joint connects the gripper and the robot. Multiple features of this design benefit the objectives set earlier in subsection 2.1, these will be explained in the following sections.

Figure 1: Ridge on the tip of the bunch of bananas

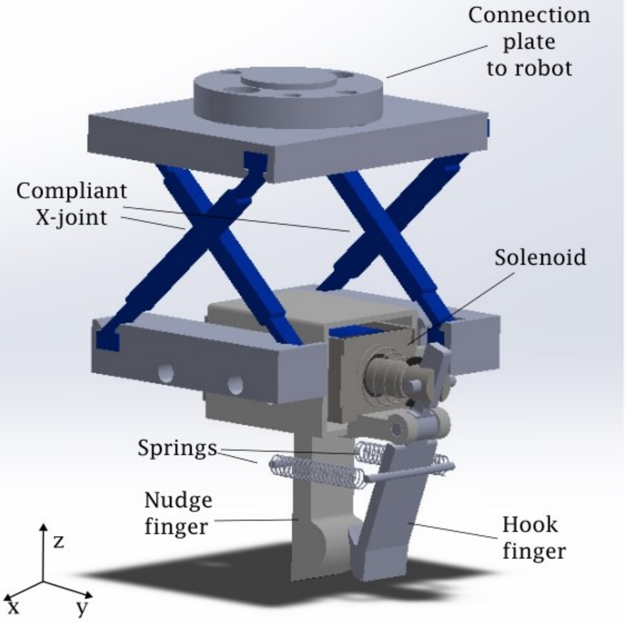


Figure 2: Render of the complete gripper, the grey material is solid, the blue material of the compliant X-joint is flexible.

2.2.1 Location of the grasp

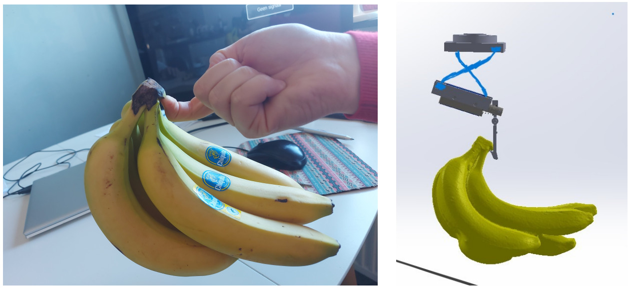
Grasping the object at the tip has multiple advantages.

1. The object is tougher here.
2. If the gripper leaves any damage, there is no risk of bruising the flesh of the fruit.
3. No chance of ripping off any individual bananas.
4. The peduncles are clearly visible for the robot, as they have a different color .
5. The peduncles lay unobstructed in the box, there is no clutter around it, see Figure 3.

Figure 3: Bananas in a box

2.2.2 Grasping method

Contrary to a pinching gripper, the designed gripper does not rely on friction force to lift the object. This means that the forces exerted on the object can be lower, decreasing the chances on damage. The gripper only needs the hook finger to lift the object, see Figure 4. The pinching force from the nudge finger is used to guide the fingers around the tip and prevent the bunch from falling of the hook. Therefore the pinching force can remain relatively small.



(a) Bunch of bananas in equilibrium on a finger

(b) Render with bananas in static equilibrium on hook finger

Figure 4: Object in static equilibrium on a point

The shape of the ridge of the hook is round, to create a bigger contact area with the ridge of the bananas, see Figure 5.

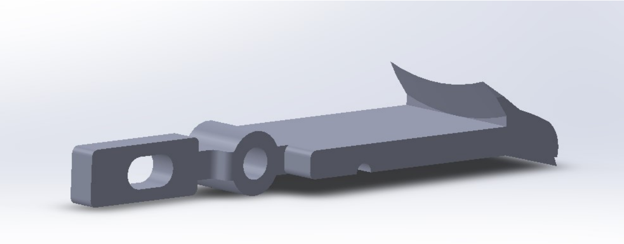
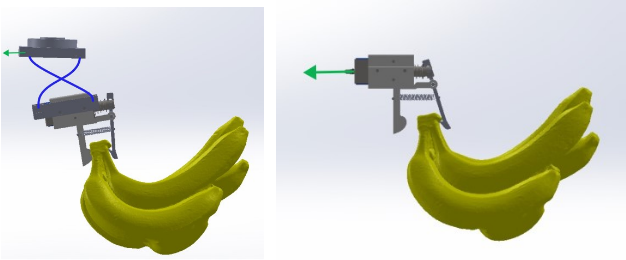


Figure 5: Hook shape of the finger

2.2.3 Compliant X-joint

The compliant X-joint has three functions in this design. Firstly, it allows the gripper to rotate together with the bunch of bananas, as in Figure 6a. This prevents the bunch to lose contact with the nudge finger and decreases the chances that the bunch rotates with respect to the hook, causing it to fall of. This is illustrated in Figure 6b. In both situations the gripper is moved to the left, but reacts differently to the movement. With the compliant x-link the gripper stays closed. The center of rotation of the joint is chosen to be vertically aligned with the center of mass of the lower part of the gripper. This means that the gripper will be level when it is stationairy.



(a) Movement with compliant X-joint

(b) Movement without compliant X-joint

Figure 6: Illustration of the reaction of the gripper on a movement to the left, either with a compliant X-joint or without

Secondly, when the fingers are lowered over the tip and the tip is not aligned with the movement, the fingers can follow the shape of the tip.

A third advantage of the compliance is that the bananas can move out of the way when the robot pushes them accidentally into a rigid object. This will not prevent all damage, but avoids catastrophic damage.

2.2.4 Variable pinching force

Three springs work together to close the finger; the compression spring of the solenoid and two tension springs force the fingers' tips towards each other. Because of Hooke's law, the pinching force will be bigger for larger deflections. For bigger bunches, the fingers will stay further apart and consequently, pinch harder on a heavier bunch.

2.2.5 Compensation of positioning errors of robot

To cope with this problem, this gripper has scissoring fingers. When opened, it works as a funnel, because of the way the tips are shaped. It provides enough clearance to easily position the tip of the bananas between the two fingers. When the solenoid is turned off, the fingers close with the tip in between. Moving the gripper up along the z-axis the fingers follow the shape of the tip until the hook meets the ridge (Figure 7). Subsequently, the gripper starts lifting the bunch of bananas. Therefore the robot does not need to have precise aiming.

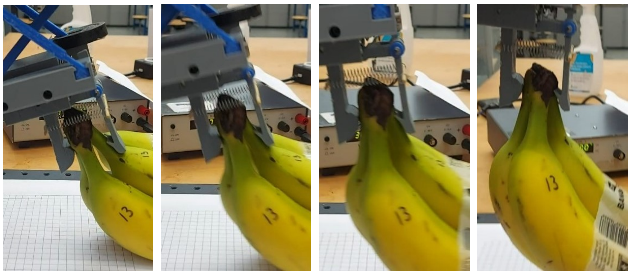

(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Figure 7: Fingers grasping the banana tip, the tips of the fingers are pulled together, following the shape of the tip. The nudge finger keeps pushing the tip against the hook finger while the gripper moves upwards.

2.3 Mechanical analysis of the pinching force

The proposed pinching force is around 10 N. In Figure 8 the free body diagram of the finger is drawn. When stopped by an object between the fingers, the fingers exert a pinching force. The pinching force depends on the deflection of the springs and therefore on angle α. To calculate the pinching force of the gripper, the moment around the finger joint is calculated. The following equation follows:

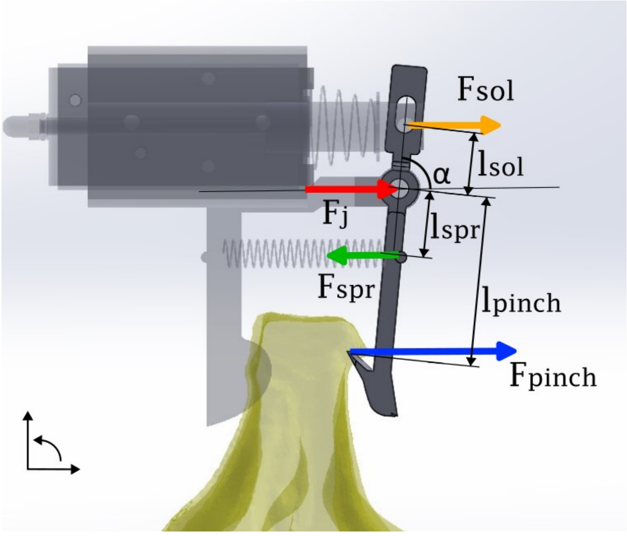


Figure 8: FBD of the hook finger just before the gripper starts lifting. Therefore there is no weight of the bananas on the finger yet. F_{sol} resembles the force of the compression spring of the solenoid, F_j is the reaction force in the joint of the finger, F_{spr} is the force the two tension springs exert on the finger, F_{pinch} is the reaction force from the banana, which equals the pinching force of the gripper

$$\sum M_{joint} = F_{sol} * r_{sol} +$$

$$2 * F_{spr} * r_{spr} - F_{pinch} * r_{pinch} = 0$$

where

$$F_{sol} = c_{sol} * x_{sol}(\alpha)$$

$$F_{spr} = c_{spring} * x_{spr}(\alpha)$$

$$r_{pinch} = l_{pinch}/sin(\alpha)$$

The range of motion of the gripper is defined by the stroke length of the solenoid. The solenoid has a stroke length of 1 cm. The angle α is 69 ° when the gripper is closed, when fully opened angle α equals 105 ° ($\alpha = [69; 105]°$). The pinching force of the gripper ranges between 4 and 10 N.

2.4 Measurements

To confirm the working principles of the gripper, the gripper is mechanically evaluated in several tests.

Test 1 *Mechanical grip evaluation:* The pinching force of the gripper is determined by the springs in the system. With a force gauge and a protractor the force is measured as function of the angle α, see setup in Figure 11. The Salter Super Samson force gauge was used, which has a maximum of 5kg and a precision of 25g. The protractor used has a precision of 1 degree. A modification had

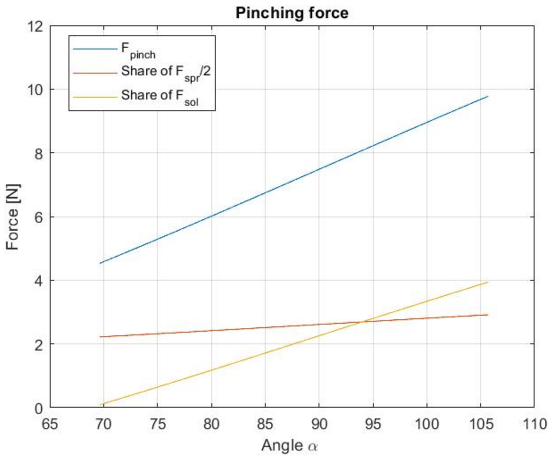


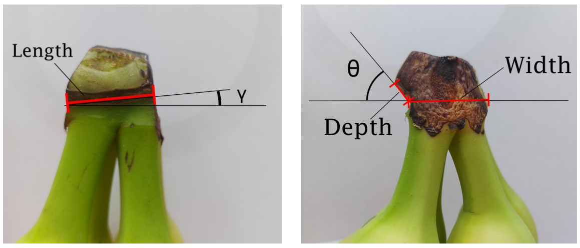
Figure 9: Pinching force of the gripper as function of angle α, F_{spr} resembles the share in the pinching force of 1 tension spring, F_{sol} resembles the share in the pinching force of the pressure spring of the solenoid

to be made in the calculations, as the pinching force is measured in a slightly different location then where the gripper exerts a force on the object.

Test 2 *Assessment of the compliant X-joint:* The stiffness of the compliant X-joint is measured in the same setup as item test 1. This time a gauge with a maximum of 1 kg and a precision of 5g is used. The solenoid is hold, the gauge is attached to the connection plate. The gauge is pulled in the direction of the movement of the connection plate.

To test the functioning of the X-joint the gripper holds one object and is held manually by the connection plate. Then the gripper is accelerated in the y-direction. Next, the gripper is held manually by the solenoid to cancel the functioning of the X-joint and accelerated in the y-direction. Both movements are filmed on the yz-plane. The footage is examined to validate the functioning of the X-joint.

Test 3 *Gripper success rate:* In this test, the The population exists out of 19 bunches of bananas, 12 had 4 bananas on them, 7 had 5 bananas. They weighted $0,84 \pm 0.081$ kg. The length of the rigde was $21,29 \pm 4,9$ mm, the width of the tip $23,88 \pm 2,1$ mm and the depth of the ridge $4,18 \pm 0,58$ mm. The angle γ was $10 \pm 8,6$ and angle θ was 51 ± 15. See Figure 10 for an illustration of the measured dimensions. The orientation around the x-axis of the object is as it settles when laid down. To start the test the object is placed on the platform underneath the gripper, see Figure 12. To ensure a consistent location of the tip of the bananas, the x- and y- coordinates are checked with a laser pointer. The midpoint of the ridge is marked and aligned with the x-laser. The y-laser is aligned with the base of the ridge. The gripper is manually opened and lowered over the tip, then the gripper is closed and lifted. The grasp is successful if the object is lifted from the platform. After releasing the object, the steps are repeated with a new object until the gripper is tested on all 19 objects.



(a) Front view of the tip (b) Side view of the tip

Figure 10: Measurements on the tip of the banana. Indicated are: (a) the length of the ridge (b) the width of the tip (c) the depth of the ridge (γ, θ) angles of the ridge

Test 4 *Examine tolerance for the positioning error:* The object is moved along one axis or rotated around one axis after which a new grasping attempt like in test 3 is conducted. This is done for 2 translations and 2 rotations.

(a) *Translation in y-direction* A grid is applied on the platform and a mark is applied on the side of the object. The translation can be measured by the different location of the mark on the grid.

(b) *Translation in x-direction* The translation is measured by the difference between the X-laser and the midpoint marking of the ridge.

(c) *Rotation around the z-axis* A photo is taken from above on the xy-plane. With the photo the angle can be measured.

(d) *Rotation around the y-axis* A photo is taken from aside on the yz-plane. With the photo the angle can be measured.

Test 5 *Check the objects for damages:* A photo of each object is taken one hour after the tests to visually examine the damage done by the gripper.

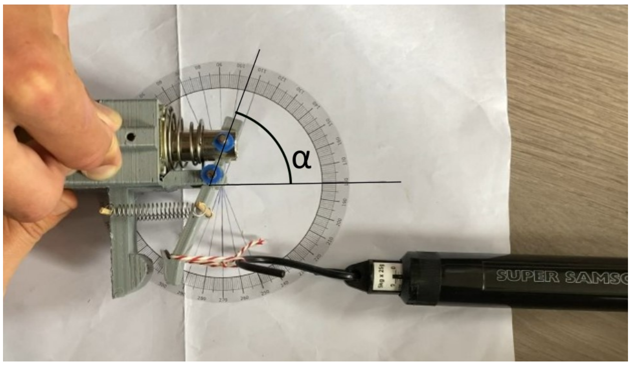


Figure 11: Setup to measure pinching force in test 1 as function of α

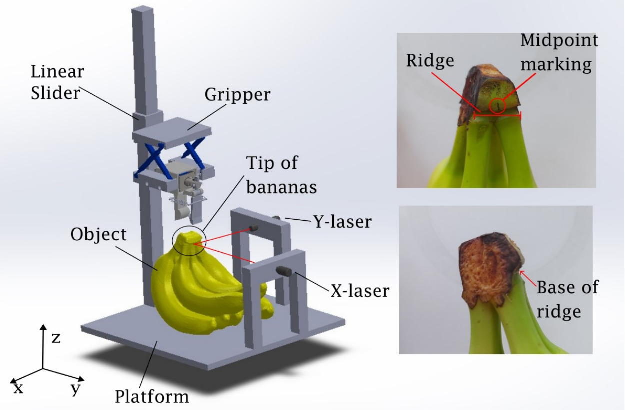


Figure 12: Test setup used in test 3 & test 4

2.5 Practical experiments

During the practical experiments the gripper was tested in a more realistic environment. Firstly, it was handheld and used to unload a box with bunches of bananas. Secondly, it was attached to a robot arm to stack the shelves like in a supermarket.

Exp. 1 *Unloading a box of bananas:* To simulate the situation in practice, a box of bananas is opened as in Figure 3. The same population as in test 3 is used. The gripper is manually controlled by holding the connection plate and used to move all bunches of bananas out of the box on to the table. The gripper is opened with the solenoid, the solenoid is controlled by a manual switch. Then the fingers are placed over the tip of a bunch, the gripper is closed and the gripper is lifted. When successful, the bunch is moved out of the box on the table and the gripper is opened to release the bunch. When unsuccessful, a new attempt is made. In this experiment, it is assumed that the robot attached to the gripper has perfect understanding of its surroundings.

Exp. 2 *Robotic shelf stocking:* Finally, the gripper will be attached to a robot arm. The robot used is the Franka Emika Panda. This is a 7 degree of freedom arm. The robot will be used to grasp a bunch out of the box and lay the bunch on the shelf. The poses of the robot are pre-programmed by moving the robot to the right position and saving its pose. Before running the program, a bunch of bananas would be positioned in the box with its tip approximately between the fingers in the robots gripping pose.

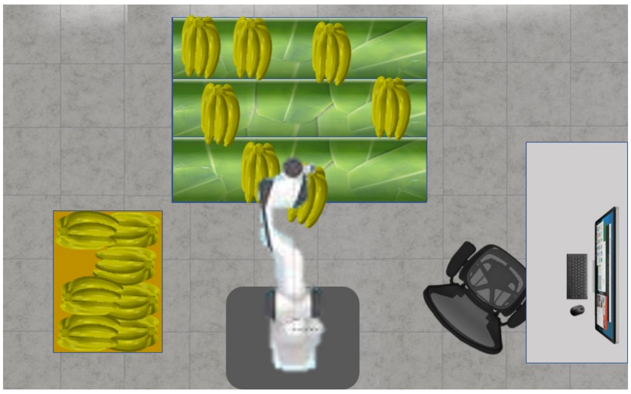


Figure 13: Top view of the supermarket experiment, on the left of the map stands the box with bananas, at the top the banana shelves, in the middle the robot arm and on the right the computer to control the robot arm.

3 Results

In this section the results of the tests and experiments described in the method section are presented. First, the results of the tests will be explained, then the outcomes of the experiments will be described.

3.1 Measurements

The results of the measurements are presented per test setup.

3.1.1 The validation of the pinching force

The data from the test are presented in Figure A3. The pinching force of the gripper increases for a increasing angle α, however the measured forces deviate from the calculated values. The average deviation of the measurements compared to the calculations is 7%.

3.1.2 The functioning of the X-joint

The linear trend in the data proves that the joint stiffness is constant. From the fitted plot can be calculated that the joint

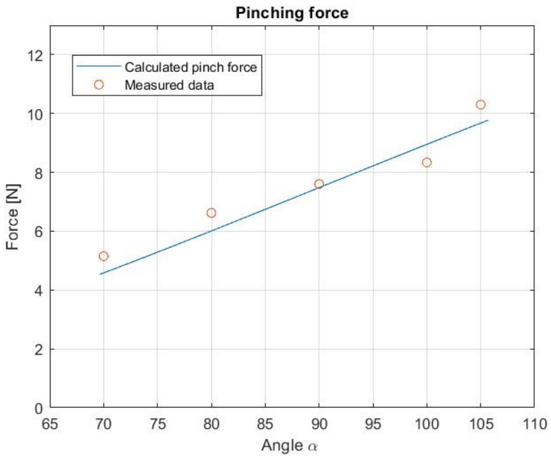
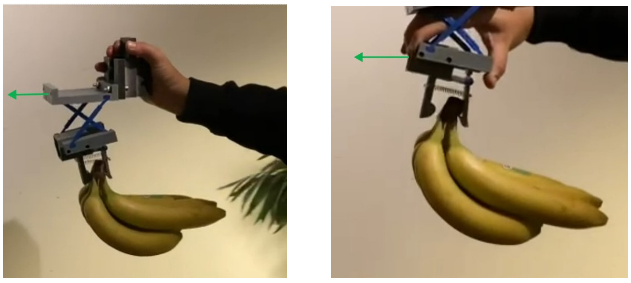


Figure 14: Measured values of the pinching force of the gripper plotted against the calculated values

stiffness is $0.13N * cm/^{\circ}$.

As can be seen in Figure 15 the functioning of the X-joint is as predicted. Without the X-joint the nudge finger is not in contact with the bananas anymore and therefore the chances of the bananas falling off increases. Additionally, it was observed that if the gripper is rotated over the x-axis, the bananas stay in place with the X-joint and fall without it.



(a) Movement with X-joint (b) Movement without X-joint

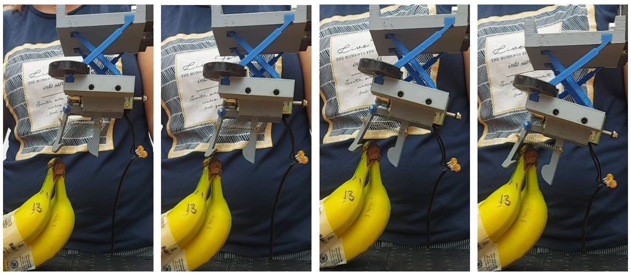
Figure 15: Stills of videos of a movement to the left, the green arrows depict the movement

3.1.3 Success rate

Out of 19 bunches 18 were grasped successfully in the first try, 1 one was grasped the second try. it was observed/noted that the gripper failed to successfully grasp the bunch when the tip of the bananas was positioned too horizontally. This has to do with the rotation around the x-axis of the object, which was not controlled in this experiment.

3.1.4 Tolerance for the positioning error

The gripper did successfully cope with misalignment. For the misalignment in the x-direction this means that when a solid part of the ridge is still within the borders of the finger, the gripper can lift the bananas. The smaller the overlapping surface, the weaker the grasp on the object is. The variability which the gripper can handle the misalignment in the y-direction depends on the shape of the tip of the bunch. When the tip looks like a wedge, it will help the funneling of the fingers, see Figure 16. In this case the gripper can grasp a bunch within a reach of 4,9 cm over the y-axis. When the tip is shaped like a trapezium with a flat platform on top, there is a bigger chance that the finger bottoms out on the flat top instead of deflecting of the tip. Therefore the reach decreases to 3.4 cm.



(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Figure 16: Funneling function of the gripper, the hook finger hits the tip on its way downwards, because of the compliant X-joint and funnel shape of the fingers, the gripper manoeuvres itself around the tip.

When the bunch is rotated around the x-axis, with the tip of the bunch almost horizontally, it causes problems. The fingers can not properly be lowered over the tip, because the hook finger bottoms out against the peduncles. When the bunch is rotated around the z-axis, the fingers rotate the bunch back to neutral when closed. This only happens if the fingers have contact with the two opposite sides of the tip(front and back). If the sides are adjacent(e.g. front and right), it squeezes the tip out of the fingers. The maximum angles of rotation that the gripper can handle depends on the geometry of the tip.

3.1.5 Damage on the bananas

The gripper only interacts with the tip of the bananas. This means that no bruising can take place as the tip does not contain any edible flesh. There are no sharp points on the gripper, so puncture does not happen either. Abrasion on the tip is the only type of damage that occurs. The hook of the gripper scrapes along the tip of the bananas. The level of abrasion is sorted into five categories, see Figure 17. In category 0 no damage is visible, in category 1 one small spot is visible, in category 2 one bigger or multiple small spots are visible, in category 3 multiple bigger spots are visible. Category four has no representing image, as there was no case of such damage. This category was defined as severe cuts through the skin. The number of bunches in each category is depicted in Figure 18.

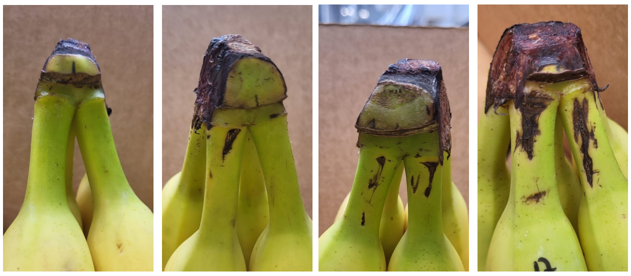

(a) Category 0 (b) Category 1 (c) Category 2 (d) Category 3

Figure 17: Damage on bananas per category, category 0-3 are represented

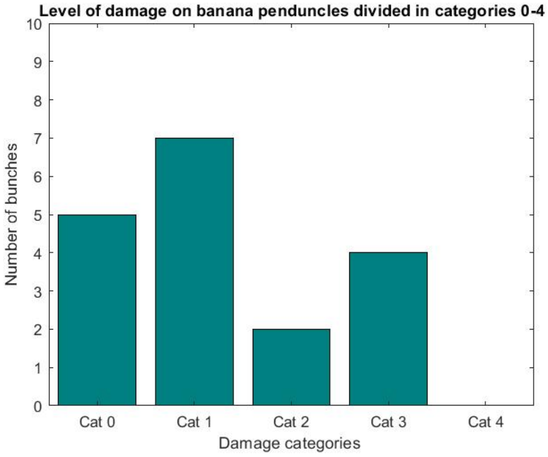


Figure 18: Damage on the bananas sorted in 5 categories

3.2 Results of the practical experiments

In the first experiment a box was emptied with the gripper manually operated. Out of 13 bunches which were attempted to be lifted, 12 attempts succeeded in one go. The grasp of 1 bunch failed twice and had to be grasped 3 times before it could be lifted.

In the experiment with the robot arm, 5 out of 9 attempts succeeded. The other attempts failed because the gripper was not lowered enough. The gripper missed the tip and would not grasp the bunches at all in that case. In four out of five cases where the grasp was successful, the gripper released the bananas on the shelf without any bruises. In the fifth case, the robot arm movement was not calibrated right and the robot hit the bananas against the shelf. It was observed that the bunch was not pushed in to the shelf forcefully because of the freedom of movement of the compliant X-joint.

4 Discussion

The discussion is divided in two parts. First, the setup and execution of the tests and experiments will be discussed. Second, the functioning of the gripper discussed. Finally, recommendations for further research are presented.

4.1 Setup of the tests & experiments

The measurements overall were not very precise. This was caused several uncertainties, for example in the evaluation of the gripping force; the increments of the gauge are 25g, slight misalignment of the camera angle resulted in a hard-to-read protractor angle measurement of the deflection. Another source of inaccuracies was the fact that the gripper was held in place by hand. For the values of the pinching force it was precise enough, the goal of the measurement was to find the order of the magnitude. Furthermore, in the test assessing the tolerance for positioning errors, the target object was moved by hand, this could have been done by a linear motion platform. However the variation in size and shape of the object, causes more precise measurements to be unnecessary. Furthermore, the gripper should be tested on a robot that makes decisions on its own in stead of executing a preprogrammed motion.

4.2 Gripper

Coming back at the functional requirements stated in subsection 2.1 the results of the test show the three functional requirements are met. First, the gripper should be able to grasp a bunch of bananas, hold it while the robot arm lifts and moves the bunch and finally release the bunch. Based on test 3 and the two experiments it became evident that the gripper is able to grasp the tips of bunches of bananas, varying in size and geometry. Some attempts had to be repeated in order to succeed, but eventually all bunches were grasped, moved and released. The tip of the bunch appears to be a reliable spot to grasp a bunch.

Secondly, the chances of damage caused by of the gripper should be minimized. None of the bunches were so severely damaged that they could not be sold. The gripper does not interfere with the parts of the fruit where the edible flesh is located. Therefore it can not bruise the flesh. However, the abrasion on the peduncles could cause the bunch not to be sold. The gripper can be improved by another mechanical closing system. The pinching force could be decreased. This would decrease the scraping of the hook finger along the peduncles and therefore decrease the chance on abrasion.

Thirdly, the gripper should compensate for the robots' positioning errors. The funneling of the fingers and the flexibility provided by the compliant X-joint make sure that it can compensate for misalignment in the y-direction. The lowest measured reach of 34 mm can make up for the vision based errors of 17.2 mm. To still lift the bunch in case of misalignment in the x-direction the hook finger has to be in contact with the ridge. When the finger(20 mm wide) is translated 17.2 mm in relation to the ridge(on average 21.29 mm wide), there is still an overlap of 3.45 mm. To improve the overlap, the finger could be made wider. How the gripper deals with misalignment in the z-direction is not evaluated. Overall it is observed during the experiments that as long as the tip of the hook finger is moved passed the ridge, the grasp will succeed. This does not make up for the 60.1 mm positioning errors made by the robot in this direction. The feedback of a force sensor or a proximity sensor could solve this problem. Rotational deviations can be compensated up to a certain degree, however in this use case, the bunches lie aligned in a box, where chances on rotational deviations is small.

4.3 Future research and uses

Overall, the chosen strategies can be used to improve the ability to grasp sensitive objects. The gripper should grasp the object at its least vulnerable part, in this case that is the tip. The hooking of the object, instead of pinching it, minimizes the forces on the object. Lastly, this gripper has proven that a clever mechanical design can compensate for some of the short comings of robotic systems. Furthermore, functioning of the compliant X-joint can be investigated for other grippers. The extra degree of freedom allows the gripper to use the environment and the object to guide itself into the right direction. The stiffness and damping of the joint can be analysed to allow movement, but reduce swinging.

5 Conclusion

In former research, grippers have been able to grasp a single banana. In this paper the first gripper that can grasp bunches of bananas is presented. A new strategy was introduced, where the gripper grasps the bananas at its peduncles with a hooking gripper.

First, the design features of this new gripper are presented. By not touching the fleshy part of the fruit, but rather the sturdy part, the gripper has a firm grip without chances of severe damage. The flexibility of the gripper caused by the compliant X-joint and the funnel shape of the fingers lead to a gripper that can cooperate with its environment to guide itself to the right location.

The mechanical evaluation of the grippers shows evident, but not very precise, results on the functioning of the gripper. The gripper, once grasped, held on to 100% of the bunches. The grasping is successful in 95% of the cases. The gripper is able to handle misalignment in all directions and rotations. The limits of the ability to handle misalignment are clear. The gripper causes minimal damage. No damage to the fruits themselves was found. There is a chance of small abrasions on the peduncle. It was advised to further look into improvements to minimize that chance.

When used in a practical case study where the gripper was used to clean out a box of bananas, it showed no problems with the environment. First, human handling was used to operate the gripper. Secondly, the gripper was attached to a pre-programmed robot arm. Even without any feedback in the robot system, the gripper perform adequately.

Overall, the design features of the new gripper allow it to successfully grasp bunches of bananas without causing significant damage. Further research is needed before the gripper can be used in real environments.

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Appendix

Bunch	**#bananas**	**Weight [kg]**	**Depth ridge [mm]**	**Length ridge [mm]**	**Width tip [mm]**	**Angle γ [deg]**	**Angle θ [deg]**
1	4	0,825	3,73	19,2	18,2		
2	5	0,8	3,59	21,94	21,25	15	38
3	4	0,925	4,15	24,76	23,52	3	43
4	4	0,9	4,28	28,05	19,12	6,5	25
5	5	0,975	4,91	22,39	26,29	20	46
6	4	0,925	5,44	24,77	19,96	8,5	46
7	5	0,975	4,1	23,34	27,8		67
8	4	0,875	4,5	24,5	22,83		
9	4	0,9	4,68	24,07	18,92	0	61
10	4	0,85	3,8	23,82	30,7	24	59
11	4	0,875	4,37	24,05	21,17	21	58
12	4	0,9	4,79	24,8	14,15	7,7	35
13	4	0,775	4,29	26,49	25,9	10,5	
14	5	0,7	3,09	22,59	14,6	0	75
15	4	0,775	4,58	27,37	22,21	25	25
16	5	0,775	3,77	22,52	28,2	0	60
17	5	0,775	3,26	22,8	13,67	3	69
18	5	0,75	3,91	21,6	16,46	14	58
19	4	0,75	4,09	24,6	19,55	10	53
Mean	4,368421	0,843421	4,175263	23,876842	21,289474	10,5125	51,125
Standard dev	0,495595	0,081156	0,579687	2,0792815	4,9155914	8,551169511	15,04161

Table A1: Measured data of the bunches of bananas, for dimensions see Figure 10

Photos bruises on bananas

(a) Bunch 1 (b) Bunch 2 (c) Bunch 3 (d) Bunch 4 (e) Bunch 5

(f) Bunch 6 (g) Bunch 7 (h) Bunch 8 (i) Bunch 9 (j) Bunch 10

(k) Bunch 11 (l) Bunch 12 (m) Bunch 13 (n) Bunch 14 (o) Bunch 15

(p) Bunch 16 (q) Bunch 17 (r) Bunch 18

Figure A1: Photos taken of bunches of bananas after picking them up with the gripper. The photos are used for inspection of the damage done by the gripper on the peduncles

Matlab Code calculation pinching force gripper

```
clear all
close all
T = readtable('C:\Users\hoi_a\OneDrive\Documenten\Afstuderen\Metingen trekproef\test veer 19aug\trekproef veer 19aug1.csv','ReadVariableNames',false);
Ts = readtable('C:\Users\hoi_a\OneDrive\Documenten\Afstuderen\Metingen trekproef\test veer 19aug\druk veer 19 aug1.csv','ReadVariableNames',false);

syms alpha;
%Alles in cm!!
l_sol = 1.58;
l_veer = 1.553;
l_haak = 4.0;

%d_prikker = 0.254;
%d_veerring = 0.484;

stop_dicht = acos((4.84-4.30)/l_veer);
stop_open =  pi/2 + asin((5.26-4.84)/l_veer);
stopDd = stop_dicht/pi*180;
stopOd = stop_open/pi*180;

l0_veer = 1.73;
a0_veer = 4.30; %buitenkant sateprikkers
a0_sol =  0.6;

x_sol = a0_sol - cos(alpha)*l_sol - 0.0273;
x_veer = 0.54 - cos(alpha)*l_veer + a0_veer; %+% l_veer*sin;
x_haak = sin(-alpha)*l_haak;

u_veer = x_veer - l0_veer;



u = str2double(T.Var2(450:end));
u = u/(10^15);
F = str2double(T.Var3(450:end));
F = F/(10^14);
figure(1)
plot(u,F)
title('Trekveer')
ylabel('Veerkracht [N]');
xlabel('Uitrekking [cm]');
%%
```

```
% P = polyfit(u,F,1);
% yfit = polyval(P,u);
% hold on;
% plot(u,yfit,'r-.');


us = str2double(Ts.Var2(2:end));
us = us/(10^15);
us = us - 39.5*ones(847,1);
Fs = str2double(Ts.Var3(2:end));
Fs = Fs/(10^14);
Fsf = flip(Fs);
figure(2)
plot(us,Fs)

title('Drukveer')
ylabel('Veerkracht [N]');
xlabel('Uitrekking [cm]');




P = polyfit(us,Fs,1);
yfit = polyval(-P,us)+10.2773;
hold on;
plot(us,yfit,'r-.');

%% Find forces in vector

%functie trekveer
a = (F(6000)-F(2000))/(u(6000)-u(2000));
b = F(6000)-a*u(6000);
F_trek = a*u_veer+b;

%functie drukveer
ad = (yfit(820)-yfit(100))/(us(820)-us(100));
bd = yfit(800)-ad*us(800);
F_druk = ad*x_sol+bd;


%% Find arm

r_druk = sin(alpha)*l_sol;
r_trek = sin(alpha)*l_veer;
r_haak = sin(alpha)*l_haak;

```

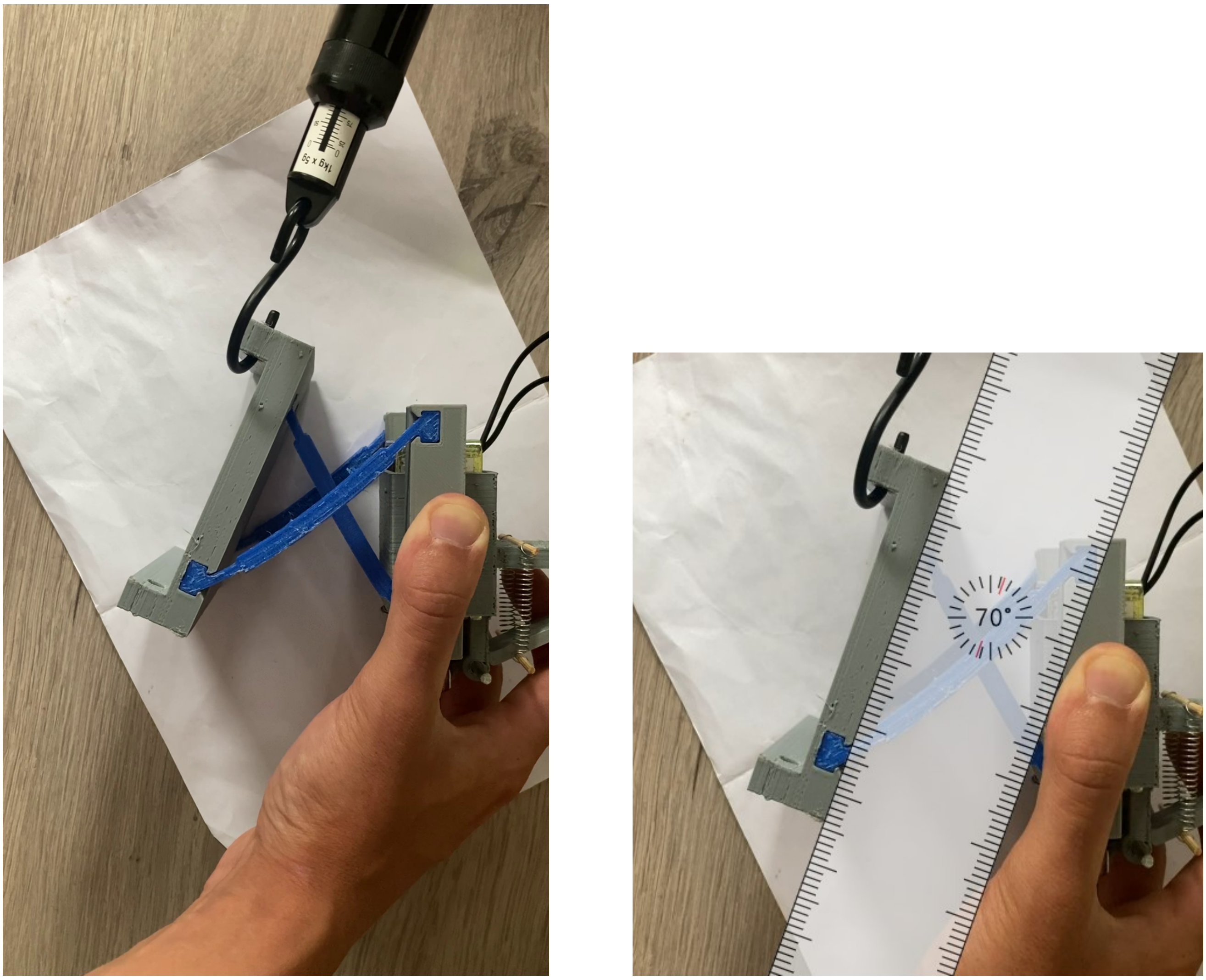
```
F = (2*F_trek*r_trek + F_druk*r_druk)/r_haak;
Ft = (F_trek*r_trek)/r_haak;
Fd = (F_druk*r_druk)/r_haak;
%%
t = 2000;
beta = linspace(stop_open, stop_dicht,t);
beta_deg = beta*180/pi;
beta_deg2 = beta_deg+(ones(1,2000)*90);
Force = zeros(1,t);
for k = 1:t
    proef = fo(beta(k),F);
    Force(k) = proef;
end

Forcet = zeros(1,t);
for k = 1:t
    proeft = fto(beta(k),Ft);
    Forcet(k) = proeft;
end

Forced = zeros(1,t);
for k = 1:t
    proeft = fdo(beta(k),Fd);
    Forced(k) = proeft;
end

%%
gr = Force/9.81;
grt = Forcet/9.81;
grd = Forced/9.81;

figure(3)
plot(beta_deg, Force)
title('Pinching force')
ylabel('Force [N]');
xlabel('Angle \alpha ');
grid on
xlim([65 110])
ylim([0 12])
hold on
plot(beta_deg, Forcet)
hold on
plot(beta_deg, Forced)
legend('F_{pinch}', 'Share of F_{spr}/2', 'Share of F_{sol}')

figure(4)
```

```
plot(beta_deg, Force)
title('Pinching force')
ylabel('Force [N]');
xlabel('Angle \alpha ');
grid on
xlim([65 110])
ylim([0 13])
% hold on
% plot(beta_deg, grt)
% hold on
% plot(beta_deg, grd)



%% scatter meetingen

draai = [70, 80, 90, 100, 105];
kracht = [0.525, 0.675, 0.775, 0.850, 1.050];
kracht2 = kracht*9.81;
hold on
scatter(draai,kracht2)
legend('Calculated pinch force', 'Measured data')
hold on

for k = 1:length(draai)
    hoek = draai(k)/180*pi;
    proef = fo(hoek,F);
    For(k) = proef;
end

for h = 1:length(For)
    perc(h) = (-For(h)+kracht2(h))/kracht2(h)*100;
end
perc
%% Function

function f = fo(j,F)
    Fo = F;
    alpha = j;
    f = double(subs(Fo));
end

function ft = fto(m,Ft)
    Fto = Ft;
    alpha = m;
    ft = double(subs(Fto));
```

```
end

function fd = fdo(n,Fd)
    Fdo = Fd;
    alpha = n;
    fd = double(subs(Fdo));
end
```

Matlab Code calculation joint stiffness compliant X-joint

The setup of the test was with a gauge with a certainty of 5 grams and a maximum of 1 kg.



(a) Still of the video taken.

(b) Still of method to determine the angle of the X-joint

Figure A2: Setup of measurements of compliant X-joint, the gauge was pulled parallel to the motion of the robot connection plate. In stills of the video, the value on the gauge and the angle of the joint were determined.

```
x1 = [0,10,21,30,39,51,58];
f1 = [0,55,115,150,195,265,290];
r = 5.32/2;
```

```
M1 = 9.81*f1*r/1000;
figure(1)
s1 = scatter(x1,M1)
l = lsline;
x2 = [10,22,30,41];
f2 = [60,115,150,205];
M2 = 9.81*f2*r/1000;
title('Assessment of the joint stiffness')
ylabel('Force [grams] ');
xlabel('Rotation of the X-joint [degrees]');
hold on
s2 = scatter(x2,M2)
legend([s1 s2 l],'Test 1', 'Test 2', 'Linear fit on data')


x = [0,10,21,30,39,51,58,10,22,30,41];
f = [0,55,115,150,195,265,290,60,115,150,205];
M = 9.81*f*r/1000;
figure(2)
scatter(x,M)
lsline

 c = 7.88/60
```

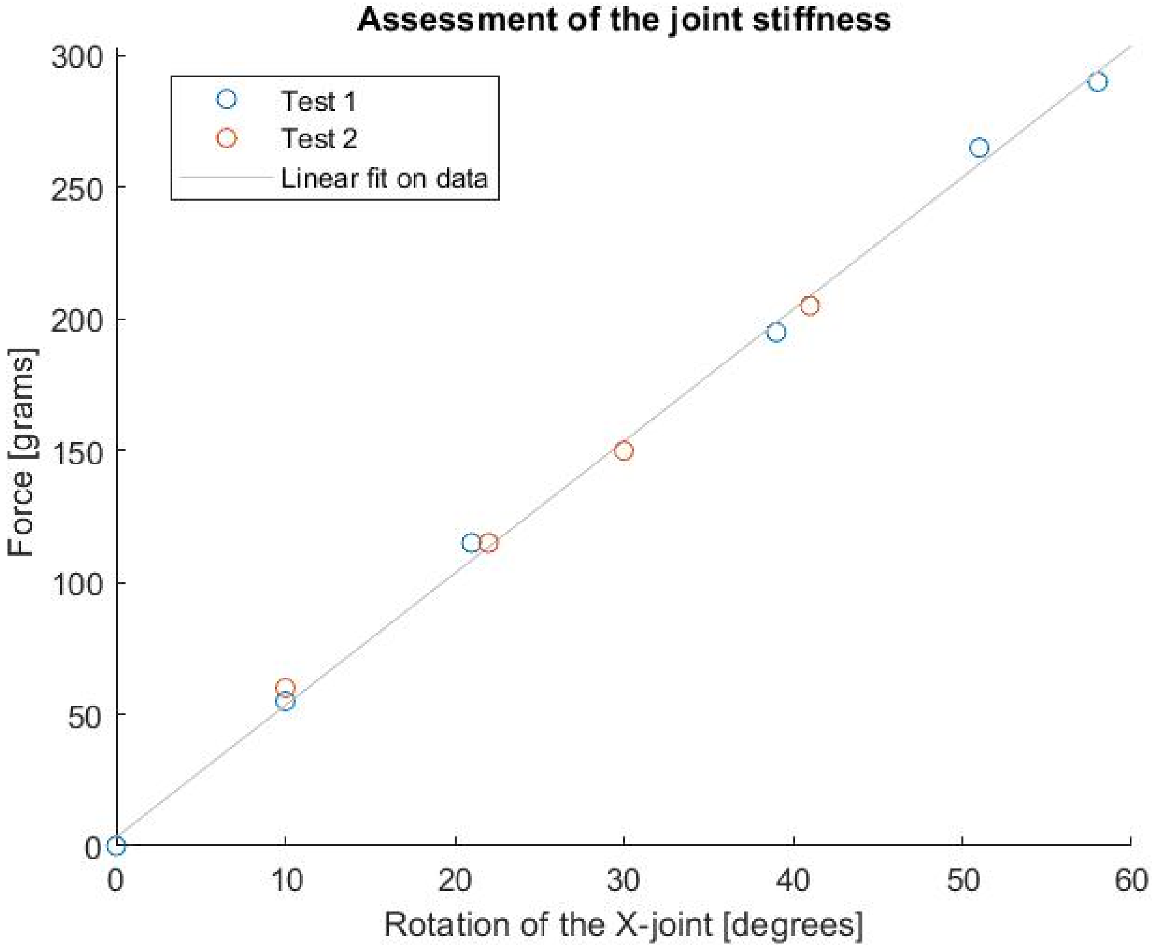


Figure A3: Measured values of the joint stiffness force of the X-joint plotted against the linear fit

Chapter 7

Conclusion

In this research project a new gripper for bunches of bananas have been presented. The goal of the gripper is to grasp bunches of bananas, relocate them and release them at a new location. This has to be done without damaging the banana fruit. In order to better incorporate the non-damaging requirement into the design, first a research into fruit damaging has been done. Fruit can damage in several ways, namely bruising, abrasion and puncture. It was found that it is difficult to asses the quantity of force that a fruit can handle before developing bruises. The resilience to damage of the fruit depends on growing circumstances, when it was harvested, the temperature and humidity of the air, etc. Therefore it was concluded that it would be better if the gripper would not interact with the fruits itself, but instead grasp the bunch at the tip. In that case, bruising the fruit could not be done by the gripper. Grasping the tip has other advantages, like that it has another colour and lays unobstructed in the box, which makes it easier for the robotic system to aim for its goal. To grasp the bananas a hook gripper was used. This gripper hooks behind the ridge of the tip of the bananas and lifts it that way. The system is statically balanced. To prevent the bunch from falling off, a nudge finger presses the tip softly on the hook finger. Another advantage of the nudge finger is that the fingers together work as a funnel. When the fingers are moved over the tip, they guide themselves to the right position to grasp. This is possible because of a compliant joint connection between the robot and the gripper. The gripper can move freely to follow the shape of the tip. The compliant X-joint also makes sure that it can absorb the movement of the bunch when moved by the robot. Because the gripper can move around, it can keep both fingers in touch with the bunch, making sure that it does not fall off. Finally, tests have been done to verify the functioning of the gripper. The gripper was able to grasp and lift all 19 different bunches of bananas. Additionally, a bruise assessment has been done. None of the edible parts of the banana were bruised, but slight cases of abrasion were visible on the peduncles. Concluding, the tactic to grasp fruit at its least vulnerable part can be used for the design of other grippers in this sector. The compliant X-joint and the shape of the grippers helped to compensate for the shortcomings of the robotic system.

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Design and evaluation of a gripper for bunches of bananas in a supermarket environment

Anne van der Star TU Delft

Abstract

In this paper the first gripper that can grasp bunches of bananas is presented. Bunches of bananas are difficult to grasp by a mechanical gripper, as they vary in size and shape and are sensitive to damage caused by mechanical impact. In former research, single bananas have been grasped with pinching- or granular grippers. The gripper proposed in this paper grasps the bunch at its most sturdy part, namely its tip, and uses a hook finger to minimize the chances on damage. The scissoring fingers allow the gripper to handle the variability of the object. Additionally, the scissoring combined with the funnel shaped finger tips ensure that the gripper compensates the position errors of robotic systems. In the evaluation of its abilities the gripper is able to pick up 19 out of 19 bunches of bananas. It has a tolerance for a maximum positioning error of 4.9 cm and causes only minor damage on the peduncles of the bananas. In practical experiments, the gripper performed adequately and showed to be able to cooperate with the object to guide itself to the right location. The novel strategies of hook gripping and the extra degree of freedom of the compliant X-joint show that bunches of bananas can be grasped mechanically, while compensating for some of the shortcomings of current robotic systems.

1 Introduction

A growing and ageing population is causing challenges for the food sector. With more mouths to feed, but less hands to do the work, a shortage of food could become a problem in the future. Automation is one of the solutions in this sector, but the interaction with biological products is difficult. The challenges are the variety of shape and size, and the fact that these products bruise easily. Post-harvesting mechanical grippers are already being used. However with harvesting and the end of the supply chain, robots need to interact directly with the products instead of their packaging.

In the agricultural sector several solutions have been proposed and designed to cope with these challenges. Grippers have been designed specifically to harvest fruit, with the ability to accommodate differences in size and shape. These grippers are mostly targeting spherical fruits like tomatoes, oranges and apples (Chiu et al. 2013, Setiawan et al. 2004, Zhang et al. 2020). Grippers for i.e. bell peppers (Bac et al. 2014), strawberries (Hayashi et al. 2010) and raspberries (Yang et al. 2021) have also been proposed. In other research, grippers are designed to grasp a variety of objects. For example the granular gripper of Krahn et al. 2017, which proved to be able to pick up, among others, an apple, a tomato, a pear and a banana. Although the granular gripper of Krahn et al. 2017 is able to pickup a single banana, there is no gripper to grasp a bunch of bananas. This paper will delve into this matter.

Besides harvesting, robots could be working in the supermarket as well. Tomizawa et al. 2006 & Cheng et al. 2017 propose a robot that can take groceries from a shelf and put them in a basket. Other use cases could be stocking the shelves or filling the baskets of online grocery orders in distribution centers. Grippers from the agricultural sector could be used in these environments. However, the implementation of such systems may still take a long time. These systems have too many shortcomings, like the fact that certain products cannot be grasped by current solutions. There is no gripper yet that has been able to grasp a bunch of bananas. Existing grippers are not fit for the job, to grasp this heavy, weirdly shaped, sensitive fruit. Currently, bananas are the most spilled fruit (Mattsson et al. 2018). Even light forces on the fruit cause brown spots, which makes it less attractive to eat. However, to lift this heavy object, light forces are not sufficient. To minimize the chances of damage, a novel gripper is proposed which grasps the tip of a bunch of bananas in order to minimize chances of damage, and be able to reliably grasp bunches of bananas considering the abilities of existing robot technology.

1.1 Research objective

The proposed gripper has to be able to grasp bunches of bananas out of their container, hold them during movement of the robot and put them down on a different location, for example on the shelf or in a crate. The chances of damage to any of the bananas in the bunch should be minimized.

1.2 Research structure

In this paper a prototype will be designed and evaluated to show that the proposed gripper is able to successfully grasp bunches of bananas. Firstly, the method section starts with the functional requirements of the gripper. Following the advantages of certain design features will be discussed. Then the setup of the measurements is explained. The method section is finalized with the setup of two practical experiments. In the next section the results are presented and discussed. Finally, in the last section the conclusions of this research are presented.

2 Method

The method section explains the functional requirements and design features of the gripper. Subsequently the test setup for the measurements and practical experiments is described.

2.1 Functional Requirements

The designed gripper has to fulfill several functional requirements to function properly with the challenges stated earlier in the introduction. Firstly, the gripper has to be able to grasp a bunch of bananas, hold it while the robot arm lifts and moves the bunch and finally release the bunch. A bunch of bananas contains 3-10 bananas and the weighs 1 kg on average.

Secondly, the gripper should minimize the chance of inflicting damage upon the object. Fruit waste has to be minimized and it helps if there is less visible damage. “We love bananas but we do not buy them if they have any brown spots," says Lisa Mattsson(Monaco 2018). Bananas can be damaged in several ways, bruising, abrasion and puncture(Li et al. 2014). Bruising is caused by too much pinching force or an impact, abrasion by friction on the skin and puncture by sharp objects penetrating the skin. All of these types of damage should be avoided in case to minimize food waste.

Thirdly, the gripper has to compensate for position errors. Robots have positioning errors (Cao et al. 2019). This means that there is a difference between the aimed location and the real location of the end effector. The errors can be caused by the vision or the sum of the errors in the joints of the robot. Vision based errors can result in a mispositioning of 17.2 mm in the x- or y-direction and up to 60.1 mm in the z-direction (Zou et al. 2016).

2.2 Design features

At the start of this design process, human handling of bunches of bananas (from now on “the object”) was investigated as inspiration for the design. Inspired by that research, the decision on where to grasp the object was made. The prototype (Figure 2) hooks the object under the ridge on the tip of the bunch (Figure 1). The gripper is actuated with a solenoid, which is a linear actuator driven by a coil. When not activated, the solenoid can move freely through its stroke length. The gripper is normally closed because of the springs. A compliant x-joint connects the gripper and the robot. Multiple features of this design benefit the objectives set earlier in subsection 2.1, these will be explained in the following sections.

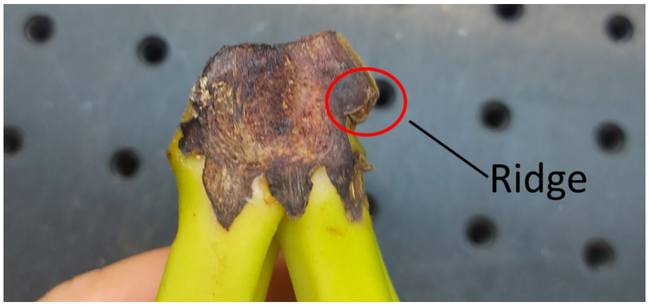


Figure 1: Ridge on the tip of the bunch of bananas

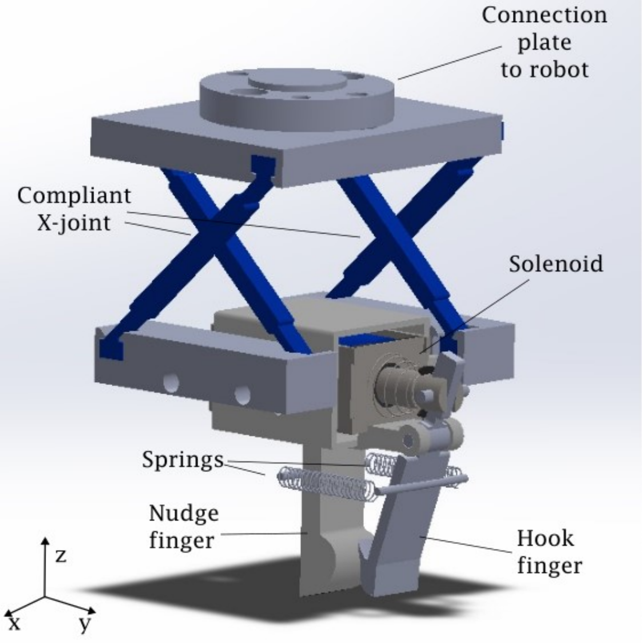


Figure 2: Render of the complete gripper, the grey material is solid, the blue material of the compliant X-joint is flexible.

2.2.1 Location of the grasp

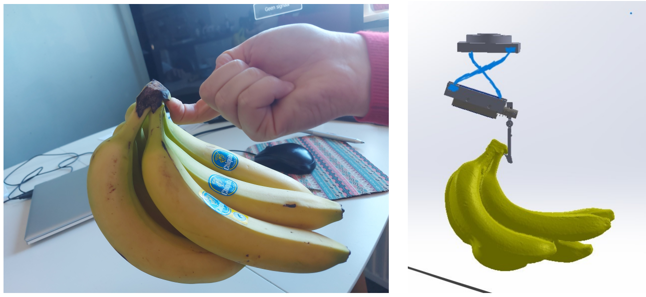
Grasping the object at the tip has multiple advantages.

1. The object is tougher here.
2. If the gripper leaves any damage, there is no risk of bruising the flesh of the fruit.
3. No chance of ripping off any individual bananas.
4. The peduncles are clearly visible for the robot, as they have a different color .
5. The peduncles lay unobstructed in the box, there is no clutter around it, see Figure 3.

Figure 3: Bananas in a box

2.2.2 Grasping method

Contrary to a pinching gripper, the designed gripper does not rely on friction force to lift the object. This means that the forces exerted on the object can be lower, decreasing the chances on damage. The gripper only needs the hook finger to lift the object, see Figure 4. The pinching force from the nudge finger is used to guide the fingers around the tip and prevent the bunch from falling of the hook. Therefore the pinching force can remain relatively small.



(a) Bunch of bananas in equilibrium on a finger

(b) Render with bananas in static equilibrium on hook finger

Figure 4: Object in static equilibrium on a point

The shape of the ridge of the hook is round, to create a bigger contact area with the ridge of the bananas, see Figure 5.

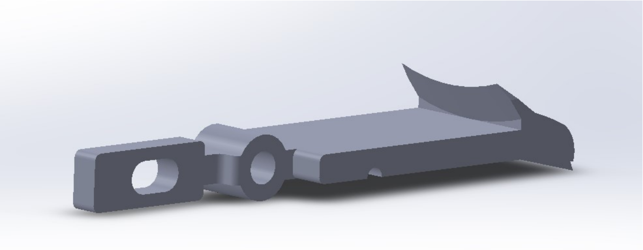
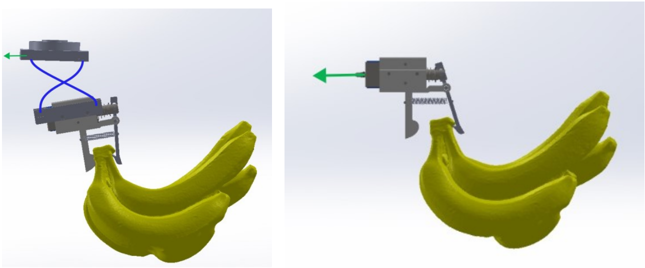


Figure 5: Hook shape of the finger

2.2.3 Compliant X-joint

The compliant X-joint has three functions in this design. Firstly, it allows the gripper to rotate together with the bunch of bananas, as in Figure 6a. This prevents the bunch to lose contact with the nudge finger and decreases the chances that the bunch rotates with respect to the hook, causing it to fall of. This is illustrated in Figure 6b. In both situations the gripper is moved to the left, but reacts differently to the movement. With the compliant x-link the gripper stays closed. The center of rotation of the joint is chosen to be vertically aligned with the center of mass of the lower part of the gripper. This means that the gripper will be level when it is stationairy.



(a) Movement with compliant X-joint

(b) Movement without compliant X-joint

Figure 6: Illustration of the reaction of the gripper on a movement to the left, either with a compliant X-joint or without

Secondly, when the fingers are lowered over the tip and the tip is not aligned with the movement, the fingers can follow the shape of the tip.

A third advantage of the compliance is that the bananas can move out of the way when the robot pushes them accidentally into a rigid object. This will not prevent all damage, but avoids catastrophic damage.

2.2.4 Variable pinching force

Three springs work together to close the finger; the compression spring of the solenoid and two tension springs force the fingers' tips towards each other. Because of Hooke's law, the pinching force will be bigger for larger deflections. For bigger bunches, the fingers will stay further apart and consequently, pinch harder on a heavier bunch.

2.2.5 Compensation of positioning errors of robot

To cope with this problem, this gripper has scissoring fingers. When opened, it works as a funnel, because of the way the tips are shaped. It provides enough clearance to easily position the tip of the bananas between the two fingers. When the solenoid is turned off, the fingers close with the tip in between. Moving the gripper up along the z-axis the fingers follow the shape of the tip until the hook meets the ridge (Figure 7). Subsequently, the gripper starts lifting the bunch of bananas. Therefore the robot does not need to have precise aiming.

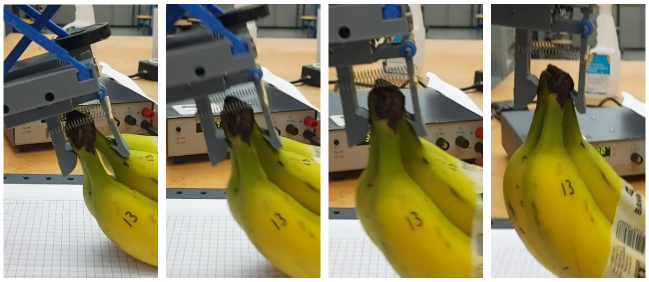

(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Figure 7: Fingers grasping the banana tip, the tips of the fingers are pulled together, following the shape of the tip. The nudge finger keeps pushing the tip against the hook finger while the gripper moves upwards.

2.3 Mechanical analysis of the pinching force

The proposed pinching force is around 10 N. In Figure 8 the free body diagram of the finger is drawn. When stopped by an object between the fingers, the fingers exert a pinching force. The pinching force depends on the deflection of the springs and therefore on angle α. To calculate the pinching force of the gripper, the moment around the finger joint is calculated. The following equation follows:

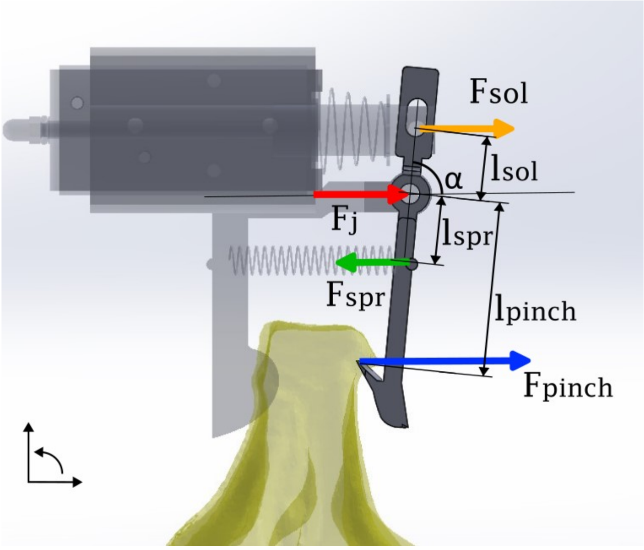


Figure 8: FBD of the hook finger just before the gripper starts lifting. Therefore there is no weight of the bananas on the finger yet. F_{sol} resembles the force of the compression spring of the solenoid, F_j is the reaction force in the joint of the finger, F_{spr} is the force the two tension springs exert on the finger, F_{pinch} is the reaction force from the banana, which equals the pinching force of the gripper

$$\sum M_{joint} = F_{sol} * r_{sol} +$$

$$2 * F_{spr} * r_{spr} - F_{pinch} * r_{pinch} = 0$$

where

$$F_{sol} = c_{sol} * x_{sol}(\alpha)$$

$$F_{spr} = c_{spring} * x_{spr}(\alpha)$$

$$r_{pinch} = l_{pinch}/sin(\alpha)$$

The range of motion of the gripper is defined by the stroke length of the solenoid. The solenoid has a stroke length of 1 cm. The angle α is 69 ° when the gripper is closed, when fully opened angle α equals 105 ° ($\alpha = [69; 105]°$). The pinching force of the gripper ranges between 4 and 10 N.

2.4 Measurements

To confirm the working principles of the gripper, the gripper is mechanically evaluated in several tests.

Test 1 *Mechanical grip evaluation:* The pinching force of the gripper is determined by the springs in the system. With a force gauge and a protractor the force is measured as function of the angle α, see setup in Figure 11. The Salter Super Samson force gauge was used, which has a maximum of 5kg and a precision of 25g. The protractor used has a precision of 1 degree. A modification had

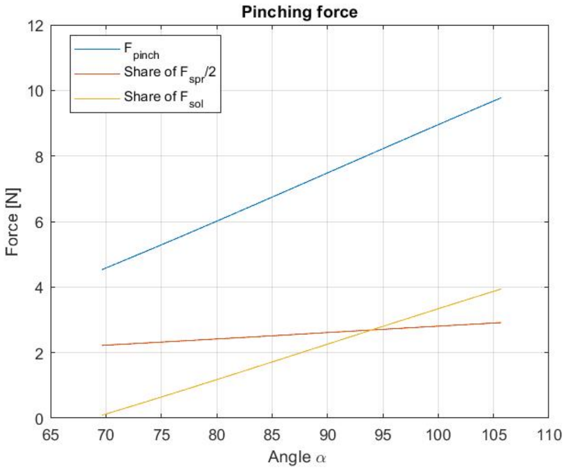


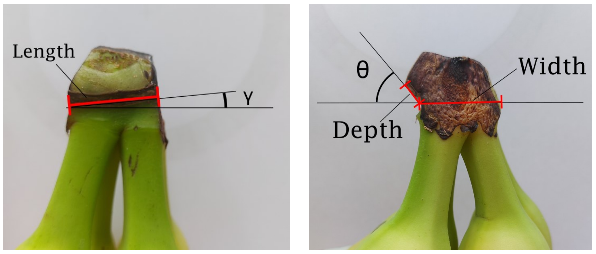
Figure 9: Pinching force of the gripper as function of angle α, F_{spr} resembles the share in the pinching force of 1 tension spring, F_{sol} resembles the share in the pinching force of the pressure spring of the solenoid

to be made in the calculations, as the pinching force is measured in a slightly different location then where the gripper exerts a force on the object.

Test 2 *Assessment of the compliant X-joint:* The stiffness of the compliant X-joint is measured in the same setup as item test 1. This time a gauge with a maximum of 1 kg and a precision of 5g is used. The solenoid is hold, the gauge is attached to the connection plate. The gauge is pulled in the direction of the movement of the connection plate.

To test the functioning of the X-joint the gripper holds one object and is held manually by the connection plate. Then the gripper is accelerated in the y-direction. Next, the gripper is held manually by the solenoid to cancel the functioning of the X-joint and accelerated in the y-direction. Both movements are filmed on the yz-plane. The footage is examined to validate the functioning of the X-joint.

Test 3 *Gripper success rate:* In this test, the The population exists out of 19 bunches of bananas, 12 had 4 bananas on them, 7 had 5 bananas. They weighted $0,84 \pm 0.081$ kg. The length of the rigde was $21,29 \pm 4,9$ mm, the width of the tip $23,88 \pm 2,1$ mm and the depth of the ridge $4,18 \pm 0,58$ mm. The angle γ was $10 \pm 8,6$ and angle θ was 51 ± 15. See Figure 10 for an illustration of the measured dimensions. The orientation around the x-axis of the object is as it settles when laid down. To start the test the object is placed on the platform underneath the gripper, see Figure 12. To ensure a consistent location of the tip of the bananas, the x- and y- coordinates are checked with a laser pointer. The midpoint of the ridge is marked and aligned with the x-laser. The y-laser is aligned with the base of the ridge. The gripper is manually opened and lowered over the tip, then the gripper is closed and lifted. The grasp is successful if the object is lifted from the platform. After releasing the object, the steps are repeated with a new object until the gripper is tested on all 19 objects.



(a) Front view of the tip

(b) Side view of the tip

Figure 10: Measurements on the tip of the banana. Indicated are: (a) the length of the ridge (b) the width of the tip (c) the depth of the ridge (γ, θ) angles of the ridge

Test 4 *Examine tolerance for the positioning error:* The object is moved along one axis or rotated around one axis after which a new grasping attempt like in test 3 is conducted. This is done for 2 translations and 2 rotations.

(a) *Translation in y-direction* A grid is applied on the platform and a mark is applied on the side of the object. The translation can be measured by the different location of the mark on the grid.

(b) *Translation in x-direction* The translation is measured by the difference between the X-laser and the midpoint marking of the ridge.

(c) *Rotation around the z-axis* A photo is taken from above on the xy-plane. With the photo the angle can be measured.

(d) *Rotation around the y-axis* A photo is taken from aside on the yz-plane. With the photo the angle can be measured.

Test 5 *Check the objects for damages:* A photo of each object is taken one hour after the tests to visually examine the damage done by the gripper.

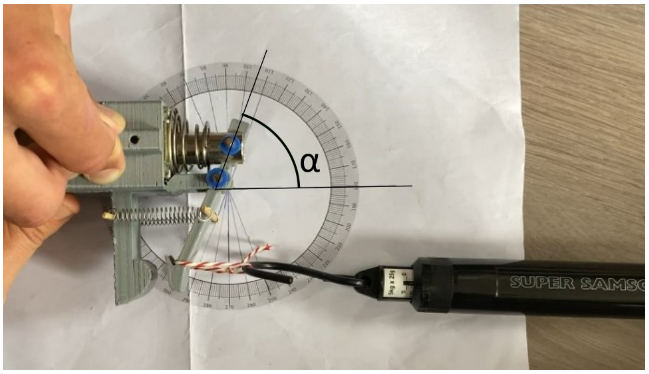


Figure 11: Setup to measure pinching force in test 1 as function of α

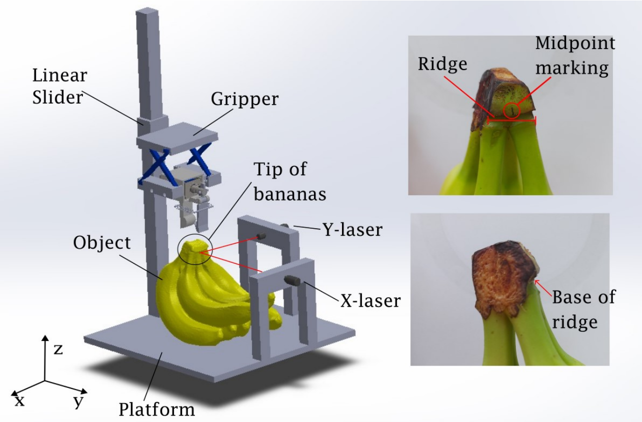


Figure 12: Test setup used in test 3 & test 4

2.5 Practical experiments

During the practical experiments the gripper was tested in a more realistic environment. Firstly, it was handheld and used to unload a box with bunches of bananas. Secondly, it was attached to a robot arm to stack the shelves like in a supermarket.

Exp. 1 *Unloading a box of bananas:* To simulate the situation in practice, a box of bananas is opened as in Figure 3. The same population as in test 3 is used. The gripper is manually controlled by holding the connection plate and used to move all bunches of bananas out of the box on to the table. The gripper is opened with the solenoid, the solenoid is controlled by a manual switch. Then the fingers are placed over the tip of a bunch, the gripper is closed and the gripper is lifted. When successful, the bunch is moved out of the box on the table and the gripper is opened to release the bunch. When unsuccessful, a new attempt is made. In this experiment, it is assumed that the robot attached to the gripper has perfect understanding of its surroundings.

Exp. 2 *Robotic shelf stocking:* Finally, the gripper will be attached to a robot arm. The robot used is the Franka Emika Panda. This is a 7 degree of freedom arm. The robot will be used to grasp a bunch out of the box and lay the bunch on the shelf. The poses of the robot are pre-programmed by moving the robot to the right position and saving its pose. Before running the program, a bunch of bananas would be positioned in the box with its tip approximately between the fingers in the robots gripping pose.

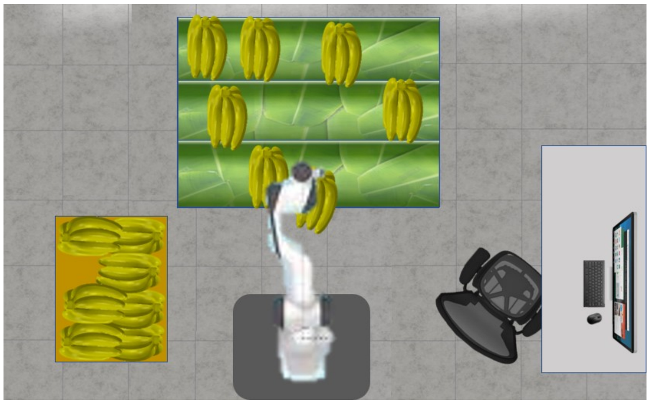


Figure 13: Top view of the supermarket experiment, on the left of the map stands the box with bananas, at the top the banana shelves, in the middle the robot arm and on the right the computer to control the robot arm.

3 Results

In this section the results of the tests and experiments described in the method section are presented. First, the results of the tests will be explained, then the outcomes of the experiments will be described.

3.1 Measurements

The results of the measurements are presented per test setup.

3.1.1 The validation of the pinching force

The data from the test are presented in Figure 14. The pinching force of the gripper increases for a increasing angle α, however the measured forces deviate from the calculated values. The average deviation of the measurements compared to the calculations is 7%.

3.1.2 The functioning of the X-joint

The linear trend in the data proves that the joint stiffness is constant. From the fitted plot can be calculated that the joint

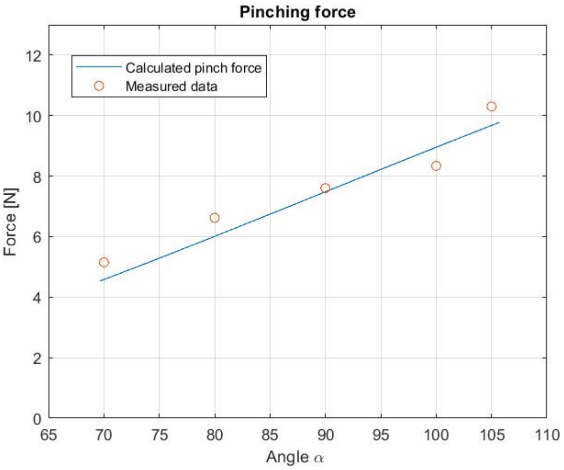
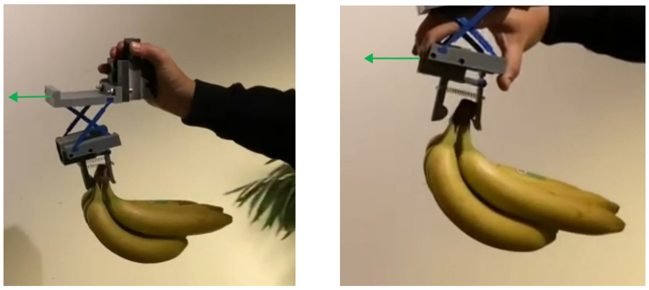


Figure 14: Measured values of the pinching force of the gripper plotted against the calculated values

stiffness is $0.13N * cm/^\circ$.

As can be seen in Figure 15 the functioning of the X-joint is as predicted. Without the X-joint the nudge finger is not in contact with the bananas anymore and therefore the chances of the bananas falling off increases. Additionally, it was observed that if the gripper is rotated over the x-axis, the bananas stay in place with the X-joint and fall without it.



(a) Movement with X-joint (b) Movement without X-joint

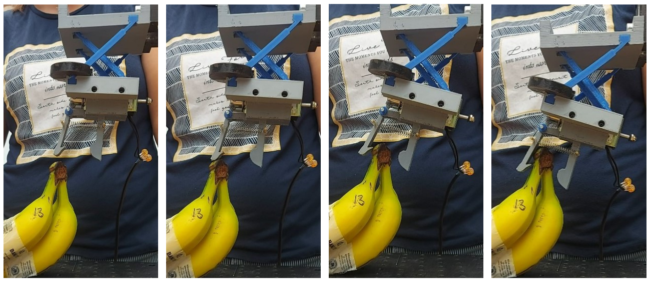
Figure 15: Stills of videos of a movement to the left, the green arrows depict the movement

3.1.3 Success rate

Out of 19 bunches 18 were grasped successfully in the first try, 1 one was grasped the second try. it was observed/noted that the gripper failed to successfully grasp the bunch when the tip of the bananas was positioned too horizontally. This has to do with the rotation around the x-axis of the object, which was not controlled in this experiment.

3.1.4 Tolerance for the positioning error

The gripper did successfully cope with misalignment. For the misalignment in the x-direction this means that when a solid part of the ridge is still within the borders of the finger, the gripper can lift the bananas. The smaller the overlapping surface, the weaker the grasp on the object is. The variability which the gripper can handle the misalignment in the y-direction depends on the shape of the tip of the bunch. When the tip looks like a wedge, it will help the funneling of the fingers, see Figure 16. In this case the gripper can grasp a bunch within a reach of 4,9 cm over the y-axis. When the tip is shaped like a trapezium with a flat platform on top, there is a bigger chance that the finger bottoms out on the flat top instead of deflecting of the tip. Therefore the reach decreases to 3.4 cm.



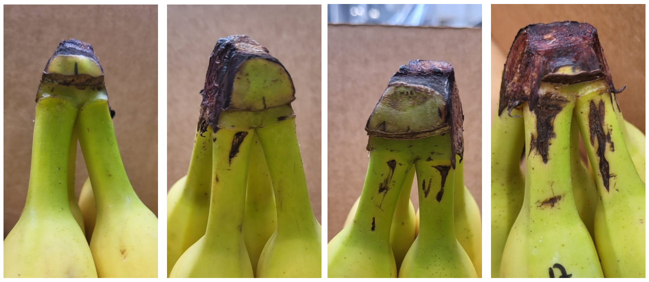
(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Figure 16: Funneling function of the gripper, the hook finger hits the tip on its way downwards, because of the compliant X-joint and funnel shape of the fingers, the gripper manoeuvres itself around the tip.

When the bunch is rotated around the x-axis, with the tip of the bunch almost horizontally, it causes problems. The fingers can not properly be lowered over the tip, because the hook finger bottoms out against the peduncles. When the bunch is rotated around the z-axis, the fingers rotate the bunch back to neutral when closed. This only happens if the fingers have contact with the two opposite sides of the tip(front and back). If the sides are adjacent(e.g. front and right), it squeezes the tip out of the fingers. The maximum angles of rotation that the gripper can handle depends on the geometry of the tip.

3.1.5 Damage on the bananas

The gripper only interacts with the tip of the bananas. This means that no bruising can take place as the tip does not contain any edible flesh. There are no sharp points on the gripper, so puncture does not happen either. Abrasion on the tip is the only type of damage that occurs. The hook of the gripper scrapes along the tip of the bananas. The level of abrasion is sorted into five categories, see Figure 17. In category 0 no damage is visible, in category 1 one small spot is visible, in category 2 one bigger or multiple small spots are visible, in category 3 multiple bigger spots are visible. Category four has no representing image, as there was no case of such damage. This category was defined as severe cuts through the skin. The number of bunches in each category is depicted in Figure 18.



(a) Category 0 (b) Category 1 (c) Category 2 (d) Category 3

Figure 17: Damage on bananas per category, category 0-3 are represented

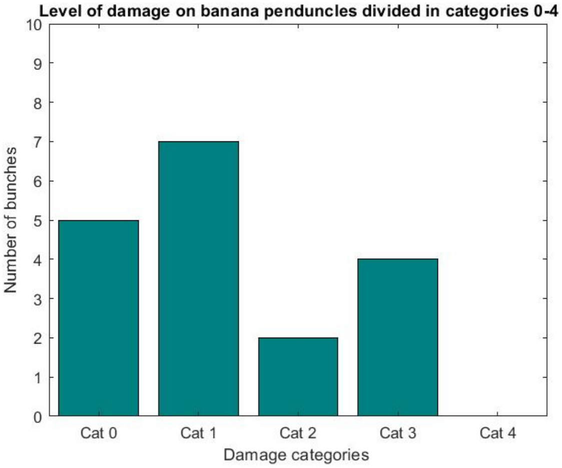


Figure 18: Damage on the bananas sorted in 5 categories

3.2 Results of the practical experiments

In the first experiment a box was emptied with the gripper manually operated. Out of 13 bunches which were attempted to be lifted, 12 attempts succeeded in one go. The grasp of 1 bunch failed twice and had to be grasped 3 times before it could be lifted.

In the experiment with the robot arm, 5 out of 9 attempts succeeded. The other attempts failed because the gripper was not lowered enough. The gripper missed the tip and would not grasp the bunches at all in that case. In four out of five cases where the grasp was successful, the gripper released the bananas on the shelf without any bruises. In the fifth case, the robot arm movement was not calibrated right and the robot hit the bananas against the shelf. It was observed that the bunch was not pushed in to the shelf forcefully because of the freedom of movement of the compliant X-joint.

4 Discussion

The discussion is divided in two parts. First, the setup and execution of the tests and experiments will be discussed. Second, the functioning of the gripper discussed. Finally, recommendations for further research are presented.

4.1 Setup of the tests & experiments

The measurements overall were not very precise. This was caused several uncertainties, for example in the evaluation of the gripping force; the increments of the gauge are 25g, slight misalignment of the camera angle resulted in a hard-to-read protractor angle measurement of the deflection. Another source of inaccuracies was the fact that the gripper was held in place by hand. For the values of the pinching force it was precise enough, the goal of the measurement was to find the order of the magnitude. Furthermore, in the test assessing the tolerance for positioning errors, the target object was moved by hand, this could have been done by a linear motion platform. However the variation in size and shape of the object, causes more precise measurements to be unnecessary. Furthermore, the gripper should be tested on a robot that makes decisions on its own in stead of executing a pre-programmed motion.

4.2 Gripper

Coming back at the functional requirements stated in subsection 2.1 the results of the test show the three functional requirements are met. First, the gripper should be able to grasp a bunch of bananas, hold it while the robot arm lifts and moves the bunch and finally release the bunch. Based on test 3 and the two experiments it became evident that the gripper is able to grasp the tips of bunches of bananas, varying in size and geometry. Some attempts had to be repeated in order to succeed, but eventually all bunches were grasped, moved and released. The tip of the bunch appears to be a reliable spot to grasp a bunch.

Secondly, the chances of damage caused by of the gripper should be minimized. None of the bunches were so severely damaged that they could not be sold. The gripper does not interfere with the parts of the fruit where the edible flesh is located. Therefore it can not bruise the flesh. However, the abrasion on the peduncles could cause the bunch not to be sold. The gripper can be improved by another mechanical closing system. The pinching force could be decreased. This would decrease the scraping of the hook finger along the peduncles and therefore decrease the chance on abrasion.

Thirdly, the gripper should compensate for the robots' positioning errors. The funneling of the fingers and the flexibility provided by the compliant X-joint make sure that it can compensate for misalignment in the y-direction. The lowest measured reach of 34 mm can make up for the vision based errors of 17.2 mm. To still lift the bunch in case of misalignment in the x-direction the hook finger has to be in contact with the ridge. When the finger(20 mm wide) is translated 17.2 mm in relation to the ridge(on average 21.29 mm wide), there is still an overlap of 3.45 mm. To improve the overlap, the finger could be made wider. How the gripper deals with misalignment in the z-direction is not evaluated. Overall it is observed during the experiments that as long as the tip of the hook finger is moved passed the ridge, the grasp will succeed. This does not make up for the 60.1 mm positioning errors made by the robot in this direction. The feedback of a force sensor or a proximity sensor could solve this problem. Rotational deviations can be compensated up to a certain degree, however in this use case, the bunches lie aligned in a box, where chances on rotational deviations is small.

4.3 Future research and uses

Overall, the chosen strategies can be used to improve the ability to grasp sensitive objects. The gripper should grasp the object at its least vulnerable part, in this case that is the tip. The hooking of the object, instead of pinching it, minimizes the forces on the object. Lastly, this gripper has proven that a clever mechanical design can compensate for some of the short comings of robotic systems. Furthermore, functioning of the compliant X-joint can be investigated for other grippers. The extra degree of freedom allows the gripper to use the environment and the object to guide itself into the right direction. The stiffness and damping of the joint can be analysed to allow movement, but reduce swinging.

5 Conclusion

In former research, grippers have been able to grasp a single banana. In this paper the first gripper that can grasp bunches of bananas is presented. A new strategy was introduced, where the gripper grasps the bananas at its peduncles with a hooking gripper.

First, the design features of this new gripper are presented. By not touching the fleshy part of the fruit, but rather the sturdy part, the gripper has a firm grip without chances of severe damage. The flexibility of the gripper caused by the compliant X-joint and the funnel shape of the fingers lead to a gripper that can cooperate with its environment to guide itself to the right location.

The mechanical evaluation of the grippers shows evident, but not very precise, results on the functioning of the gripper. The gripper, once grasped, held on to 100% of the bunches. The grasping is successful in 95% of the cases. The gripper is able to handle misalignment in all directions and rotations. The limits of the ability to handle misalignment are clear. The gripper causes minimal damage. No damage to the fruits themselves was found. There is a chance of small abrasions on the peduncle. It was advised to further look into improvements to minimize that chance.

When used in a practical case study where the gripper was used to clean out a box of bananas, it showed no problems with the environment. First, human handling was used to operate the gripper. Secondly, the gripper was attached to a pre-programmed robot arm. Even without any feedback in the robot system, the gripper perform adequately.

Overall, the design features of the new gripper allow it to successfully grasp bunches of bananas without causing significant damage. Further research is needed before the gripper can be used in real environments.

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