3D-printed Robotic Gripper Fingers with Lattice Structures for Kiwifruit Harvesting

A thesis
submitted in fulfilment
of the requirements for the degree
of

Master of Engineering in Mechanical Engineering
at
The University of Waikato

by

Karan Dhanotra

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2025

Abstract

With the growing demand for agricultural automation due to labour shortages and rising costs, the robotics industry must develop effective and sustainable solutions. Soft robotics has emerged as a transformative approach, offering flexibility and safety for handling delicate objects. Advancements in 3D printing technology further enable innovative gripper designs tailored for specific applications. This research focuses on developing 3D-printed soft robotic gripper fingers for kiwifruit harvesting, aiming to overcome challenges such as fruit damage, slippage, and inefficiencies in automated processes.

The study investigates enhancing the coefficient of friction through textured surfaces and optimising bulk stiffness using lattice structures with varying wall thicknesses to maximise contact area and grip stability. Using 3D printing, multiple testing samples were designed with various textured surfaces and advanced lattice configurations, including gyroid, honeycomb, and Schwarz primitive structures, to improve grasping performance while optimising stiffness.

Experimental results revealed that textured surfaces increased the coefficient of friction by 8–10%, while gyroid infill patterns nearly doubled the contact surface area compared to rigid designs, significantly improving grip stability and reducing pressure on the fruit. Rubber was identified as the most effective material for soft gripper fingers, offering a high coefficient of friction, flexibility, and the ability to conform to the irregular shapes of kiwifruit. Conversely, silicone and nylon were less effective, with silicone providing inadequate friction and nylon exhibiting rigidity that risked fruit damage. Among the tested lattice structures, gyroid patterns demonstrated superior mechanical properties, outperforming other designs that exhibited failure modes, such as buckling under compressive loads.

Overall, this research highlights the potential of 3D-printed soft robotic gripper fingers in horticultural automation by integrating advanced materials, textures, and lattice structures to improve performance. The findings provide critical insights into design principles for developing durable, adaptable, and effective grippers for delicate agricultural applications. While the results are promising, further research is required to address challenges such as scalability, extensive field testing, and seamless integration with automated harvesting systems.

Acknowledgements

Firstly, I would like to thank the Ministry of Business, Innovation and Employment (MBIE), New Zealand, for supporting this work under Grant No. UOWX2203.

Secondly, a huge thank you to my supervisors, Dr Ben McGuinness, especially for your technical help, and Dr Ajit Pal Singh for helping me write this thesis. I couldn’t have done this without you guys. Thank you to Professor Mike Duke for giving me the great opportunity to do this work and believing in me.

I want to extend my heartfelt thank you to everyone in the D.G.12 Lab for allowing me to participate in such an awesome project and for providing continuous support. Additionally, I want to acknowledge Judith Rees and Paul Martinsen from Plant & Food Research for providing me access to Kiwifruit Orchard. I also thank Anthony Pangborn for helping us access the commercial kiwifruit orchard in Te Puke, New Zealand.

Thank you to Sophia Rodrigues and Raj Kumar Das for providing lab training and helping with testing materials in the lab.

Lastly, a massive thank you to my family for your consistent love and support during this challenge. I appreciate it more than you know.

Declaration

In submitting this thesis to the University of Waikato, School of Engineering, I declare that:

1. This thesis is composed independently by me. Except where clearly stated through references or acknowledgements, the work presented is entirely my own.

2. I have employed an artificial intelligence (AI) language model (ChatGPT) to assist with editing this thesis. As English is not my native language, this support was sought to:

    - Identify and correct spelling and grammatical errors,
    - Ensure coherence and consistency in language use,
    - Refine the phrasing of case studies for greater precision.

    Meticulous attention was devoted to ensuring that the AI's corrections of grammatical errors and linguistic inconsistencies did not inadvertently introduce any elements of plagiarism.

3. The following specific tests were included in my research:

    - Friction testing using three different materials,
    - Friction testing using various textures,
    - Compression testing using lattice structures,
    - Surface area testing.

I affirm my awareness of the university's standards concerning academic integrity.

Name : ___________________________________

Signature : _________________________________

Table of Contents

List of Tables

List of Figures

List of Equations

Chapter 1: Introduction

1.1 Background

Kiwifruit is a small fleshy green fruit containing a high number of small black seeds, covered with fuzzy brown skin, and is native to mainland China and Taiwan. It is grown commercially globally, with the largest producers being China, New Zealand and Italy, as shown in Table 1.1. The productivity of kiwifruit has increased dramatically over the last century. Global kiwifruit production amounted to approximately 4.5 million tons in the year 2022, which is more than double the global production volume of 1.87 million metric tons in the year 2000. Exports of kiwifruit rapidly increased from the year 1960 to the early 1970s in New Zealand [2]. By 1976, exports exceeded the amount of kiwifruit consumed domestically outside of New Zealand [3] . Kiwifruit exports earned $987 million dollars in 2009, making up over 30 percent of New Zealand’s total horticultural export earnings [4]. Kiwifruit exports were valued at approximately NZ$2.8 billion, equating to 4.5 per cent of total merchandise exports by value in the year 2021 [5].

Table 1.1: Kiwifruit production in 2024 by country (in thousand metric tons)

Nation	**Production**
China	2,400
New Zealand	628.5
Italy	416.1
Greece	313.4
Chile	139.6
Portugal	55.5
France	46.0
Spain	28.4
Japan	21.7
Israel	6.2

The majority of kiwifruit produced in New Zealand is marketed under the Zespri label, a grower-owned company that is responsible for selling 30 percent of the world’s kiwifruit by volume [6]. Two main varieties of kiwifruit are marketed by Zespri: Hayward and Gold. Zespri also allocates up to 1.5 percent of its New Zealand profit back into an integrated innovation program where they develop new cultivars of kiwifruit; for example, red kiwifruit has just been introduced to the market. Zespri's growth goal is to increase annual sales revenue to NZD 4.5 billion by 2025. To achieve this, Zespri is planning to dramatically increase the production volume of their higher-value golden strains.

1.1.1. Challenges in Kiwifruit Harvesting

Kiwifruit is very difficult to harvest because of its soft and delicate nature that requires gentle manipulation in order to prevent damage to the fruit [7]. Harvesting of kiwifruit is performed by skilled workers, who can handle this delicate fruit without damaging it. To minimize fruit damage, the fruit is harvested early in the morning when it is cold. The cost of kiwifruit is influenced by long harvesting times, high labour costs and fruit damage.

The kiwifruit industry is facing labour shortage problems, which will become more challenging in the upcoming years, particularly if the industry grows as projected [8, 9]. Kiwifruit picking jobs are physical, seasonal, hard and repetitive, and as a result the industry is struggling to secure labour domestically to perform the task. Therefore, there is a strong reliance on the Recognised Seasonal Employer Scheme (RSE), where labour is imported from overseas [10].

1.1.2. Need for Automation and Current Limitations

Harvesting is the most important element of orchard production since it is the most expensive and most labour-intensive task. In the last few decades, the horticulture sector has undergone a deep transformation to cope with the growing demand for kiwifruit. One of the most important tasks in horticulture processes involves the handling or manipulation of kiwifruit, which is difficult, time-consuming, and labour-intensive, resulting in low efficiency and limited competitiveness. This circumstance is exacerbated by the labour shortages of seasonal workers unable to travel between some regions, leading to the accumulation of fresh kiwifruit and a large number of fruit loss.

To address issues like fruit damage and high labour costs, there is growing interest in automation. However, despite this demand, there is no commercial solution available for the commercial harvesting of kiwifruit. This high cost of labour in the stage of harvesting limits the development of the kiwifruit industry. Researchers have completed several projects and made considerable progress in technologies like positioning, system integration, efficient harvesting and end-effector design [11].

Generally, an automated system consists of soft robotic gripper contact interfaces, often referred to as gripper fingers, an end effector, a vision system, a control system, a power supply, and a mobile platform. All these components need to work together to enable efficient kiwifruit harvesting. One of the critical steps in robotic fruit harvesting is grasping. During harvesting, traditional robotic fingers have issues due to their high stiffness, which results in damage to the kiwifruit [12]. Grippers not only need to be light and stable but also soft and reliable to grasp and ensure the fruit is not damaged which prevents commercial sale. Therefore, the research on non-destructive kiwifruit harvesting soft grippers or fingers for safe, reliable and soft gripping is an important topic for agricultural fruit harvesting robots.

Kiwifruit are grown in long bays in clusters, as shown in Figure 1-1. Gripper properties, including size and thickness, must be optimised to harvest kiwifruit successfully, particularly as they grow in tight clusters.

Figure 1-1 Typical growing structure of kiwifruit

1.1.3. Emergence of Soft Robotics and Grippers

Soft robotics and grippers are promising approaches that lead to new solutions in this field due to the need to meet hygiene and manipulation requirements in unstructured environments and in operation with delicate products [13-15]. To eliminate the rate of fruit damage or fruit loss, soft grippers and robotics are attracting the attention of researchers more and more. Many researchers construct fingers and grippers from soft materials to increase flexibility and prevent fruit damage [16, 17]. However, the hard support of the finger's main body causes damage to the fruit very easily. Moreover, the structure of the finger is complex, and the grasp stability is insufficient. Meanwhile, the grippers having soft structures have high adaptability, a wide range of variability, and excellent working ability to grip fruit that is susceptible to damage.

1.1.4. Potential and Scope of Grippers Development

A number of New Zealand researchers have been devising an automation solution to the kiwifruit industry labour shortage and to reduce fruit loss and fruit damage. The multipurpose orchard robotic project was a collaborative effort between many universities in New Zealand, including the University of Waikato, Massey University, Auckland University of Technology, Plant and Food Research, and commercial partners, including Robotics Plus Limited. The project goal was to produce an automated kiwifruit harvesting robot. One of the prototypes for the harvesting robot is pictured in Figure 1-2.

The scope of the soft grippers is not limited to a particular fruit but can be designed with various shapes and materials to fit around different objects and grip them securely. The compliance of the soft materials also means that the gripper can conform to irregular shapes, making them ideal for handling objects of varying sizes and shapes. Soft robotic grippers have the potential to address these challenges by offering reliable and adaptable solutions for handling agricultural and food products and soft fruits, such as kiwifruit, oranges and plums. Advances in additive manufacturing technologies and materials have enabled the manufacture of complex structures that are impossible with traditional manufacturing techniques. Such technology has the potential to be applied to soft grippers for handling delicate objects.

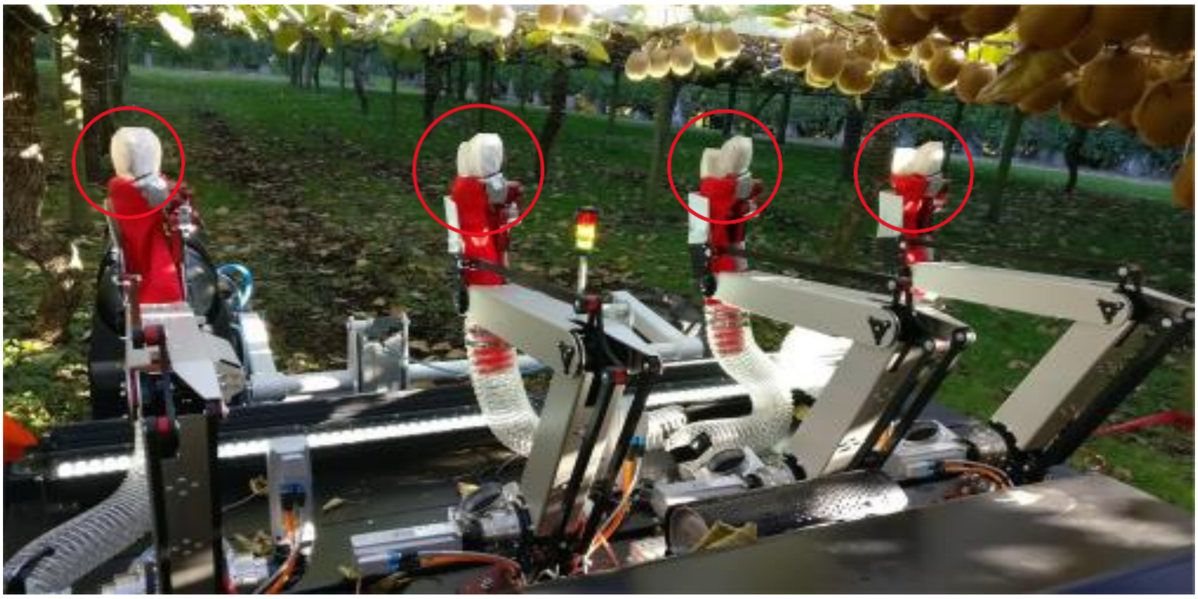


Figure 1-2: Kiwifruit harvesting robot produced in New Zealand[18].

1.2 Research Objectives

The goal of this thesis is to investigate how the finger design for a fruit harvesting gripper can be optimised using high-resolution 3D printing of flexible resin to minimise grasping pressure on the fruit and minimise fruit damage. Two main aspects will be addressed: minimising required grasping forces by increasing the coefficient of friction through different surface textures and investigating various lattice structures to optimise the bulk stiffness of the gripper fingers to maximise the contact area between the finger and the fruit. This study's scope is limited to designing the soft fingers for a robotic gripper and does not include the gripper mechanism, actuation, or other areas of an automated system.

1.3 Contribution

The contributions of this work are as follows:

1. Knowledge of how certain surface textures affect the coefficient of friction.
2. The effect of different lattice unit cell structures and wall thickness on bulk stiffness of material.
3. Optimise the finger structure for a robotic gripper to maximise contact area with kiwifruit.

1.4 Thesis Overview

The thesis is structured as follows:

Chapter 1 provides the background information, sets the context for the research, and outlines the motivation, objectives and contribution of the thesis.

Chapter 2 reviews literature relevant to soft grippers, specifically concerning grasping methods and their application to fruit harvesting.

Chapter 3 covers the friction tests and methods used to analyse the coefficient of friction between three materials and kiwifruit with results.

Chapter 4 investigates how the bulk stiffness of the material can be changed by using various lattice structures with different wall thicknesses.

Finally, Chapter 5 presents the conclusions and recommendations for future work.

Chapter 2: Literature Review

This chapter aims to provide a literature review on fruit harvesting end-effectors and grippers to summarise key past developments. It discusses various gripper designs and mechanisms, detailing their evolution and how they have been adapted to meet the challenges of handling delicate fruits/items/products without causing damage. This includes exploring different materials used in gripper construction, the impact of surface textures on grip stability, and the role of advanced design features like lattice structures for enhancing gripper functionality. The corresponding sections present a detailed analysis of specific literature.

2.1 Overview of End-Effectors and Grippers

Over the past several decades, a range of end-effectors and grippers have been developed to harvest various fruits and crops [19, 20]. This section outlines historical and current methods for picking soft fruits and vegetables using specific end-effectors. These end-effectors and grippers employ various mechanisms to detach fruit, either by cutting the stem or by manipulating the fruit through motion or rotation at certain angles.

The review of end-effectors and grippers functionalities concentrated on soft fingers, crucial components of harvesting robots that directly interact with the fruit and environment. These fingers must embody key attributes such as softness, speed, and effective fruit handling. Often, there are trade-offs among these attributes, particularly between softness and fruit handling, leading to suboptimal performance [16]. Generally, end effectors and grippers were engineered to demonstrate the feasibility of harvesting specific fruits and vegetables. Unfortunately, many designs lacked practical consideration and effectiveness [21]. While numerous studies have explored robotic end-effectors and grippers for kiwifruit harvesting, they failed to fully integrate the grab-pick-unload processes effectively [22-24].

Previously designed end-effectors and grippers faced numerous issues, including slow fruit-picking speeds, high costs, complex designs, poor performance, environmental incompatibility, and potential fruit damage [25, 26]. Current advancements aim to simplify the harvesting process and employ more effective robotic methods that minimise harm to the produce.

Despite ongoing improvements, significant challenges persist, particularly the limited capability of end-effectors and grippers to handle a diverse range of products efficiently and effectively.

Some of the other challenges of end effectors and grippers are as follows:

1. When moved quickly, the fruit can slip out of the end effector.
2. When fruit is grasped, it can be damaged due to the rigidity of the finger.

Historically, the majority of end-effectors and grippers used in industry are created for specific tasks, either complex or simple [27], but these are not designed to adapt to the shape of different objects. Therefore, there is a need to create more adaptable end-effectors and grippers to grasp a wide range of objects rather than just specific ones. One approach is to design under-actuated grippers, meaning they have more degrees of freedom than the number of actuators. Therefore, some other passive parts are used with these grippers to achieve the gripping goal. Some underactuated grippers have been studied with fingers to adapt to an object's shape both with rigid and soft gripping fingers [28, 29] It has been shown in the literature that grippers require a much simpler algorithm than more complex grippers, and they can perform more grasping tasks.

Recently, numerous studies have been conducted to develop more flexible grippers capable of picking and placing objects of various shapes and weights, aiming to enhance their versatility [30], [31], [32, 33]. Most of these grippers are categorised as passive grippers. These types of grippers have a passive gripping element, like an elastic element which conforms around the object being picked [30]. The formation of the elastic element can be done by various methods. One method is using a combination of negative and positive pressure inside a sealed gripper to jam material in the gripper [31]. Other approaches of passive grippers can be using a pneumatic actuator and a series of chambers embedded in elastomers [32] hydrostatic skeleton [33], suction-based, and much more.

2.1.1. Soft Grippers

Passive grippers made from soft, typically elastomeric materials are referred to as soft grippers. These grippers engage with objects through mechanisms like actuation, controlled stiffness, or controlled adhesion of the elastomer [34]. The mechanical simplicity of soft grippers usually results in less complex control systems due to their soft membrane construction [35]. Contact grasping grippers, including soft grippers, are often classified based on the number of fingers, actuation types, mechanism types, and physical gripping principles [36].

Soft grippers, with their compliant nature, are particularly suitable for safely interacting with delicate items such as fruits, crops, and even humans. For example, small-scale compliant-robotic grippers have been used for blackberry harvesting [37], and more robust designs facilitate large-scale apple harvesting [1].

One significant advantage of soft grippers over more active gripper designs is their more straightforward construction. Some grippers, like those using a jamming mechanism, incorporate a granular material within an elastomer shell. The gripper moulds to the object, and the air is evacuated to solidify its grip, although this often necessitates a vacuum pump [38]. Some researchers have used vacuum pumps [21, 39, 40], where they use tips like suction cups to seal the membrane of the gripper to the object (Figure 2-1) and create a suction to pick it up, but they mostly work with lightweight objects [41]. Furthermore, the design of some grippers often follows the bionics principle, shaped to match the object or fruit being grasped, which minimises damage during the harvesting process.

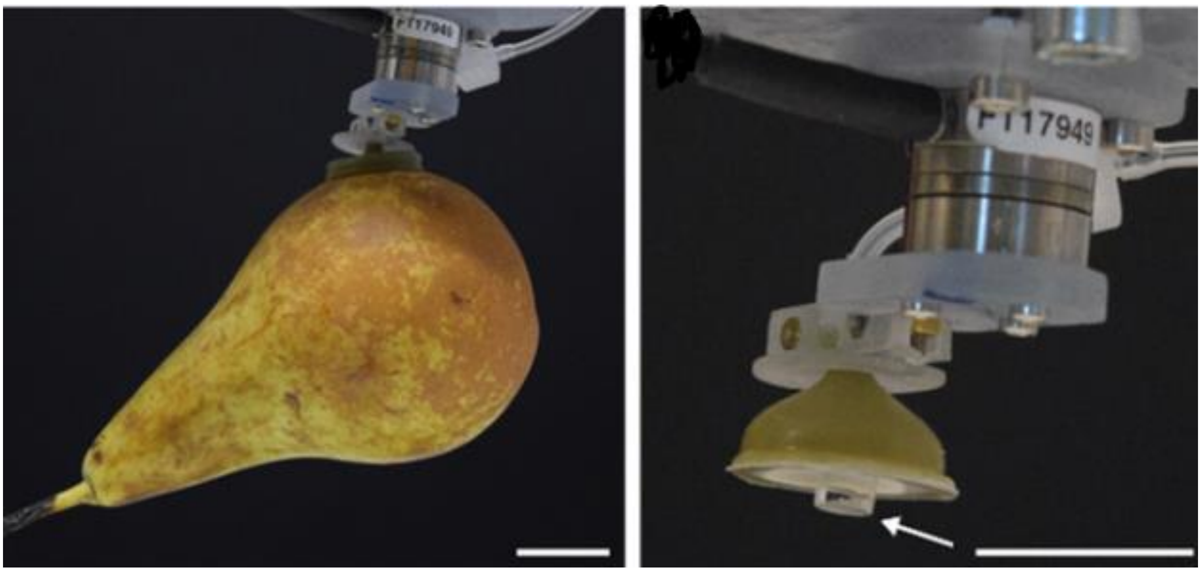


Figure 2-1: Suction cup with seal membrane for picking up small objects

2.1.2. Bernoulli Principle Gripper for Handling 3D Objects

Petterson et al. developed a gripper based on Bernoulli’s principle, which increases the flexibility of robots to handle different types of 2D and 3D objects. To enable individual product handling, a deformable surface has been used which provides sufficient lifting force for flat and non-flat objects. To be able to grasp 3D objects [40], a deformable surfaced gripper was designed based on a matrix pin board, including rows and columns, as shown in Figure 2-2. The thin, 1.5 mm, latex rubber sheet covered the surface of the pins and is attached to each pin. During grasping, the targeted object is gently pressed by the gripper using deformable surface. At this point, the gripper’s surface deforms to match the contour of the object’s surface.

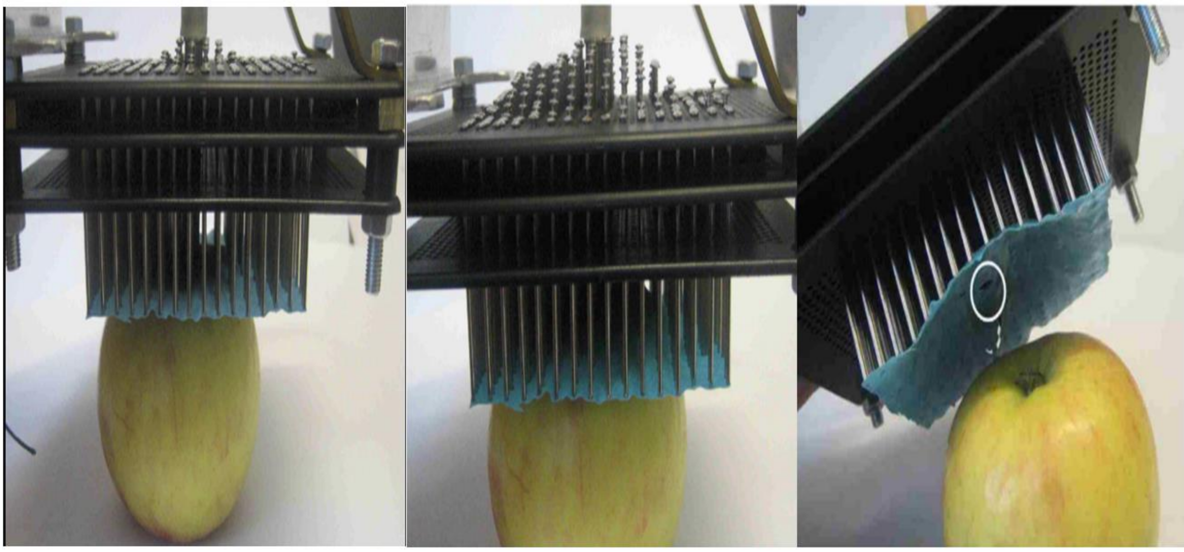


Figure 2-2 Shows the Bernoulli's gripper for handling round object[42]

After the completion of the moulding, the locking mechanism is activated to lock the shape of the gripper’s surface. A few tenths of a millimetre are lifted by the gripper from the object, forming a small air gap between the gripper and the surface of the object. Static pressure above the object is reduced by applying airflow, generating lift for grasping the object. The gripper fails due to a lack of force of friction between two surfaces and the lack of surface area required by a gripper to grasp an object. For this case, with the 3D Bernoulli gripper, the shape of the flow path strongly depended on the shape of the target product and suggested that for a spherical product, a spherical form would be appropriate. The flow area initially increases linearly, flattens out, reaches a maximum and then starts to decrease with an increasing radius.

2.1.3. Soft Bionic Gripper

Liu et al. created a soft bionic gripper with tactile sensing and slip detection for damage-free grasping of fragile fruits and vegetables [43]. To achieve safe and non-destructive handling of products, he designed a flexible biomimetic robot gripper inspired by the octopus predation mechanism whose gripping module combines innovative memory metal wire and flexible silicone film, while the control structure simplifies the pneumatic mechanism with enhancing grip precision. This design achieves enveloping-like slight-force grasping like pneumatic actuators, resulting in passive compliance grasping and adaptive grasping. The design achieves enveloping-like slight-force grasping like pneumatic actuators, resulting in passive compliance grasping and adaptive grasping, as shown in Figure 2-3.

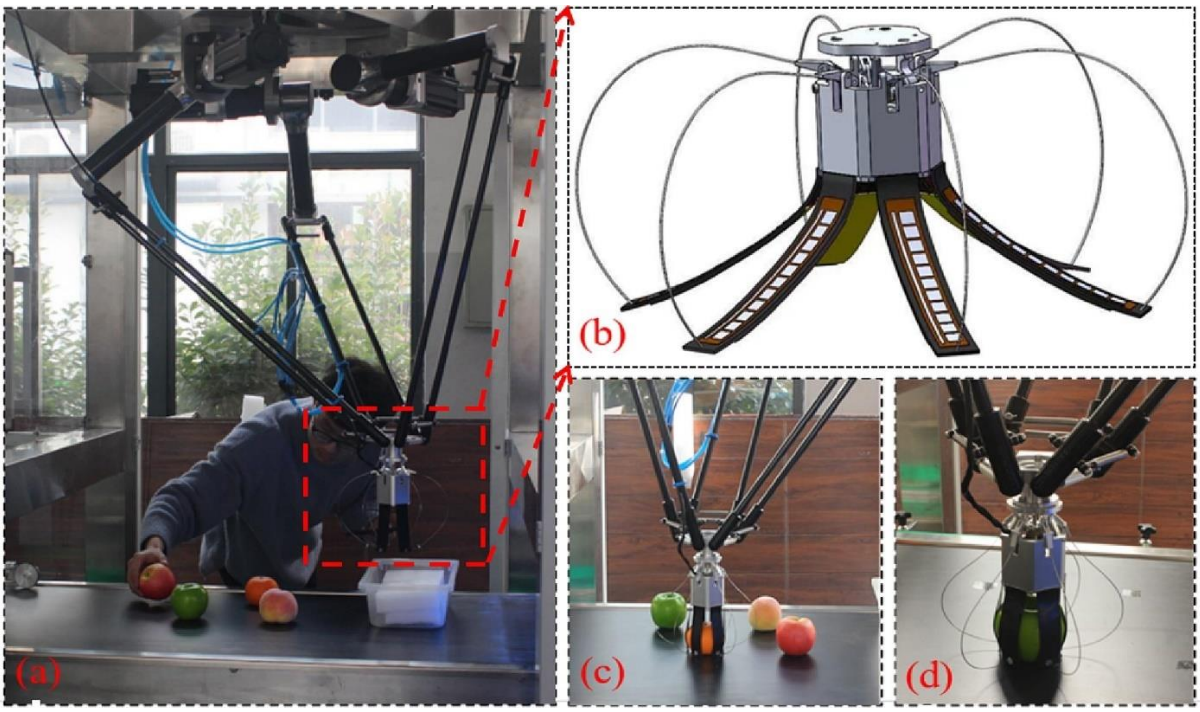


Figure 2-3: Six-finger silicone grippers[43]

2.1.4. Three-Finger Fin Ray Gripper

Chen et al. developed a three-finger gripper based on the Fin Ray structure specifically for apple harvesting [1]. This gripper includes front, rear, and cross beams with a base to enhance structural integrity. A key feature of this gripper is its incorporation of slip detection to mitigate fruit damage caused by excessive gripping force, a necessity given the rough surface of the gripper's fingers [44]. Shin et al. further explored this concept by analysing the changes in stress and displacement as the gripper's fingers made contact with objects, adjusting variables such as the number of cross beams and the angles of the front and cross beams [45]. The design of the gripper is divided into three functional parts: sensing, transmission, and grasping, which clamps the fruit with feedback mechanisms for torque and position managed by the driving part, as shown in Figure 2-4. The fingers connect to moving plates attached to support rods, facilitating vertical movement. The three Fin-Ray finger units are strategically positioned around the gripper disc's bottom and linked to the transmission mechanism.

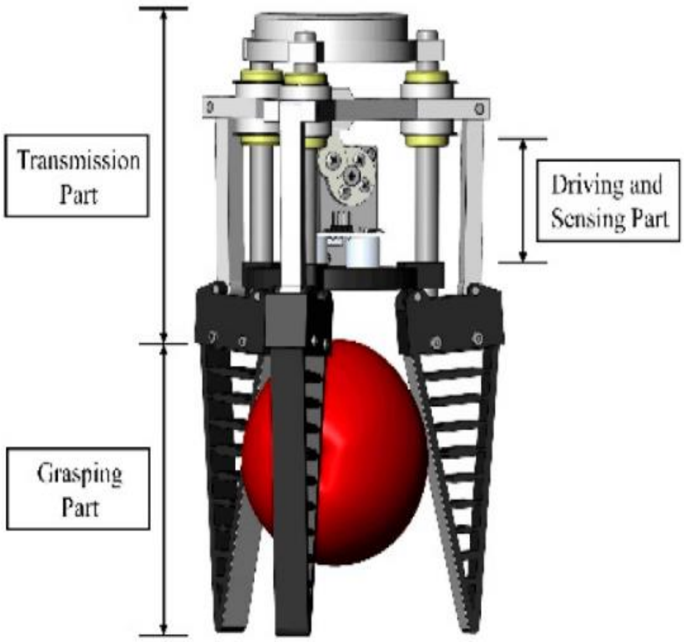


Figure 2-4: Three-finger gripper grasping an apple[1]

The design's geometric efficiency is enhanced by a triangular configuration and the parallel alignment of the fingers' bottoms with the connector, although preventing relative slippage during fruit detachment remains a complex challenge [1]. The application of rough silicone pads on the fingers increases the friction between the gripper and the fruit, which is critical when slippage occurs.

2.1.5. Gripper for Kiwifruit Harvesting

The grippers shown in Figure 2-5 were designed by Williams et al. using a soft silicone structure specifically designed to ensure the safe handling of kiwifruit [18]. This approach minimises damage during harvesting operations by prioritising a gentle grip on delicate kiwifruit. However, during extensive testing in a real-world orchard environment, it became evident that the M4 gripper's overall size posed a significant challenge. This high rate of fruit loss likely resulted from difficulties in a reduced capacity to adapt to varying fruit sizes and positions on the tree. Although the soft silicone material succeeded in mitigating mechanical damage, the gripper's size appeared to compromise its operational efficiency and precision.

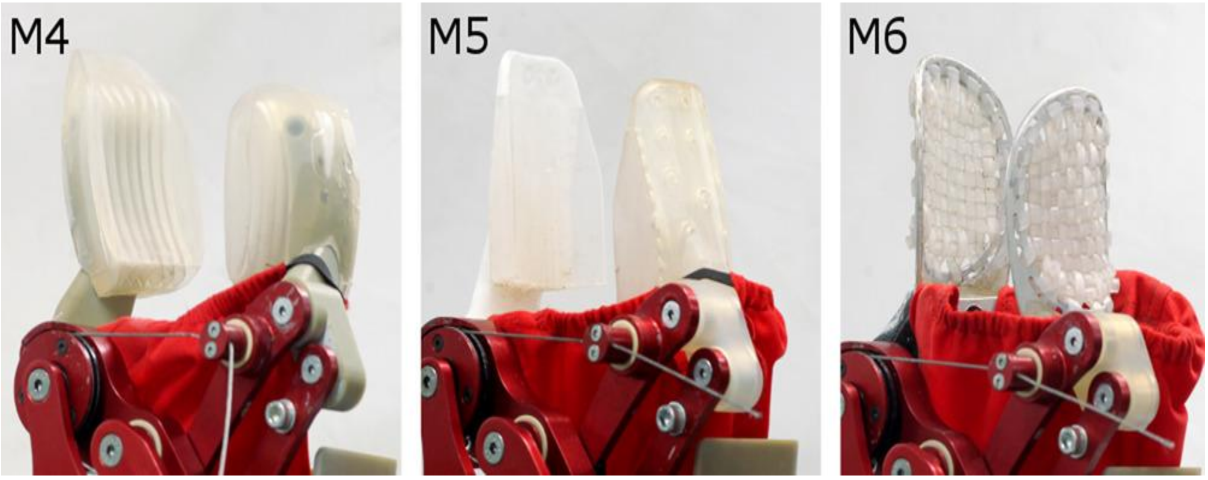


Figure 2-5: The M4, M5 and M6 silicone gripper for kiwifruit harvesting[46]

After conducting fruit harvesting field trails, it was observed that the cause of the fruit loss was due to contact between the high-friction silicone gripper and the fruit calyx region, which caused fruit neighbouring the targeted kiwifruit to be rotated and pushed upwards as the gripper was moved into position. As a result, the neighbouring fruits were detached from the stem, leading to fruit dropping from the canopy. The M4 gripper was a major contributor to the high fruit loss rate of approximately 25.0%. Two new grippers, M5 and M6, with thin cross-sections, were developed to fix the problems identified with the M4 gripper. The M5 gripper was a thinner version of the M4 gripper with a much smaller top radius and a tapered, smooth back whose thickness started at 4 mm at the top and increased to 21 mm at the bottom. The M6 gripper was even thinner than the M5 gripper, as shown in Figure 2-5. It was made from a 3.3-mm-thick rotary laser-cut aluminium metal tube with a weaved silicone tubing mesh.

A racket-style design was used to minimise the thickness of the gripper while allowing high deformations for the fruit to conform to the soft contact surface. The gripper was correctly placed but did not detach the kiwifruit from the canopy; that is, the gripper slipped off the kiwifruit due to insufficient contact area or grasping force. This was typically caused by an unusual orientation of the kiwifruit or a positional error of the gripper [18]. Fruit flesh firmness of kiwis is very high at harvest (60 N)[47].The high success rate to harvest kiwifruit is at 60° with 60N [46].

2.2 Fruit Slippage Due to Lack of Friction

Effective grasp acts as an important component in improving the robot's overall grasping abilities. Safe gripping not only requires controlling the gripping force to avoid damaging agricultural products but also detecting possible sliding during the gripping process to prevent fruit detachment [48]. The grip quality evaluation is based on whether slippage has occurred and if a grasping process is continued. Appropriate grasping force can enhance the accuracy of grasping the fruit. However, many fruits have the characteristics of tenderness and vulnerability; therefore, how to grasp fragile objects is still a challenge faced in current research [36, 49]. Wang et al. discussed three main different methods of slip detection, which were based on tactile sensing and by conducting frequency domain analysis on the force signals during grasping and separating high-frequency components, utilised distributed tactile information and discrete wavelet transform theory to obtain the DWT, which explains the coefficients of three-dimensional grasping forces, and detected grasping slip through a thresholding approach [50].

Chen et al. have implemented silicone pads on each finger of the gripper to enhance fruit grasping and increase contact friction. This modification promotes clamping stability, as illustrated in Figure 2-6 [1]. Avoiding slippage is necessary to reduce fruit damage. In their evaluation, Shin et al. employed a slip detection method, attaching silicone pads to the fingers to boost grip performance by augmenting surface friction [45]. A silicone pad was attached to the surface of the finger to improve the grasping performance by increasing the friction of the fruit's surface. To quantify the maximum static friction coefficient (μ) between the silicone pad and the fruit, the pressure was applied via Model E43, with silicon sheets affixed to both the upper indenter and lower support. The horizontal pulling force necessary to initiate fruit slippage was then measured [1].

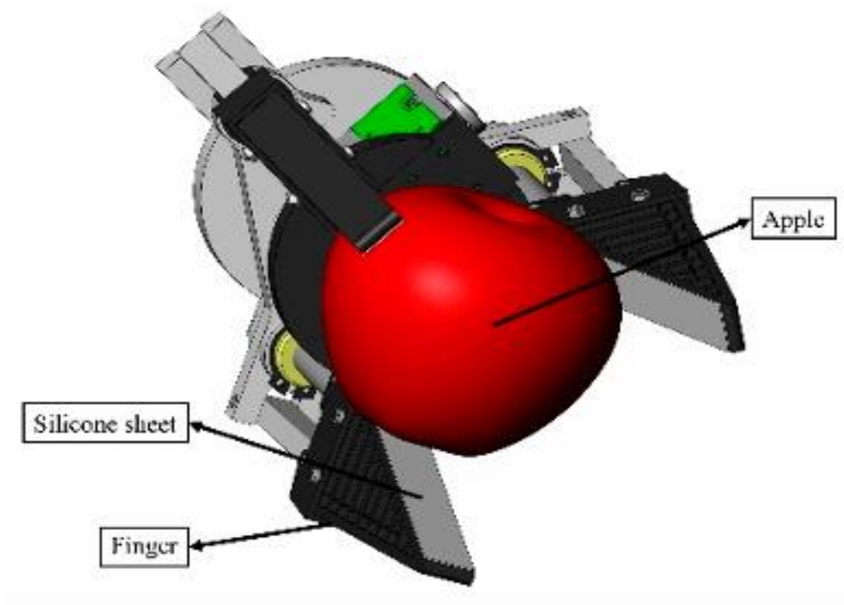


Figure 2-6: Three finger grippers with silicone pad [1]

The effectiveness of the gripper was also tested in various scenarios involving both rigid and soft fingers, with and without slip-detection features. In one experiment, 25 apples were harvested without skin damage; however, observations indicated that 36% of the fruits slipped from the gripper, with 8% suffering picking damage and 12% slippage damage in tests using soft fingers without slip detection. Another trial involved harvesting 20 fresh apples of diverse sizes, shapes, and weights using soft fingers equipped with slip detection. This setup resulted in a 65% slippage rate during picking, though no picking damage was recorded.

Ultimately, visible slippage was a common issue in both scenarios, with most damage occurring during fruit slippage within the gripper. In the rigid fingers experiment, three fruits were damaged by slippage and one by grasping, indicating that even with a flexible silicone gasket, the rigid structure is susceptible to causing fruit damage. Conversely, in the soft fingers experiment, damage was exclusively due to slippage. Slip detection, which monitors the relative movement between the target objects and the actuator surface, proves crucial for early slippage prevention in agricultural product handling [51, 52]. Effective control of fruit slippage within the gripper is thus essential for minimising the risk of damage. This highlights the importance of integrating slip detection, especially considering the rough texture of the gripper's fingers, in preventing damage due to excessive gripping force.

2.3 Soft Surface of Gripper and Effects of Textures

Naturally grown objects like fruits have uneven shapes and surface areas. Due to irregularities, some fruits are impossible to harvest using suction grippers, such as kiwifruit [53]. To achieve strong grasping similar to the human hand, robotic gripper fingers play an important role as it affect reliable and successful grasping [28]. To avoid slippage, some of the grippers have special surfaces. Dadkhah et al. used electrostatic and gecko-like adhesives and developed the gripper to avoid slippage [54]. Zhou et al. proposed a different strategy for soft robotic finger design in which they used passive compliance to achieve a stable grasp without requiring additional actuation and designed a soft gripper that could successfully grasp objects of different shapes, stiffnesses, and sizes. The tests were conducted using two different surfaces, one with a smooth surface and another using a rough surface, and noticed that there was more grasping stability in a rough surface than a researcher investigated the effect of a smooth surface. The proposed surface feature helped to maintain a firm grasp even with odd-shaped objects [55].

The frictional effect between the gripper surface and the object plays a crucial role in ensuring a successful grasp [56, 57]. Another approach to increase the operational effectiveness is by increasing the friction coefficient of the contacting surfaces [58]. Perfect grasping objects of various shapes and sizes is one of the key advantages of utilising flexible friction pairs. In the soft grippers, these friction pairs often employ materials on their surface that are flexible and deformable, which enables the gripper to establish a secure grip with the object being held, resulting in improved efficiency in transferring frictional forces [59]. Incorporating textures and protrusions onto the surface of soft fingers can increase frictional force, enhancing the contact surface's effective friction coefficient.

Glowania et al. investigated how differences in object roughness affect grasp point selection when lifting objects [60]. They conducted an experiment using large aluminium bars that were either completely covered in anti-slip tape to increase roughness or polished aluminium bars that were much smoother and had a lower friction coefficient than the rough bars. They concluded that the rough surfaces have a higher friction coefficient and are more stable when grasping an object.

Linghu et al. investigated the effect of millimetre-level microscopic features of soft polyurethane skin on friction on smooth surfaces. As a result, it was found that compared to skin designs without patterns, incorporating a small amount of nanoscale fingertip features maximised friction under lubricated conditions [61]. Hao et al. conducted an experiment using flexible silicone rubber films with loop, whorl, and arch surface textures to investigate the gripping ability of textured or fingerprints and smooth surfaces whose results revealed that the presence of surface texture increases the grasping capabilities due to high friction than of the plane and smooth surfaces [62]. While materials and surface textures in gripper contact zones are vital for efficiency and safety in fruit handling, systematic investigations into their influence on fruit interaction remain limited. Addressing this research gap is essential for optimizing gripper performance and reducing fruit damage during harvesting operations.

2.4 Shapes and Contact Surface Area for Adequate Gripper

Ting et al. have developed a new Flexi gripper for kiwifruit harvesting, similar to the M4 and M5 grippers, as shown in Figure 2-7 [46]. Silicone was placed on the grippers' inner walls, and several lab tests were performed using fake kiwifruits in the lab and in the orchard.

Figure 2-7: Flexi gripper for kiwifruit harvesting [46]

During the lab testing, the fruits were made of silicone with a modelling flock to simulate a real kiwifruit. However, the real kiwifruit had a much lower coefficient of friction. Therefore, the flexible gripper was effective at grasping the fake kiwifruit made of silicone but not the real kiwifruit in the orchard without slipping out. In orchard testing using a single arm, it was found that the flexi gripper had considerable design errors, such as a low coefficient of friction, which caused fruit slippage, and it had a low contact surface area. In orchard testing, 30% of kiwifruit were damaged due to grip failure, and 15% accounted for entry failure. These two major shortcomings with low stiffness resulted in many failed grasps and a high number of attempts.

In soft robotic harvesting, the vision system and end-effector work play an important role in determining the success of the harvest. However, all the fruits and objects are different in shape and size, and growing conditions of different fruit varieties present a challenge. Due to this, the end-effectors designed for specific fruits cannot be universally applied across all crops [63] . The differences in fruit characteristics make it necessary to design differently shaped fingers for grasping different objects [64, 65]. Therefore, the design, including the shape and size of the end effector, is very important as the component that comes into physical contact, especially when it comes in terms of soft fruit like kiwifruit, strawberry or tomatoes [65].

To increase the stability of pneumatic-driven soft grippers, the stiffness of the gripper designer can change the design and the material of the gripper. Incorporating two flexible surfaces increases the contact surface area and significantly enhances the stability of the grasping process. Xiao et al. designed a gripper inspired by a Venus Flytrap that shows a gripper can observably enhance the grasping adaptability and reliability of a large contact area between the gripper and the object [66].

Rong et al. designed the watermelon harvester end-effector using SolidWorks software (Figure 2-8). After many versions, the final fingers were designed according to the physical properties of watermelon, such as a pedicel diameter of 5.5 mm, a pedicel length of 98 mm, a fruit width of 150 mm, a fruit length of 186 mm, and a fruit weight of 1.89 kg. This finger, designed according to the watermelon, has long fingers which cover a large surface area of the watermelon, which helps the gripper for easy grasping [63].

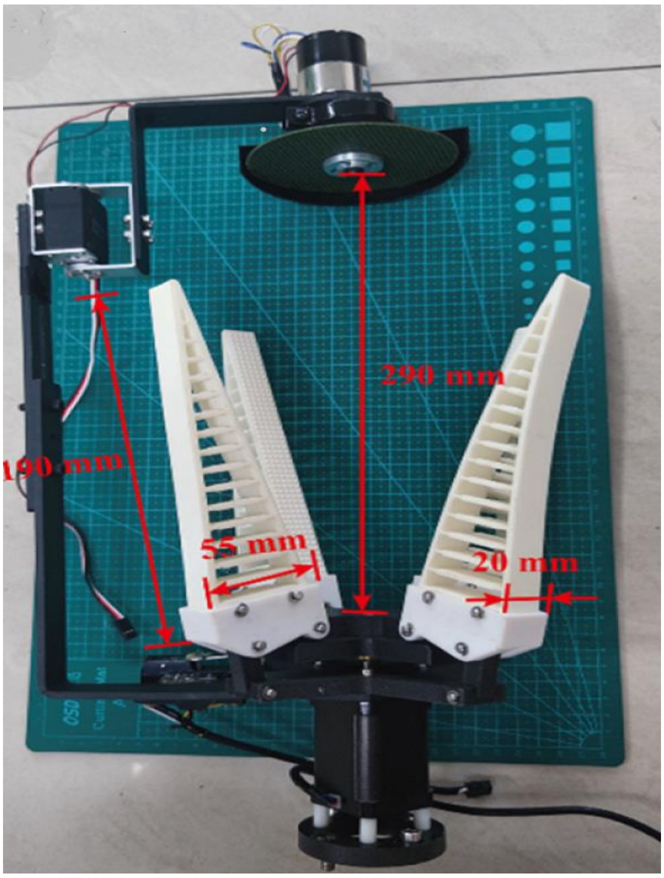


Figure 2-8: Watermelon harvesting gripper [63]

Generally, there are two main shapes of grippers: plane and arc-shaped grippers of the finger. In an experiment of grasping an apple, it was found that the contact area between the arc-shaped finger was more than that of the plane finger [67]. Additionally, round-shaped fingers were used, and flexible materials were placed inside the gripper to increase the gripper's grasping ability. Then, the experiment was conducted to evaluate the changes in contact force between the apple and different knuckles of the fingers during the grasping process, verifying the adaptive grasping ability and the stability of the round-shaped finger. Due to the more fixed arc during the grasping process of picking small fruits such as cherry tomatoes and plums, Zhang et al. [68] also designed a gripper with oval-shaped fingers based on biomimetic principles, is shown in Figure 2-9. The structural parameters of the gripper were determined while meeting the requirements of the grabbing range. A structural model of a single finger of the gripper was established. Based on this model, grasping experiments were conducted at six speeds and with three fruit sizes. The results show that when the speed is 0.08 m/s, the gripping time and maximum gripping force during clamping meet the requirements of high-speed and low-damage sorting.

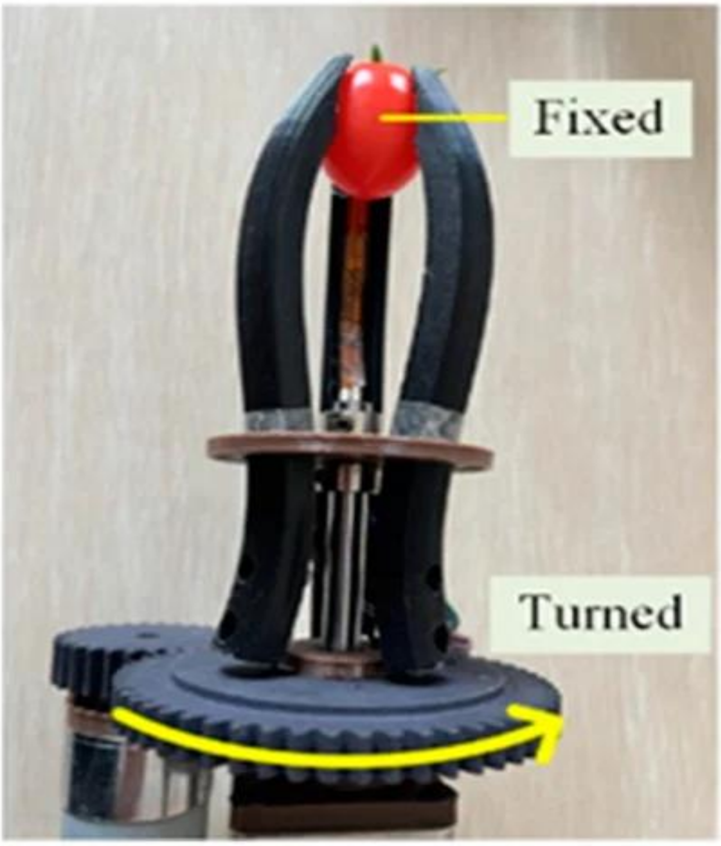


Figure 2-9 Shows arc-shaped grippers for cherry tomatoes [77]

2.5 Analysis of Lattice Structures in Grippers to Optimise Stiffness

Simple lattices can be recreated using a simple network structure frame and transformed to various geometric structures. This allows for powerful parameter variations to create differing structures from a single source structure. A lattice structure is a space-filling unit cell that can be tessellated along any axis with no gaps between cells (Figure 2-10), which is a solution to weight, time and energy saving. Two different topologies are used in lattice structures: periodic and stochastic. To increase stiffness, Li et al. designed a soft gripper that was similar to human fingers, which used an endoskeleton mechanism [69]. The stiffness and stability of the soft grippers also depend on the manufacturing process. Peele et al. printed a stiffer pneumatic soft clamp using 3D printing with photopolymerised elastic materials [70]. The lattice structures whose distribution of cells and shapes is defined through a random probability distribution are called stochastic lattice structures. These structures can be analysed and approximated statistically but cannot be recreated. These types of structures include those present in bone structures [71].

These lattice structures have become more prominent and are used to reduce the material used in manufacturing. Also, the lattice structures reduce the amount of energy utilised in manufacturing the object and reduce the weight of the object produced. These lattice structures are now commonly used in medical industries to produce implants [72]. There are many methods to create lattice structures, which are divided into manual and mathematical. Beams and truss structures are utilised with joints to create seamless transitions between unit cells to create lattice structures manually [71].

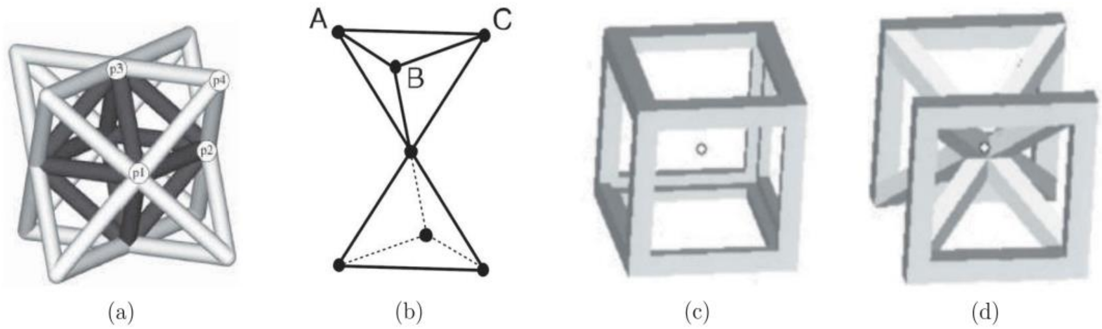


Figure 2-10: (a) Octet truss [73],(b) 3D Kagome structure [74], (c) G6 structure [75], G7 structure [76]

There are numerous advantages of lattice structures when it comes to stiffness and strength, which have been applied to designing lightweight structures with additive manufacturing. The unique design flexibility of AM has enabled the fabrication of a functionally graded lattice by changing the size of the lattice and its efficiency [77]. Many studies have investigated the deformation characteristics of the lattice structures. The four lattice structures considered were body-centred cubic with x-directional horizontal struts (BCC), edge-centred cubic (ECC), octet-truss cubic (OTC), and hexagon cubic (HXC) structures show the unit lattice cells and the resulting cellular cubes for each unit lattice (Figure 2-11). Here, the isometric and front views are illustrated for each lattice structure. Autodesk Netfabb ® (Autodesk Inc., USA) was used to generate these lattice structures. In all cases, the sizes of the base cube and the unit cell were set to 40 and 5 mm, respectively. The number of struts is different for each lattice structure.

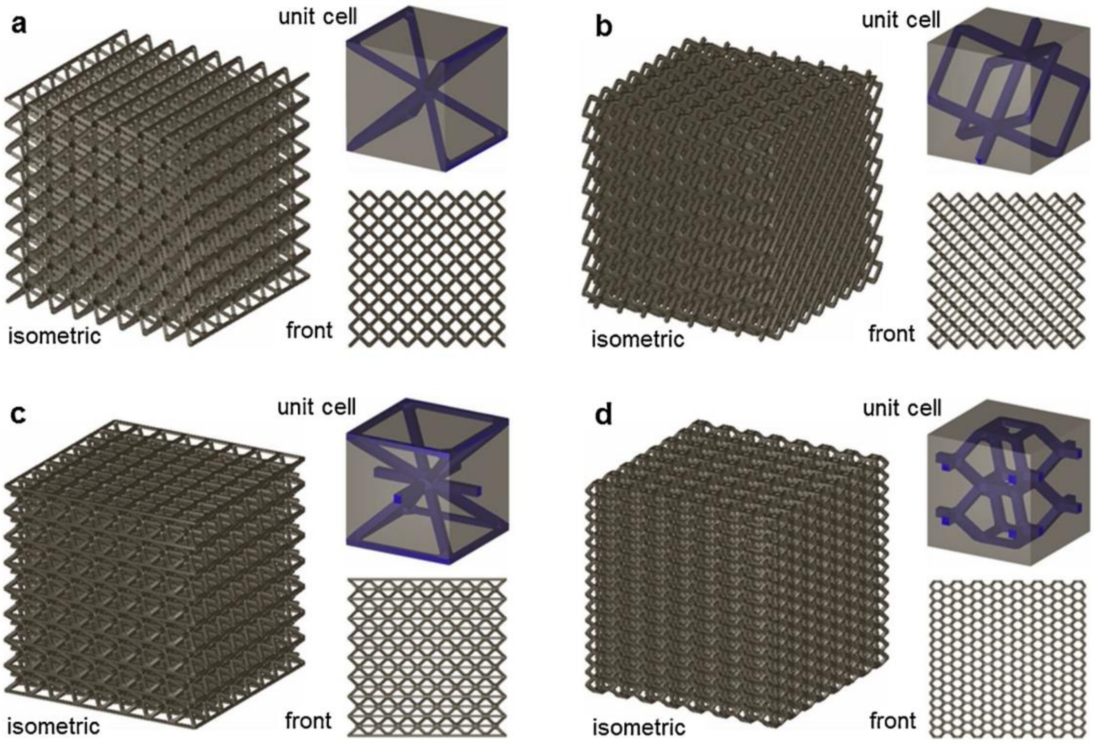


Figure 2-11: Unit lattice and periodic structures BCC, OTC and HXC [77]

Photo-curable polyurethane resin (CFY063W, Carima Inc., Korea) printed these soft lattice structures. Compression tests were performed to investigate the compressive behaviour of the specimens. A universal test machine (NA-2M, Nanotech, Korea) was used to conduct the tests, and the compression speed was set to 12 mm/min. Compression tests were performed on five samples for each lattice structure. Deformation behaviours during the compression test were recorded using a digital imaging system (EOS-60d, Canon Inc., Japan). Microscopic images of the fabricated lattices were obtained.

H. Park and K. Park conducted tests on four types of lattice structures (BCC, ECC, OTC, and HXC), which were designed to have a 15 % volume fraction, which showed hyperelastic bending behaviours overall, with the OTC lattice also showing a slight stretch [77]. Their initial stiffness values were in between 17.1 and 26.9 N/mm, and the ECC was selected as the softest lattice because it demonstrated the lowest stiffness until reaching a 50 % compressive strain. The stiffness of the ECC lattice was reduced to 0.33 N/mm by changing the strut diameter to 0.3 mm and was further reduced to 0.005 N/mm. He concluded that the proposed compliance based on a soft lattice structure can be used to impose the desired functionality of industrial soft grippers [77].

The deformation nature of polymeric lattice structures has also been studied, most of which are fabricated using photo-polymerisation type 3D printers that can generate complicated 3D lattices without a support structure [78]. Li et al. tested gyroid under compression, whose work depicts that different types and gradients of gyroid cellular structure can achieve different deformation behaviours and mechanical responses under compression testing [79].

The potential of lattice structures in the design of robotic gripper contacts interfaces, often referred to as gripper fingers, remains largely untapped in the field of agricultural robotics. This oversight represents a significant research gap, particularly given the advantages of lattice designs in optimising stiffness and minimising damage to fruits during harvesting. Addressing this gap by developing specialised lattice structures for gripper fingers could greatly enhance the efficiency and effectiveness of robotic grippers, ultimately improving both yield and quality in fruit harvesting operations.

2.6 Summary

This chapter presents a comprehensive review of scientific literature on robotic end-effectors and grippers used in fruit harvesting. It identifies key gaps in the current body of research that the study aims to address, focusing on three primary areas:

1. *Material and Texture of Gripper Fingers:* The review highlights the need for a more detailed exploration of the materials and textures used in gripper fingers. Understanding how these factors influence the coefficient of friction, gripper efficiency, and safety during fruit handling is crucial. Improved knowledge of material and texture interactions with fruit could significantly enhance harvesting outcomes.

2. *3D Printed Lattice Structures:* The literature reveals a scarcity of studies on the application of 3D printed lattice structures in gripper fingers. These structures have the potential to transform gripper functionality by enhancing flexibility and adaptability to accommodate various fruit shapes and sizes without compromising the fruit's integrity.

3. *Contact Surface Area:* The review emphasises the insufficient research on optimal contact surface area designs for gripper fingers. Properly designing this feature is critical for ensuring a secure yet gentle grip on the fruit, which is vital to prevent damage during harvesting. This gap highlights the need for targeted research to develop more effective gripper contact interfaces.

By addressing these gaps, this research aims to deepen the understanding of how the design, representation, and production of gripper technologies impact their performance. The guiding research question for the subsequent chapters is:

"Is the 3D printed gripper finger from a suitable material with infill patterns and textured surfaces more effective in reducing kiwifruit slippage and damage during harvesting?"

This question drives the exploration of experimental and design modifications aimed at refining gripper technology to achieve better agricultural outcomes.

Chapter 3: Coefficient of Friction and Grasping

This chapter investigates the coefficient of friction of real and fake kiwifruits using three different materials: rubber, silicon and nylon.

Section 3.1 discusses the physical properties of kiwifruit. Section 3.2 demonstrates the experimentation conducted to determine the coefficient of friction. Segment 3.3 reveals data on lab testing using fresh, real kiwifruit harvested, and subsection 3.4 shows friction testing using textured printed specimens with adequate results.

3.1 Physical Properties of Kiwifruit

All fruits differ in size, shape, and weight, which makes it difficult for automated machines to harvest them. It is challenging to compare human hands with the robotic gripper in terms of flexibility. However, the human hand can pick fruits quickly by performing complex actions. The gripper is a mechanical mechanism (or end-effector) that holds the object and releases it as it receives a signal from the processor. There are different types of grippers available today, each with its own advantages and disadvantages, which makes it difficult to conclude which is the best.

The main obstacle is to hold the object carefully and gently when it comes to soft fruits like kiwifruit. There are two types of kiwifruits: green kiwifruit and gold kiwifruit. To design a gripper for kiwifruit harvesting, it is very important to analyse the physical properties of both types of kiwifruits. The two varieties were manually harvested from the orchard, and their physical properties were examined. The design of the gripper depends on parameters such as size, shape, weight, and the overall cost-effectiveness of the soft kiwifruit harvesting gripper.

The skin of kiwifruit is thin and covered with soft and fuzzy hairs. It is delicate and susceptible to bruising and damage if handled improperly. Unripe kiwifruit is firm, but it becomes very soft when ripe. Kiwifruits contain moisture in their flesh, which means they are more prone to damage, as bruising can lead to rapid fruit degradation.

3.1.1. Size and Weight of Green and Gold Kiwifruit

The very common commercial variety of matured kiwifruit was chosen for this study. To analyse the physical properties of kiwifruit, approximately 100 random fully developed fruits of various shapes and sizes were picked up from the orchard at Te-Puke in the morning on 14 May 2024. The selected fruits were visually inspected to ensure they were free from physical defects. These fruits were then taken into the university laboratory. A primary visual investigation based on the samples indicated differences in the shapes, sizes, and mass of all the kiwifruits. Some are tall and round, while some are elliptical and flattened. To obtain the required parameters for size and shape detection, the length, the minimum diameter and the maximum diameter were measured using a digital vernier calliper with ± 0.1 mm accuracy Figure 3-1. The mass of each kiwifruit was measured using a digital precision weight scale with ± 0.1 g accuracy.

Figure 3-1: Measuring length and diameter of kiwifruit using digital vernier calliper

The standard deviation, σ, was calculated using Equation 3.1:

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{n}} \quad \text{Equation 3.1}$$

Where:

- n is the total number of measurements
- x is the measured value
- μ is the average of the measurements

Some physical attributes and characteristics of gold kiwifruit, such as length, mass and diameter, are shown in Table 3.1. From the data, it is apparent that the average fruit mass is 145.4 g, and the average length is 72.8 mm. The minimum and maximum diameters are 52.8 mm and 56.98 mm, respectively.

Table 3.1: The mean values, Standard Deviation (S.D), lower limit and upper limit of length, minimum diameter, maximum diameter and the mass of gold kiwifruit.

	Mean	**S.D.**	**Lower limit**	**Upper limit**
Length (mm)	72.78	6.00	60.76	84.79
Mass (g)	145.40	18.4	108.55	182.24
Min. dia. (mm)	52.83	1.12	50.58	55.07
Max. dia. (mm)	56.98	1.47	54.02	59.93

In terms of green kiwifruit, the physical properties are given below in Table 3.2. The mean mass is 130 grams, and the length of green kiwifruit is 72 mm. The minimum and maximum diameters of the kiwifruit are 50.7mm and 56.55mm, respectively.

Table 3.2 Shows physical properties of green kiwifruit (length, mass, minimum diameter and maximum diameter)

	Mean	**S.D.**	**Lower limit**	**Upper limit**
Length(mm)	72.07	3.81	64.44	79.71
Mass(g)	130.96	12.02	106.91	155.0
Min. Dia (mm)	50.71	1.75	47.20	54.21
Max. Dia (mm)	56.55	2.99	50.55	62.54

Both varieties of kiwifruit are similar and oval in shape, and there is no significant difference between the average size of green and golden kiwifruits. The golden kiwifruits are slightly heavier and have a smoother texture than the green ones. In an ideal scenario, a single geometric configuration of the robotic gripper could effectively handle the harvesting of both types.

3.1.2. Geometry and Clustering

The section represents the design requirement of the fingers that adequately meets the needs of kiwifruit harvesting grippers. The kiwifruit grows in clusters, which makes robotic harvesting a challenging task. Some clusters consist of five fruits, and some consist of seven, but it can also be less than this, and sometimes there is a single kiwifruit. One main clustering aspect is the distance measured between neighbouring fruits and stems. The distance of one kiwifruit stem to the another was measured from the five clusters. The mean difference between the two stems of kiwifruits is around 25 mm, as shown in Figure 3-2 which states that the gripper's thickness should be lower than 25 mm so it can easily grab the kiwifruit in the cluster without hurting another kiwifruit.

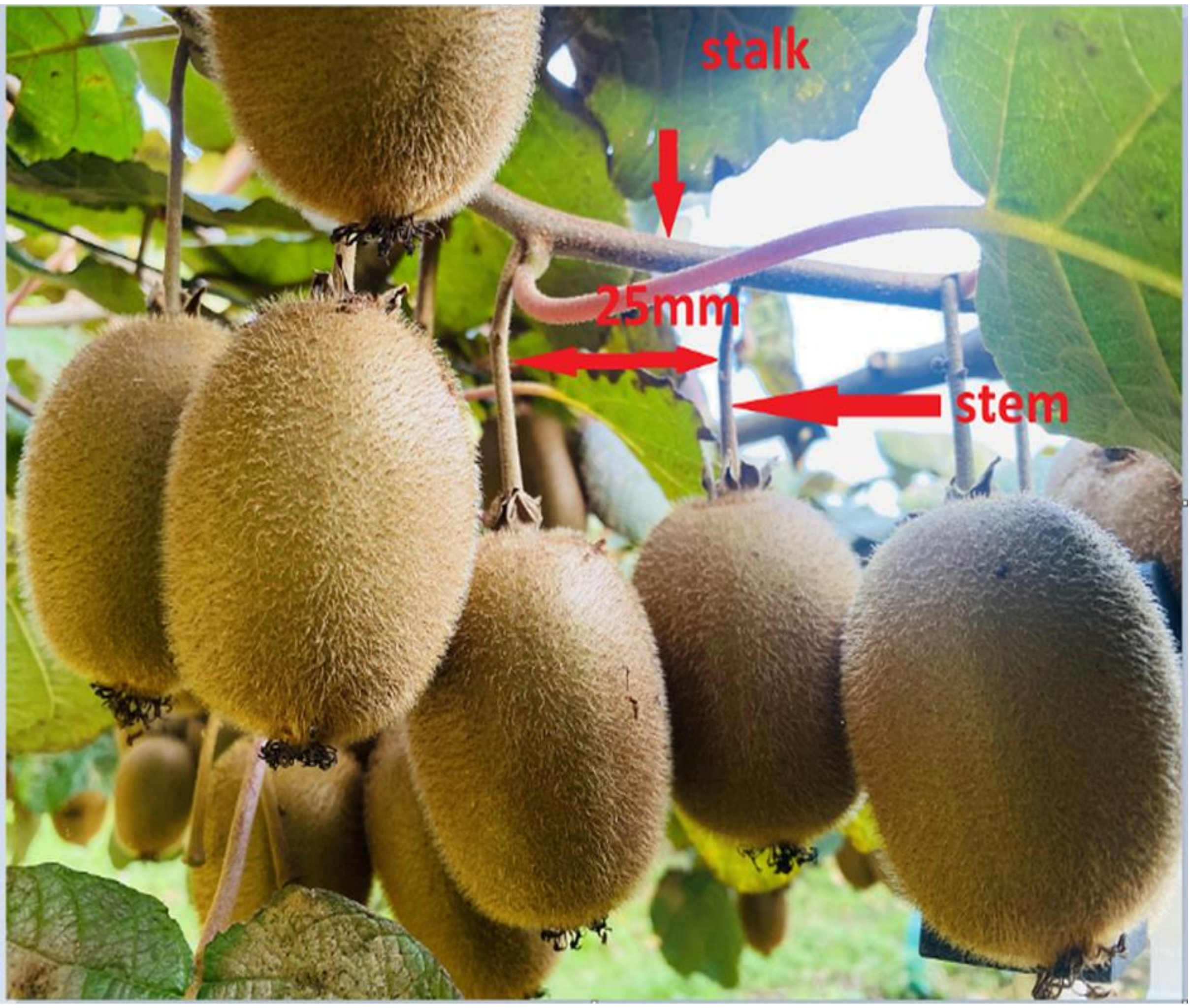


Figure 3-2: Kiwifruit clustered tightly in an orchard

3.1.3. Grasping and Coefficient of Friction

Grasping can be defined as holding an object using the hand configuration. In robotics, grasping refers to the ability of the robot to manipulate objects, similar to the human hand's ability to grasp physically. Mechanical grippers have been developed to enable robots to grasp objects with different geometric properties. During object manipulation or fruit picking, the grippers adjust the grip force according to the coefficient of friction of the object, as the slippery objects are squeezed more firmly than the sticky ones. The coefficient of friction is directly related to the effectiveness of grasp. A higher coefficient of friction ensures a more secure grip, while a lower coefficient of friction makes it challenging to hold onto an object or grasp.

Friction plays an important role in grasping any object, influencing stability and effectiveness. Friction contributes to overall grasping stability, preventing unintended slips. Force-closure grasps depend heavily on friction, typically requiring fewer contact points than form-closure grasps. However, force-closure grasps may not fully cancel external disturbances if frictional forces are weak. To design an effective soft gripper, it is necessary to ensure the coefficient of friction because the more friction, the less grasping force will be required.

The amount of friction is directly proportional to the normal force exerted between the surfaces. The gripping force equation generally pertains to how the force is distributed or applied by an object to grip another.

The gripping force can be calculated using Equation 3.2:

$$F_{grip} = \mu N \qquad \text{Equation 3.2}$$

Where:

- F_{grip} is the gripping force.
- μ is the coefficient of friction between the gripping surfaces.
- N is the normal force applied by the grip.

Friction force depends mainly on the nature of the material and the surface. To develop an efficient gripper, three materials—silicone, nylon, and rubber—were tested using both fake and real kiwifruits. The static coefficient of friction between fake kiwifruit and these materials was measured through lab testing. The process used to identify the static coefficient of friction between fake kiwifruit and the three different materials is stated in the following section.

The static coefficient of friction can be measured by placing the object on the material of interest and increasing its inclination until the object slides down the incline. Figure 3-3 shows a free-body diagram of an object on an inclined plane, where F_N is the normal force between the fruit and the platform, F_F is the frictional force resisting the object's motion, and F_W is the weight of the fruit. θ represents the angle of inclination.

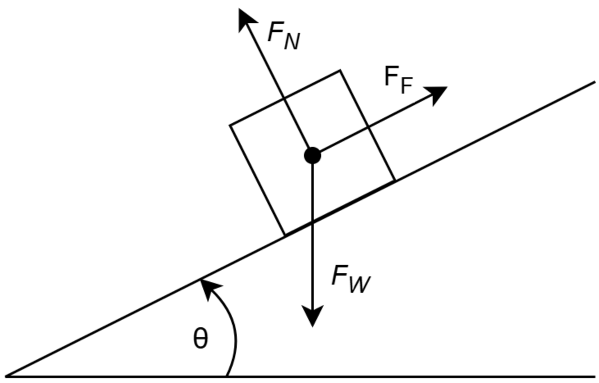


Figure 3-3: Free body diagram showing forces on the kiwifruit on an inclined plane

At the instant when the object first begins to move, the gravitational force pointing down the incline is equal to the frictional force between the object and the material, and therefore it slips, as defined in Equation 3.3. The coefficient of friction depends upon the nature of two surfaces in terms of materials and surface properties.

$$F_F = F_W \sin\theta \qquad \textit{Equation 3.3}$$

The frictional force is defined by Equation 3.4.

$$F_F = \mu F_N = \mu F_W \cos\theta \qquad \textit{Equation 3.4}$$

Combing Equation 3.3 and Equation 3.4, and eliminating F_W gives:

$$\mu = \frac{\sin\theta}{\cos\theta} = \tan\theta \qquad \textit{Equation 3.5}$$

Hence, the coefficient of friction can be calculated based on the angle of inclination of the platform when the fruit begins to slip, and knowledge of the mass or other fruit properties is not required.

3.2 Experimental Method to Determine the Coefficient of Friction

Figure 3-4 Shows the coefficient of friction on three different materials using fake kiwifruit. The experiments were conducted on 22 March 2024, during the off-season for kiwifruit harvesting. This testing involved five sets of fake kiwifruits and the three aforementioned materials to evaluate the sliding angle and tangent for each material. To conduct an experiment, a digital protractor, fake kiwifruits and a steel plate surface were used to measure the inclination angle. Firstly, the pair of kiwifruits was tightly packed with the cello tape from the sides and placed on the rubber sheet, silicon sheet and nylon sheet simultaneously. The surface of the kiwifruit was placed in contact with the horizontal rubber, silicone and nylon sheet. The angle of the surface with the kiwifruit kept increasing manually until the kiwifruit started slipping on the surface. The inclination angle θ of the three materials was recorded when the kiwifruit began to slide, and the static friction coefficient was calculated from this angle. Each of the five fruit groups was tested twice, then the data was noted.

The following equation ensures the kiwifruit is held securely by calculating the necessary force based on friction and the number of fingers used (2).

$$F_{grasp} = \frac{F_{\text{pick}}}{2\mu}$$

Equation 3.6

Where:

- F_{grasp} represents the grasping force required to securely hold a kiwifruit without causing it to slip from the gripper's grasp.
- μ represents the coefficient of friction between the gripper's material (e.g., rubber, silicone, nylon) and the kiwifruit.
- 2 reflects the distribution of force between two fingers while grasping kiwifruit.
- F_{pick} is the required picking force.

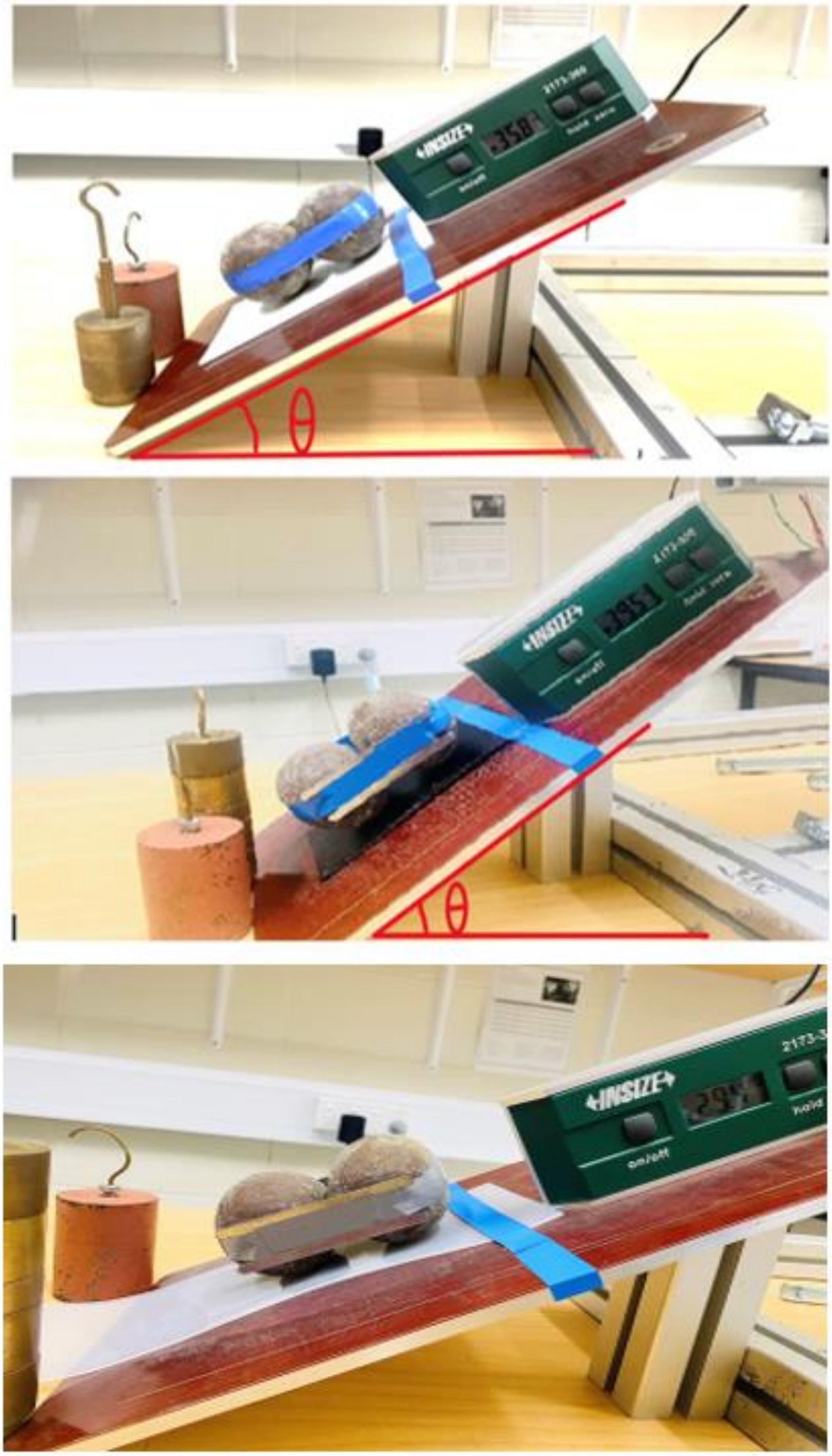


Figure 3-4 Shows the coefficient of friction on three different materials using fake kiwifruit

3.2.1. Results and Discussion

The results of the experiment are given in Table 3.3. When tested using silicone, the kiwifruit slipped at 29.7 degrees. However, nylon and rubber had high tangents of 35.9 and 39.7 degrees, respectively. Rubber exhibited the highest coefficient of friction (0.8302), which was 15% and 46% higher than nylon and silicone, respectively. The higher coefficient of friction for rubber means lower grasping forces are required, and hence, the risk of fruit damage is reduced significantly.

Table 3.3: Mean of sliding angle and coefficient of friction of three different materials.

Material	**Mean of sliding angle (°)**	**Coefficient of friction (μ)**
Rubber	39.7	0.8302
Silicone	29.7	0.5703
Nylon	35.8	0.7212

3.3 Lab Testing using Real Kiwifruit Harvested on the Same Day

The objective of this experiment was to determine the coefficient of friction for real kiwifruit against three different materials: rubber, silicone, and nylon. Conducted on 23 May 2024 during the peak kiwifruit harvesting season, the experiments took place in a laboratory setting, where the room temperature was maintained between 18°C and 23°C. For the experiments, eight pairs of real kiwifruits, including both green and gold varieties, were used. These pairs were tested on rubber, silicone, and nylon sheets to measure the sliding angles and tangents. The experimental setup, shown in Figure 3-5, was designed similarly to previous tests conducted with fake kiwifruits. Each pair of kiwifruits was tightly wrapped with cello tape to ensure uniformity and stability during testing. The fruits were labelled as A and B for the initial setup. A digital protractor and a steel plate were employed to accurately measure the inclination angle at which the kiwifruit began to slip, which is essential for calculating the static friction coefficient.

The testing procedure involved sequentially placing each fruit pair on the designated material sheets—rubber, silicone, and nylon. The angle of inclination was manually increased until the kiwifruit began to slip. This process was repeated by rotating the fruits to positions -A and -B, and then -B and -A, to comprehensively test each material under varied conditions. The sliding angle for each configuration was recorded, and each setup was tested twice to ensure the reliability of the results. The gravitational force ($W = mg$) was calculated for each fruit, where g is the gravitational acceleration (9.81 m/s^2) and m is the mass of the fruit. Based on the recorded inclination angles, the minimum and maximum grasping forces necessary to prevent slippage were computed. Four tests were conducted for each pair of fruits, with each configuration tested twice to confirm accuracy. The mean results from the four tests for each pair were calculated and meticulously recorded.

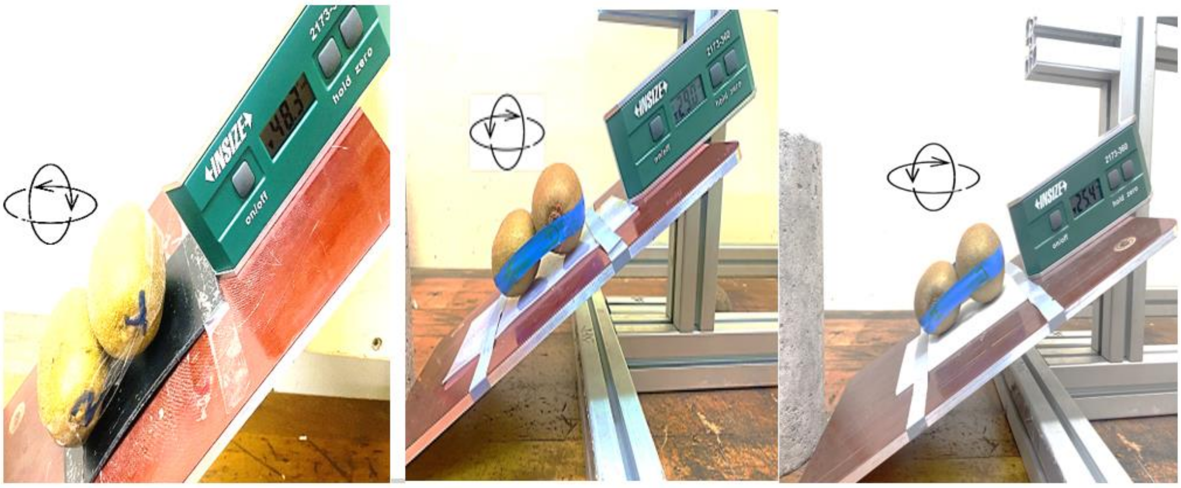


Figure 3-5 Experimental setup to determine the coefficient of friction using freshly harvested kiwifruits

The experimental data collected is designed to closely mimic the frictional conditions that kiwifruits face during commercial handling and processing. By methodically modifying the contact surfaces and testing configurations, following section provides a comprehensive dataset from which well-founded conclusions about the interactions between various materials and kiwifruit can be inferred.

3.3.1. Results and Discussion

The experiment results are given in Table 3.4, which shows that the angle of inclination of kiwifruits was much higher on rubber, 47.2°. In contrast, the tangent of real kiwifruits on nylon and silicone was 25° and 28.9°, respectively, the lowest. Rubber has a high mean sliding angle, which means a high coefficient of friction. This high friction gives rubber its strong gripping ability. In terms of rubber, the minimum force required to grab kiwifruit is 0.4932N, which is almost half that of nylon and silicone.

Table 3.4 Shows the mean tangent, min. grasping force and max. grasping force.

Material	**Mean Sliding angle (θ)**	**Coefficient of Friction**	**Minimum grasping force (N)**	**Maximum grasping force (N)**
Rubber	47.2	1.0799	0.4932	0.8420
Silicone	28.9	0.5520	0.9542	1.600
Nylon	25.0	0.4663	1.1317	1.919

Tests were conducted on all three materials using the same procedure, and then it was recorded that the coefficient of friction is higher on rubber than that of nylon and silicone, as shown in Figure 3-6. This means the rubber would have more friction. The more friction, the less grasping force is required to wrap the kiwifruit using the rubber gripper. Grasping force here is a critical factor ensuring that kiwifruit is firmly grasped without slipping and is a force just to hold kiwifruit securely. Grasping force is influenced by weight of the object, surface texture, shape, material properties and coefficient of friction between two objects.

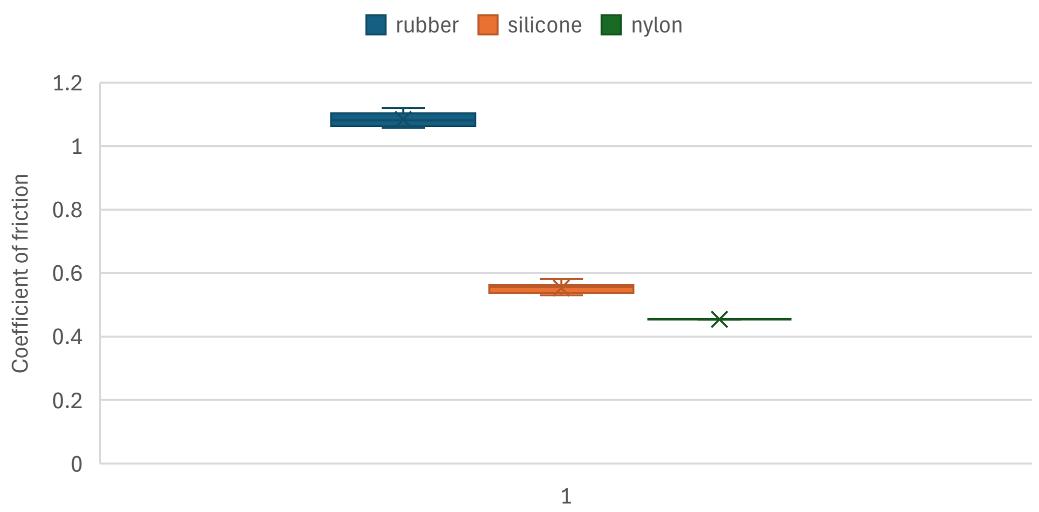


Figure 3-6: Measured the coefficient of friction of three different materials, Textures and its effects on friction

The coefficient of friction of rubber is much more than that of silicone and nylon when tested using real kiwifruit. The rubber provides a higher resistance to sliding when compared to nylon and silicone. The rubber sticks better to the surface of the kiwifruit and the fruit slippage with minimal fruit slippage.

In general, humans can accurately pick soft fruits of different sizes and shapes in an environment through the coordination of the brain, eyes and hands without causing damage to the fruit. Similarly, kiwifruit-picking grippers or fingers can improve performance through bionic design based on human hand-grasping technology, which requires a very good understanding of human picking behaviour. The texture cue of the human hand and the soft skin of the fruit is shown in Figure 3-7. Therefore, it is necessary to observe the habit of human grasping kiwifruit, study the factors that affect the grasping action, and summarise the commonly used grasping methods. The natural irregular fingerprint on the human hand increases the friction between the fruit and hand surface, which reduces the slippage of kiwifruit and prevents fruit loss. The implementation of an effective grasping strategy and the realisation of efficient, accurate and non-destructive picking.

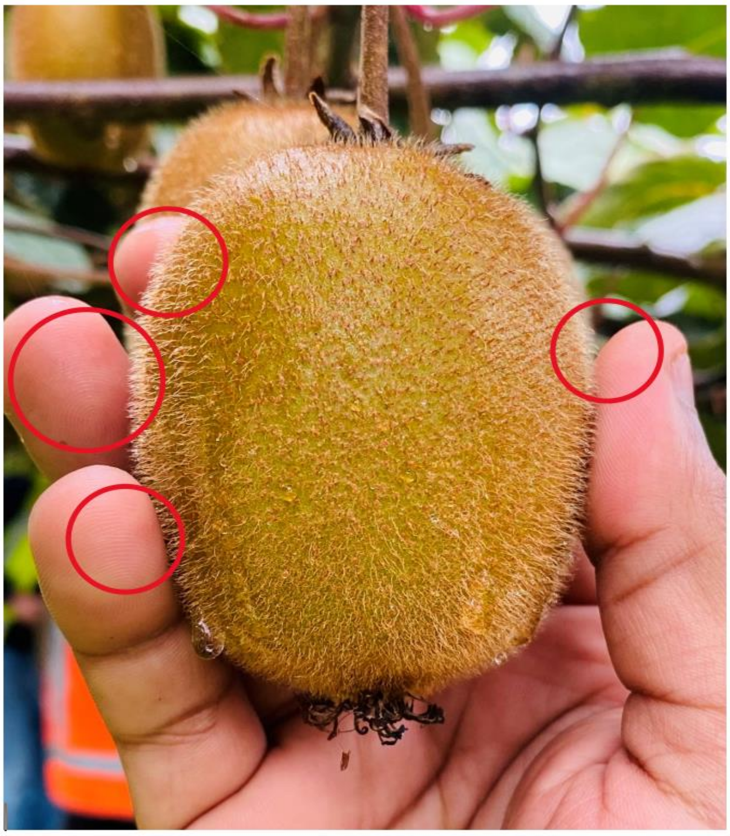


Figure 3-7 Texture on the human hand for grasping

Textures increase friction as rough surfaces have more asperities. Different materials react differently to textures. Rubbers having rough surfaces or textures on them might increase friction. The patterns of the textures also affect the friction. Sliding opposite to the textures also results in an increase in friction.

3.4 Friction Testing using Textures and Kiwifruit

This experiment aims to determine how different textures can influence friction when kiwifruit interacts with it and to understand how textures and patterns can improve performance and durability. Firstly, five different textures (knurling, extruded dots, lines, extruded cross and angular extruded lines) were printed using the F80 elastic resin and 3D printer, as shown in Figure 3-8. The dimensions of the thin rubber sheets were 80 mm in length and 50 mm in width. All these textured sheets printed in a 3D printer are about 0.3 mm extruded. All the textured sheets have irregularities, extruded lines, and grooves, which also increase the contact area, leading to high friction.

The extrude and dotted patterns are printed at a distance of 1.5 mm on both the X and Y axes, whereas all other printed textures are printed at a difference of 5 mm.

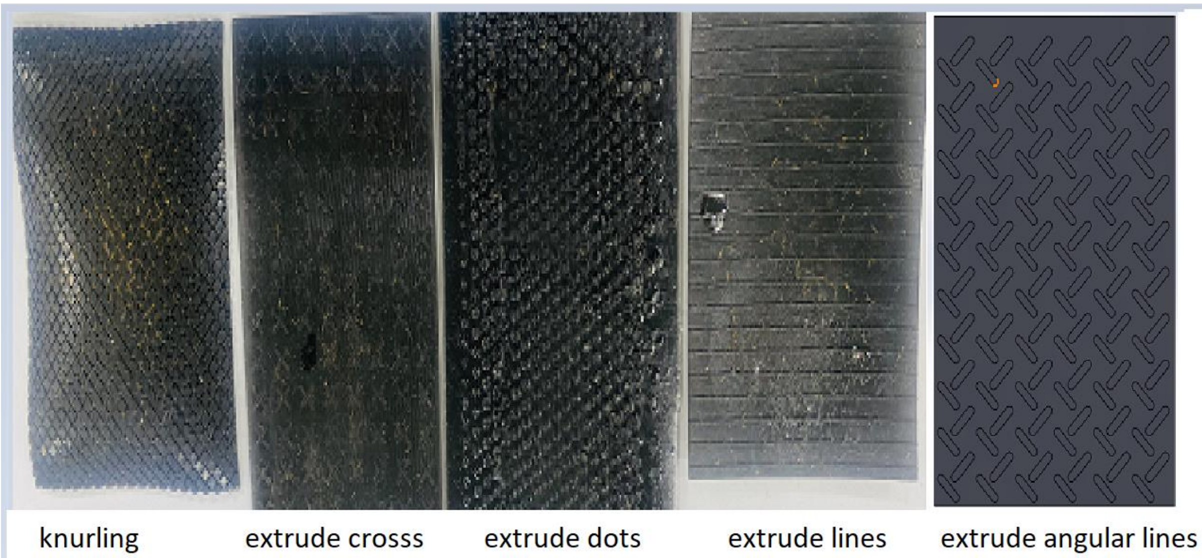


Figure 3-8: Five different textures printed by F80 resin

To conduct an experiment, a full-size digital protractor, real kiwifruits, and a steel plate surface were used to measure the angle of inclination. Five tests were conducted on one textured sheet using five different pairs of fruits. The surface of the kiwifruit was placed in contact with the horizontal textured F80 resin textures. The angle of the surface with the kiwifruit was kept increasing manually until the kiwifruit started slipping on the surface.

Figure 3-9 Shows the coefficient of friction using textured surfaces and real kiwifruits

The inclination angle θ of the five different textures was recorded at the point where the kiwifruit began to slip, as shown in Figure 3-9. Each of the five pairs of kiwifruits on one textured surface was tested twice. The tests were conducted on plane rubber surfaces, and the readings were compared with rough patterned surfaces.

3.4.1. Results and Discussion

Based on the experiments, the results presented in Table 3.5 compare the average tangent, coefficient of friction, and the minimum and maximum grasping forces required to pick kiwifruit.

The smooth or plane rubber sheet has a low coefficient of friction, whereas all the textured sheets have a more frictional value of 8% to 10%. From the experiment, it is noticed that the texture, like knurling, has a high coefficient of friction. The textured surface also contributes to distributing the forces more uniformly across the surface. The grippers with textures also require less gripping force than the plane and smooth surface grippers

Table 3.5 Shows mean of tangent, coefficient of friction, minimum and maximum grasping force on textures

No.	Textures	Mean tangent	Coefficient of friction (μ)	Min grasping force (N)	Max grasping force (N)
1	Extruded lines	50.8	1.226	0.444	0.696
2	Extruded dots	50.1	1.195	0.443	0.689
3	Extruded cross	51.2	1.243	0.434	0.686
4	Knurling	51.4	1.252	0.415	0.666
5	Angular lines	51.0	1.234	0.445	0.723
6	Plane surface	47.2	1.0838	0.493	0.842

The analysis reveals no measurable impact on frictional property, or the force required for grasping across all the tested textured surfaces. Therefore, while a textured surface increases the coefficient of friction, details on textural patterns appear to be non-critical. The raised portions of all the textures tested can also absorb and distribute wear and tear more evenly, increasing the gripper's life.

Chapter 4: Compression and Contact Surface Area Testing

This chapter outlines the development of a soft finger for grasping kiwifruit using different infill patterns. It provides a comprehensive review of the mechanical properties and performance of 3D-printed lattice structures, focusing on compressive behaviour. The investigation evaluates a selection of lattice structures is investigated to determine the most appropriate for grasping tasks.

To make the robotic finger softer using lattice structures to harvest kiwifruit, the focus was placed on designing the lattice in a way that optimises compliance, flexibility and stiffness while maintaining structural integrity. Customisation of the lattice structure allows for controlling the stiffness and flexibility of the material. A lattice with high porosity and lower stiffness can be used to make a soft robotic finger. By increasing the porosity of the lattice structure, the overall stiffness is reduced, making the robotic finger more compliant. High porosity means more empty spaces in the material, allowing it to deform easily under force.

Section 4.1 covers the production of lattice structures, including the selection and geometry of these structures. The compression testing of lattice structures, along with its detailed procedures, is addressed in Section 4.2, with the results of these tests discussed in Section 4.2.2. The examination of contact surface area and further experimentation are detailed in Section 4.3, with the corresponding results reviewed in Section 4.3.2. Drawing on the findings from Sections 4.2 and 4.3, Section 4.4 proposes a design for soft fingers suitable for harvesting grippers, accompanied by a preliminary evaluation.

4.1 The Production of the Lattice Structures

The production of lattice structures encompasses multiple steps and varies based on the chosen material, which can significantly influence the softness of the final product. To achieve softer fingers, various infill patterns were designed using SOLIDWORKS 2022 CAD software. These designs involved combining small unit cells to form a complete lattice structure. The resulting structures were then 3D printed using a Phrozen Sonic Mighty 8K Resin 3D printer with F80 resin. The slicing of the models for printing was carried out using CHITUBOX V1.9.0, which allowed for an XY resolution of 0.022 mm and layer thicknesses between 0.01 mm and 0.30 mm.

Figure 4-1: Phrozen Sonic Mini 3D Resin printer

The operations and the default settings on which the printer works are given below in Table 4.1.

Table 4.1: Shows the operations and specifications of a mini 4K 3D printer

System	Phrozen OS
Slicer software	CHITUBOX V1.9.0
XY resolution	0.022 mm
Layer thickness	0.1 mm
Maximum speed	80 mm/hr

4.1.1. The Production of Unit Cells using Resin

3D-printed unit cells are small structural elements engineered as fundamental building blocks, designed in various shapes and sizes to fulfil specific functional requirements. They can be designed to optimise material usage, maximise performance, and minimise weight. Unit cells can be tuned for properties like stiffness and strength, balancing compliance and robustness. These unit cells represent an intersection of material science and manufacturing technology, which enables high-performance structures across many fields.

Additionally, these unit cells provide force distribution, flexibility, and a high strength-to-weight ratio as shown in Figure 4-2 illustrates five distinct types of unit cells utilised in this study to assess their suitability for crafting a soft gripper for fruit harvesting:

a) *Cubic lattice structure:* This structure features two diamond-shaped frames interlocked with each other and oriented horizontally. It is simple yet robust, likely providing good load distribution while maintaining minimal material usage.

b) *Schwarz primitive:* This unit cell is based on a complex surface that repeats periodically in three dimensions and is used for applications requiring a high strength-to-weight ratio.

c) *Honeycomb:* This unit cell consists of hexagonal cells, which gives it strength. It is light weight, has less material, and has strong properties.

d) *FCC diagonal strut:* FCC unit cells are face-centred cubic cells positioned at the corners of each cube face, offering ductility and strength.

e) *The gyroid:* This is a three-dimensional, highly complex unit cell with an interconnected structure. It has unique properties, is lightweight, offers good stiffness, and is highly functional.

All the printed unit cells have the same dimensional values of 10 mm in length, 10 mm in width and 10 mm in height. The angular designs like honeycomb and simple diagonal cubic structures are printed at a 45-degree angle to enhance their structural integrity. All these unit cells have a base of 1mm on them.

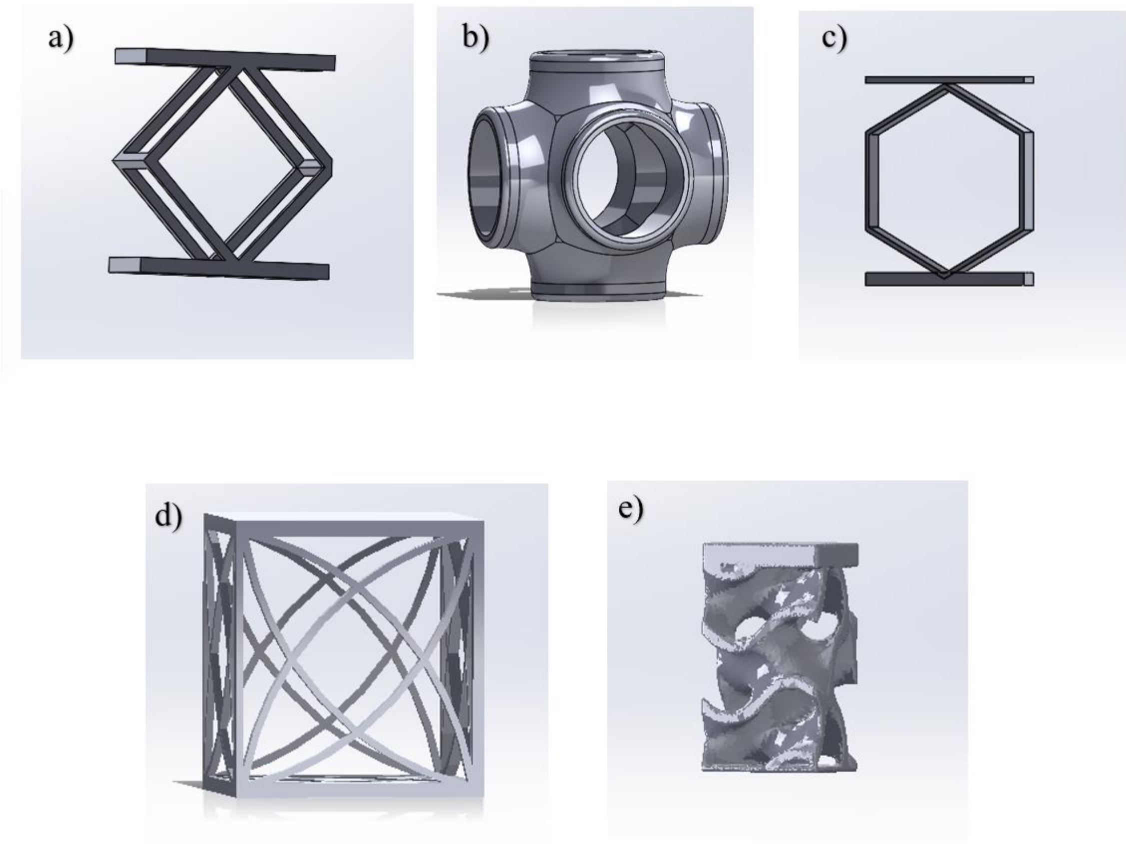


Figure 4-2: Five different 3D-printed unit cells used in this study. a) Cubic lattice structure, (b) Schwarz primitive, (c) honeycomb, (d) FCC diagonal strut, and (e) gyroid

4.1.2. Details the Selection and Geometry of the Lattice Structure

The selection and geometry of the lattice structure are critical factors that directly influence the mechanical performance and functionality of a device. Lattice structures are repeating patterns that provide structural support and adaptability and enable them to conform to varying object shapes while maintaining strength and adaptability. The geometry of these structures also influences the properties of the gripper, such as stiffness and the ability to adapt to differently shaped objects. The stiffness of the lattice is influenced by both the geometry of the cells and the thickness of the struts. Five different lattice structures have been printed using 3D printer: Simple Cubic Angled, Gyroid, FCC Diagonal Strut, Honeycomb and primitive Schwarz are given below in Figure 4-3.

Following the design phase, the unit cells were systematically expanded along the X-axis and Y-axis to achieve the desired dimensions. Each unit cell measures 10 mm in length, width and height. All the lattice structures are of the exact dimensions with 65 mm length, 55 mm width and 10 mm height.

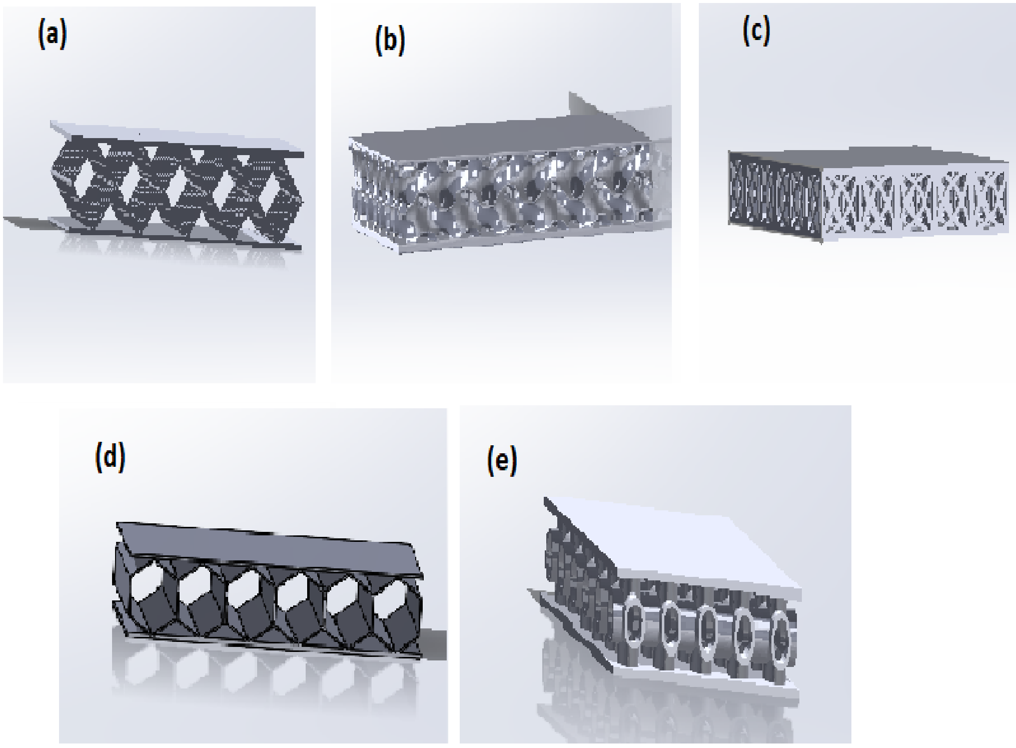


Figure 4-3: Five different lattice structures used in this study: a) Cubic lattice structure, (b) gyroid, (c) FCC diagonal strut, (d) honeycomb, and (e) Schwarz primitive

4.2 The Compression Testing of Lattice Structures

Understanding the impact of lattice geometric structures on their failure modes is crucial. This section builds on previous discussions by primarily examining how the geometric configuration of lattices influences their mechanical properties. Compression testing is a standard method used to determine the mechanical properties of materials under load conditions.

Many structures carry compression loads, and therefore, the mechanical behaviour of their materials must be determined by compression testing. It is often assumed that the tension and compression properties of materials are the same; this may not always be the case.

The compression testing of 3D-printed lattice structures involves evaluating their mechanical responses under compressive loads. This test is crucial for assessing how different lattice structures behave when subjected to forces that tend to compress them, an important factor in fruit handling applications. The goal of the compression test is to identify which lattice structure offers the optimal stiffness and uniformity for kiwifruit harvesting. Additionally, the testing ensures uniformity in dimensions and consistency in the material's properties. The Instron machine was employed for these compression tests.

4.2.1. Compression Testing Procedure

To conduct an experiment, the Instron 5982 machine was used for compression testing, with its minimum running speed set at 0.5 mm/sec. Five different lattice structures (FCC diagonal strut, simple Cubic angled, Gyroid, Honeycomb, and Schwarz primitive) samples were printed using a 3D printer using F80 resin. Each lattice structure sample was printed four times with different wall thicknesses of 0.3 mm, 0.5 mm, 0.7 mm, and 1 mm after ensuring uniformity in size and geometry.

Once the printing was completed, all these samples were cleaned using Isopropanol. Subsequently, they were placed in a UV chamber for 15 minutes to ensure the specimens were dry and would not stick to the plates of the Instron machine during compression tests. After this, the dimensional measurements (height, width, and thickness) were recorded using a digital vernier calliper.

The load cell used in conducting the compression test had a capacity of 500 N. The lattice structures were positioned at the centre of the compression plates to avoid any off-axis loading and errors. To avoid uneven loading, the plates were carefully aligned to be parallel. According to the manufacturer's specifications, the load cell was correctly connected to the data acquisition system. The testing machine was configured at the desired test speed, which was 0.8 mm/sec. This speed was used to get at least 10 data points. Then, the data acquisition system was set up to record force vs. displacement. The specimen was monitored carefully to ensure its stability during loading. The specimens were squished up to 8 mm for the detailed analysis of their behaviour under compression

Stiffness: It is the material's ability to resist deformation under load. it is measured in terms of the modulus of elasticity.

Thickness: this is the dimension of the infill lattice structures.

$$K = \frac{F}{\delta} \qquad \textit{Equation 4.1}$$

Where K is the stiffness (N/m), F is the applied force, and δ is the compressive displacement.

Figure 4-4: Instron 5982 compression testing machine

Figure 4-5: Shows the compression testing of lattice structures in an Instron machine

The dimensions of each specimen were recorded before and after the test. Each specimen was tested three times to get the appropriate data. After the experiments, the data was collected continuously as the load was applied, the force and displacement until failure occurred, and the signs of deformation were noted.

4.2.2. Results and Discussion

The relationship between thickness and stiffness in 3D-printed structures is complex. Stiffness properties obtained from compression tests of various specimens are presented in Figure 4-6:. Stiffness is plotted on the *y-axis in kPa, and thickness is plotted on the x-axis* in millimetres to illustrate the relation. As thickness varies, stiffness changes correspondingly; the maximum and minimum stiffness values across all specimens are found at 1 mm and 0.3 mm, respectively. Of all five materials, the maximum recorded stiffness was observed at 1 mm for the gyroid, reaching just over 350 kPa.

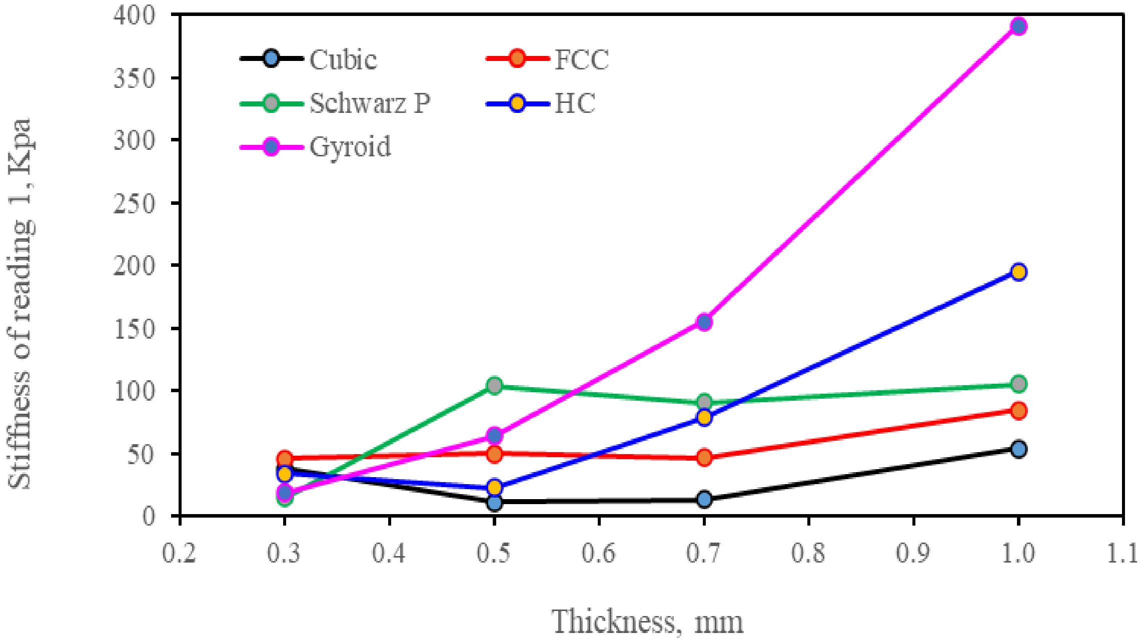


Figure 4-6: Showing stiffness of different lattice structures of different infill thickness

As the thickness of the infill pattern increases in the gyroid, the structure becomes stiffer. The gyroid demonstrates a linear increase in stiffness with thickness, showcasing a material where increased thickness significantly enhances resistance to deformation. The stiffness consistently increases linearly with the thickness of infill patterns. Among all the lattice structures, the cubic lattice structure was found to be less stiff at all tested geometrical thicknesses due to its higher porosity. The structure with the cubic infill patterns is less stiff because there is more empty space in it, or it is more porous. It was also observed that all the lattice structures having infill unit cells with 0.3 mm wall thickness are the least stiff lattice structures.

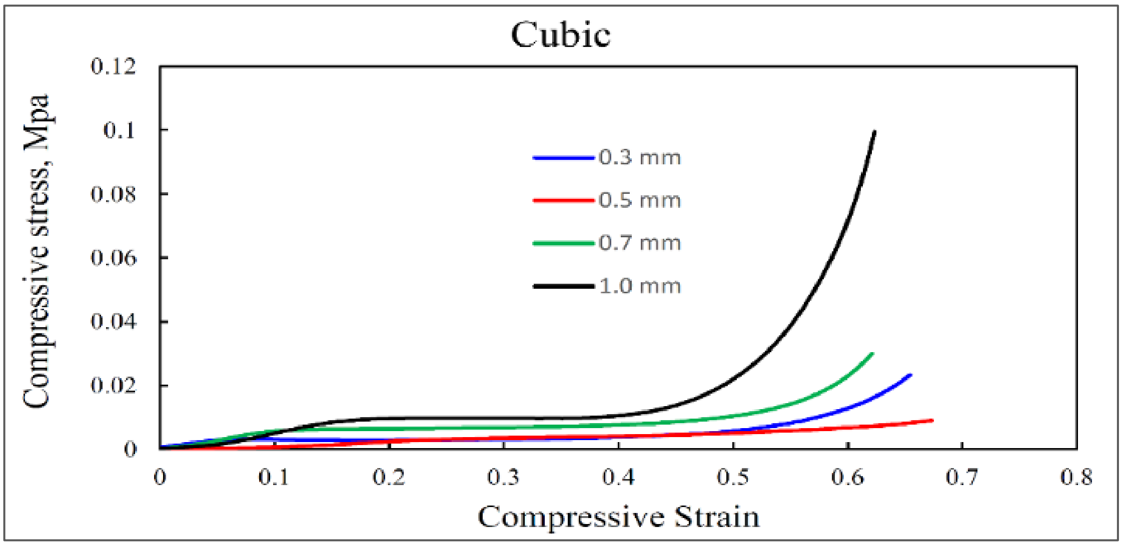
Cubic, Schwarz primitive, and FCC infill patterns exhibit only slight sensitivity to variation in thickness when subjected to compression thickness, suggesting that changes in thickness do not significantly alter the structural behaviour or mechanical performance of these infill configurations under compressive stress.

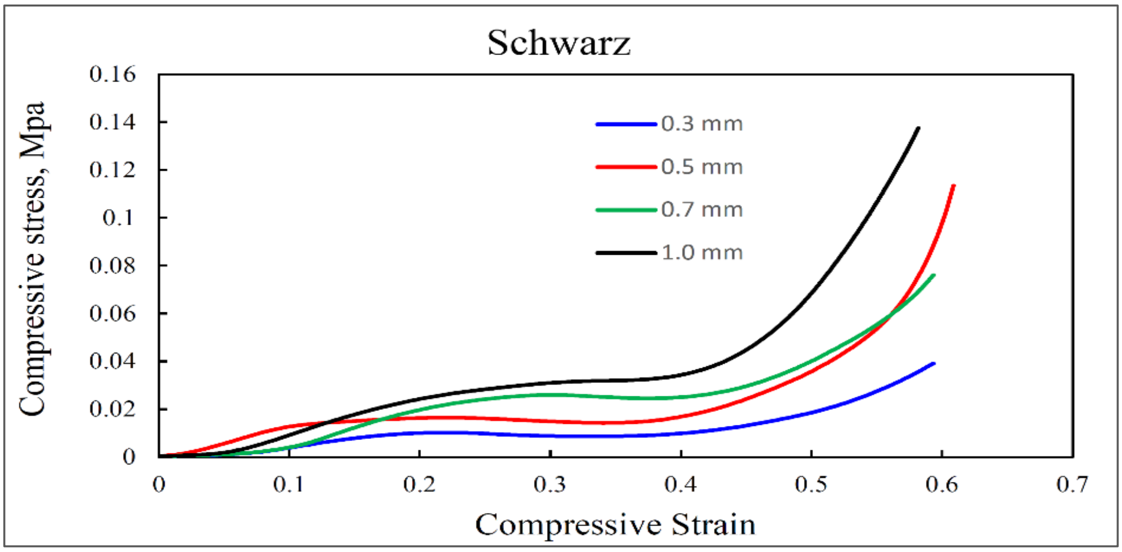
The honeycomb structure also displays good stiffness when printed with a 1 mm wall thickness of infills but tends to buckle and deform easily when the load is applied to it, as shown in Figure 4-7: . This buckling can lead to failure or reduction in load-bearing capacity.

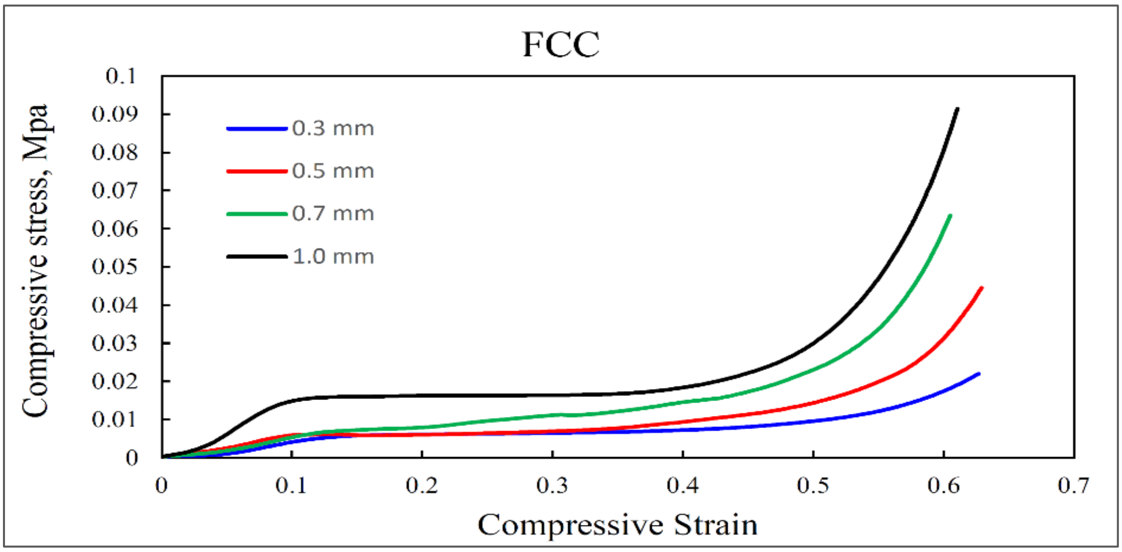
Figure 4-7: Shows buckling of honeycomb under load

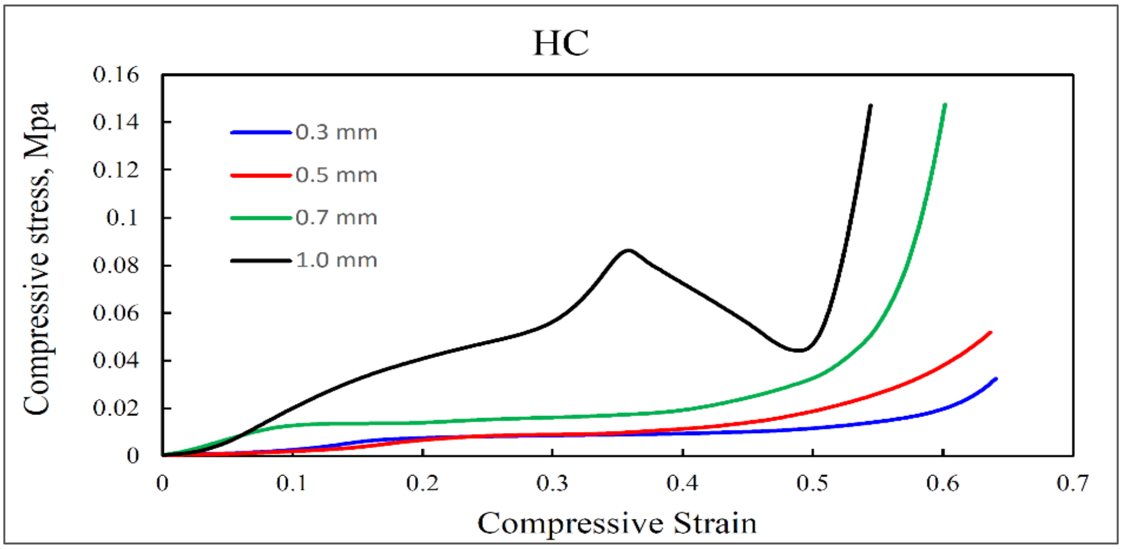
The Graphical Representation of Structures under Compression:

The graphical representation, shown in Figure 4-8 presents the stress-strain curves that reveal the deformation of the lattices under compressive loads. This is important when designing a soft gripper. By studying the stress-strain curve, the gripper's stiffness and strength can be effectively assessed. Table 4.2 shows the stiffness of all the lattices with different infill thicknesses.




Schwarz
Compressive stress, Mpa
Compressive Strain
0.3 mm
0.5 mm
0.7 mm
1.0 mm
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.1
0.2
0.3
0.4
0.5
0.6
0.7


FCC
Compressive stress, Mpa
Compressive Strain
0.3 mm
0.5 mm
0.7 mm
1.0 mm
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.2
0.3
0.4
0.5
0.6
0.7


HC
Compressive stress, Mpa
Compressive Strain
0.3 mm
0.5 mm
0.7 mm
1.0 mm
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.1
0.2
0.3
0.4
0.5
0.6
0.7

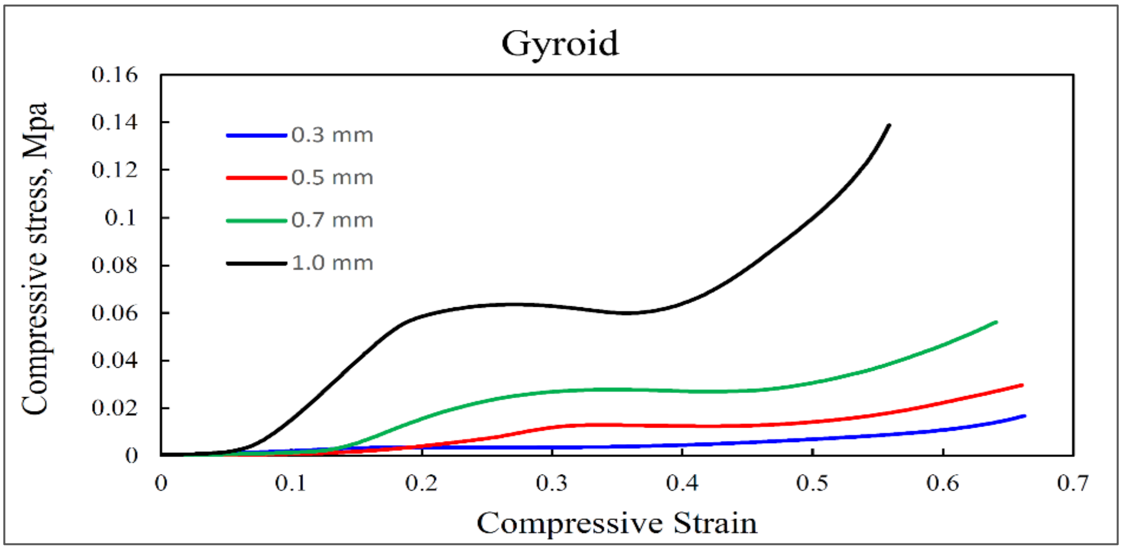


Figure 4-8: Stress/strain of different lattice structures with different thicknesses

Table 4.2: The stiffness and compressive stress/strain of all specimens.

Type of structure	Constant Comp. Stress, MPa	Range of strain provide constant comp. stress	Structure height, mm	Corresponding range of displacement, mm	Stiffness of structure, MPa
Cubic 0.3 mm	0.0032	0.07 – 0.32	10.70	0.75 – 3.42	0.0468
Cubic 0.5 mm		Note 1	10.40	Note 1	0.0196
Cubic 0.7 mm	0.0062	0.15 – 0.35	11.27	1.69 – 3.94	0.0689
Cubic 1.0 mm	0.01	0.15 – 0.40	11.23	1.69 – 4.49	0.0801
FCC 0.3 mm	0.006	0.15 – 0.38	11.17	1.68 – 4.24	0.069
FCC 0.5 mm	0.007	0.10 – 0.33	11.13	1.11 – 3.67	0.0798
FCC 0.7 mm		Note 1	11.57	Note 1	0.0755
FCC 1.0 mm	0.017	0.10 – 0.38	11.47	1.15 – 4.36	0.2155
Schwarz P 0.3 mm	0.01	0.18 – 0.42	11.80	2.12 – 4.96	0.0843
Schwarz P 0.5 mm	0.015	0.10 – 0.39	11.50	1.15 – 4.49	0.159
Schwarz P 0.7 mm	0.025	0.25 – 0.42	11.80	2.95 – 4.96	0.1821
Schwarz P 1.0 mm	0.03	0.28 – 0.40	11.10	3.11 – 4.44	0.1788
HC 0.3 mm	0.008	0.20 – 0.40	10.93	2.19 – 4.37	0.0751
HC 0.5 mm	0.009	0.24 – 0.36	11.00	2.64 – 3.96	0.064
HC 0.7 mm	0.017	0.10 – 0.38	11.33	1.13 – 4.31	0.156
HC 1.0 mm		Note 1	10.87	Note 1	0.2861
Gyroid 0.3 mm	0.00342	0.15 – 0.33	10.57	1.59 – 3.49	0.0284
Gyroid 0.5 mm	0.0125	0.30 – 0.45	10.60	3.18 – 4.77	0.0596
Gyroid 0.7 mm	0.027	0.30 – 0.45	10.93	3.28 – 4.92	0.2097
Gyroid 1.0 mm	0.06	0.20 – 0.38	10.87	2.17 – 4.13	0.4951

Note:

- (red) Structure does not show constant compressive stress for a range of displacement / strain.
- (yellow) Structure shows constant compressive stress for a range of displacement / strain. But the required surface area to maintain constant stress is much higher than the actual fruit contact area when applied load is 60 N. Hence this is not considered.
- (blue) Structure shows constant compressive stress for a range of displacement / strain. But the required surface area to maintain constant stress is slightly higher than the actual fruit contact area when the applied load is 60 N. Hence this is not considered.
- (green) Structure shows constant compressive stress for a range of displacement / strain. Required surface area to maintain constant stress is less than the actual fruit contact area when applied load is 60 N. Hence this is considered.

Maintaining constant compressive stress is crucial for optimising the gripper's durability, functionality, and efficiency. It ensures that the grip provides constant force distribution, which leads to long-lasting performance.

Some lattice structures do not show constant compressive stress for a range of displacement vs strain. However, some structures require surface area to maintain constant higher stress than the actual contact area of the fruit when a 60 N load is applied to it. Some structures show constant compressive stress, but the required area to maintain the constant stress is slightly higher than the actual fruit contact area. However, in gyroid 1 mm, it is noted that there is constant compressive stress for a range of displacement overstrain, and the required area to maintain constant stress is less than the actual fruit contact area when a 60 N load is applied to it, which makes it more effective and durable. A honeycomb with a 1 mm wall thickness is the second stiffer structure, but it is not considered because the structure does not show constant compressive stress for a range of displacement/strain.

4.3 Determination of Contact Surface Area

One of the most important aspects of designing a soft gripper is the contact surface area, where its material comes into contact with the object while grasping it. To determine the contact surface area for the kiwifruit harvesting gripper, it is important to consider the interaction between the surface of the gripper and the kiwifruit, which is irregular, soft and delicate. To reduce the risk of fruit damage, it is important to maximise the contact area between the finger and the fruit, distribute the force more evenly, and reduce the overall pressure on the fruit. The contact surface area influences frictional force to prevent slippage of kiwifruit and maintains a grip. The surface area depends on the object's shape, structure, and material. Soft materials such as rubber can be moulded to fit the shape of the kiwifruit.

The samples whose surface area was tested showed constant compressive stress for the displacement range, but the required surface area to maintain constant stress is much higher than the actual fruit contact area when the applied load is 60 N.

4.3.1. Experimental Testing of Contact Surface Area

Contact surface area testing of the 3D-printed fingers was conducted to assess the gripper's performance. Materials used in the testing are soft rubber lattice structures, a digital scale, a vernier calliper, white powder, weight, and surface area calculation software. To get comparable results, all the specimens are 10 mm thick.

Figure 4-9: Applying a 60 N load to the kiwifruit to compress the 3D printed sample.

To conduct the experiment, all the specimens were cleaned thoroughly to remove contaminants and ensure uniform size and thickness. Then, the white body powder (silica silylate) was applied to the surface of the specimen, and the fake kiwifruit was covered with a soft glue. A

6.2 kg mass, which is equal to 60.8 N, was used to apply a force to the fruit, which was then compressed to the 3D printed test sample. The fake kiwifruit was placed on each powdered lattice structure rubber plate, and then the mass of 6.2 kg was placed on the kiwifruit as shown in Figure 4-9.

When the glued fake kiwifruit was forced with 60.8 N on the powdered lattice structure, the powder was removed and adhered to the kiwifruit. Upon release, contact points provide a visual representation to quantify the total contact surface area. The camera then captured pictures of the lattice structures. All images were taken from the top of the sample at a fixed distance to facilitate subsequent image processing.

To accurately determine the surface area of the specimen, a meticulous methodology was employed, integrating microscopic visualisation with advanced image analysis software. The specimen was initially positioned under a microscope to capture a high-resolution image, which was displayed on a computer interface. Using this image, a precise outline of the specimen's perimeter was manually delineated using digital drawing tools within the computer interface. Following this, the delineated area was quantified using the Essentials Olympus Stream software, specifically designed for such measurements. This software utilises a predefined scale set at 10 mm for this experiment to calibrate and ensure the accuracy of the area calculations. This scientific approach enables precise and reproducible measurements of the specimen's surface area.

Understanding the relationship between the applied load and the contact area is critical for ensuring safe handling of delicate objects like kiwifruit. This relationship can be expressed mathematically to guide the design of grippers. To determine the minimum required contact area (A_{min}), the following equation is used:

$$A_{min} = \frac{F}{\sigma}$$ *Equation 4.2*

In this equation:

- A_{min} is the minimum cross-sectional area
- F is the applied force
- σ is the constant compressive stress.

This formula ensures that the material will not fail under the given load, provided the stress applied does not exceed the material's tensile strength.

The Equation 4.2 establishes the minimum required contact area between a gripper and an object, such as a kiwifruit, to ensure safe handling. This equation highlights the balance required between applied force, contact area, and material limits, guiding the design of grippers that are both effective and gentle for fragile objects like kiwifruit.

The compressive stress (σ) can be calculated using:

$$\sigma = \frac{F}{A}$$

Equation 4.3

In this equation:

- σ is the constant compressive stress.
- F is the applied force.
- A is the actual surface area.

This relationship provides insights into the force distribution over the contact area and its implications for fruit safety and gripper efficiency.
Furthermore, understanding the strain is equally important as it quantifies the deformation experienced by both the gripper and the kiwifruit when force applied. Compressive strain is

$$\varepsilon = \frac{\Delta t}{t}$$

Equation 4.4

In this equation:

- ε is the compressive strain
- Δt is the change in thickness of the sample
- t is the original thickness of the sample.

A larger contact area results in less strain, making the gripper gentler on delicate objects like kiwifruit. Together, these equations form the foundation for optimising gripper design, ensuring a balance between structural integrity and fruit safety during harvesting operations.

4.3.2. Results and Discussion

Among all the 3D-printed lattice structures, the specimens with infill patterns of 0.7 mm and 1 mm were stiffer than lattice structures of 0.3 mm and 0.5 mm thick infill walls. So, the only specimen tested for surface area was 0.7 and 1 mm, as they have more structural integrity to undergo under 60 N of force. Figure 4-10: shows the surface area the specimen covers when 60.8 N of force is applied to the fruit placed on the specimen.

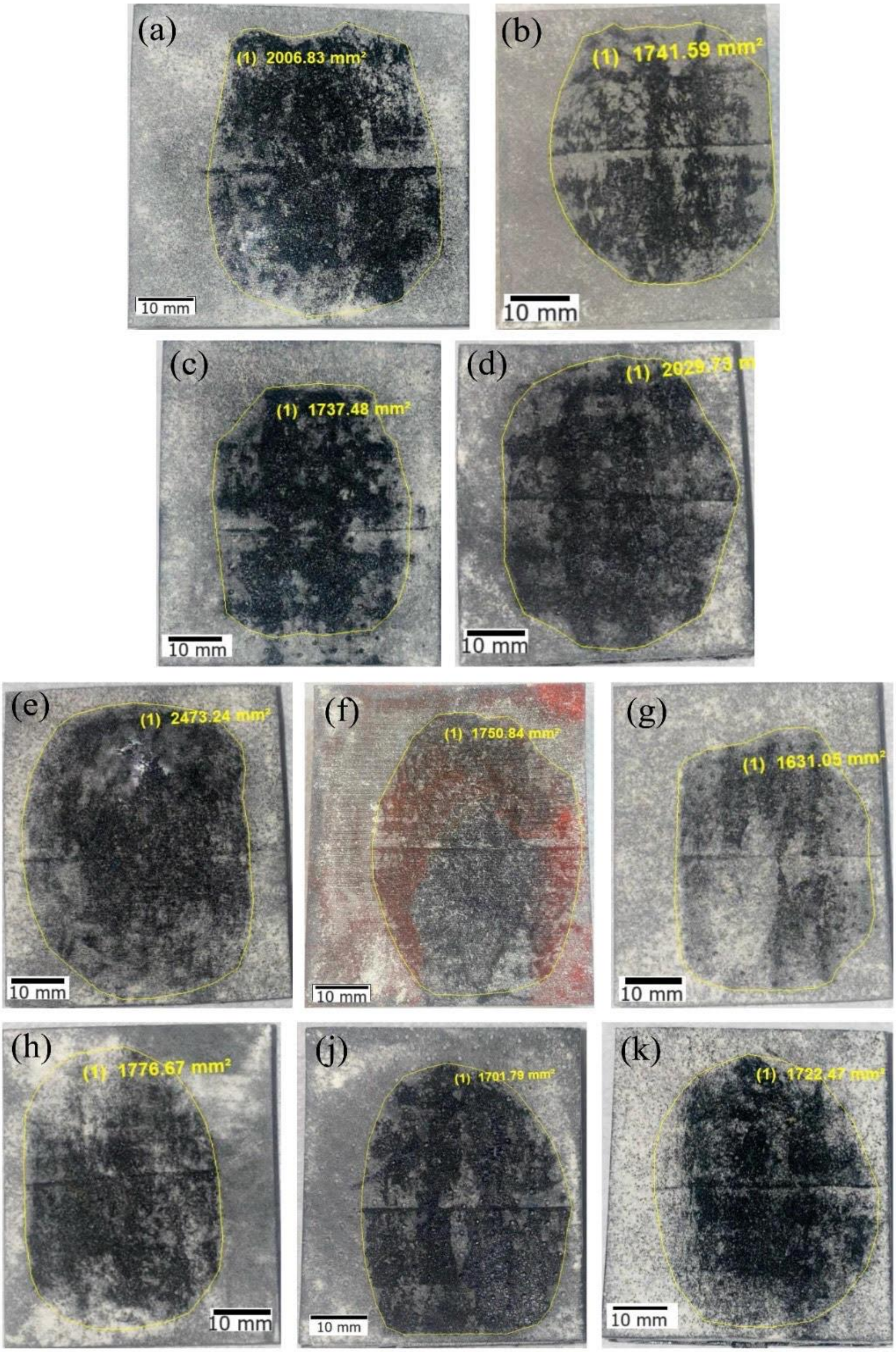


Figure 4-10: Surface area covered by fake kiwifruit when 60N force applied on specimen (a) Cubic 0.7 mm, (b) Cubic 1 mm, (c) FCC 0.7 mm, (d) FCC 1 mm, (e) Gyroid 0.7 mm, (f) Gyroid 1 mm, (g) Honeycomb 0.7 mm, (h) Honeycomb 1 mm, (j) Schwarz Primitive 0.7 mm, (k) Schwarz Primitive 1 mm

The contact surface area of five different lattice structures gyroid, face-cantered cubic (FCC), Schwarz primitive, honeycomb, and cubic lattice interacting with kiwifruit under a 60 N load vary significantly due to differences in their geometric configuration, surface topology, and mechanical properties.

In comparison, when the same test was conducted using a rigid rubber resin specimen using the same procedure and the same fake kiwifruit, it showed the contact surface area covered by the fruit and specimen was 913.09 mm^2, which is almost half of the specimen with infill patterns as demonstrated in Figure 4-11. This result highlights the impact of surface texture and material flexibility on contact dynamics. Whereas the infill-patterned specimens provide a larger contact area due to their deformability, the rigid rubber resin maintains a smaller contact area due to its rigidity. Infill specimens are more softer, light weighted, flexible, durable and provides large surface area which is beneficial for handling uneven fruits and objects.

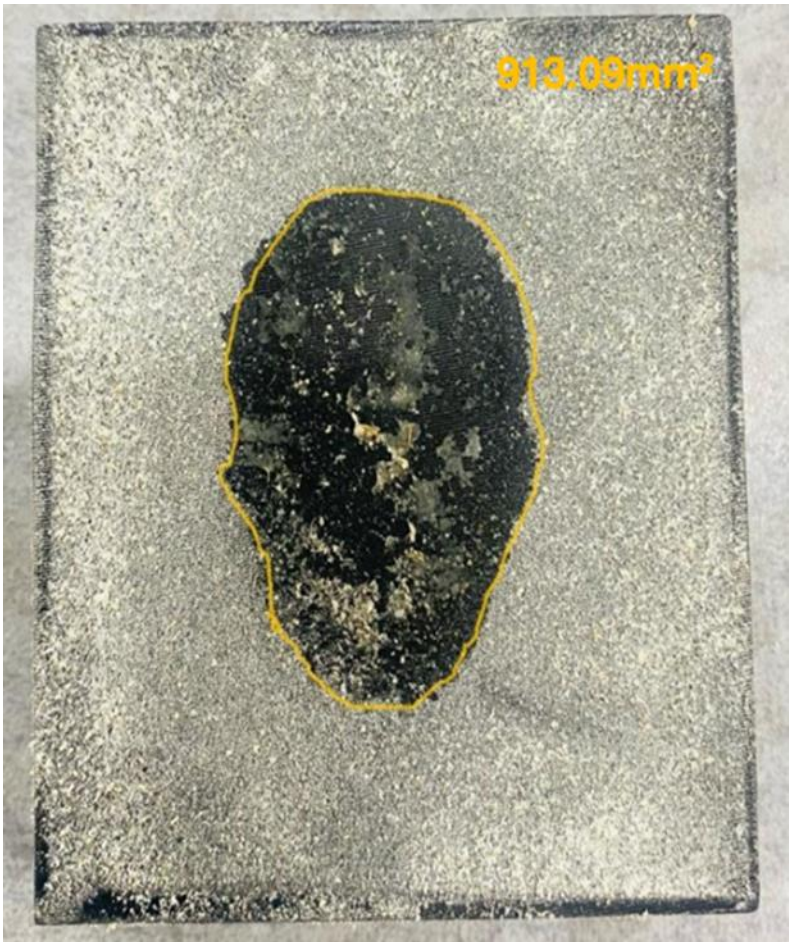


Figure 4-11: The surface area is covered by rigid specimens and fake kiwifruit

Table 4.3: The required surface area and actual surface area from the compressive test.

Type of structure	Constant Comp. Stress, MPa	Minimum required surface area, mm^2	Actual surface area obtained from test, mm^2
Cubic 0.3 mm	0.0032	18750	
Cubic 0.5 mm			
Cubic 0.7 mm	0.0062	9677	2007
Cubic 1.0 mm	0.01	6000	1742
FCC 0.3 mm	0.006	10000	
FCC 0.5 mm	0.007	8571	
FCC 0.7 mm			1738
FCC 1.0 mm	0.017	3529	2030
Schwarz P 0.3 mm	0.01	6000	
Schwarz P 0.5 mm	0.015	4000	
Schwarz P 0.7 mm	0.025	2400	1702
Schwarz P 1.0 mm	0.03	2000	1723
HC 0.3 mm	0.008		
HC 0.5 mm	0.009	6667	
HC 0.7 mm	0.017	3529	1631
HC 1.0 mm			1777
Gyroid 0.3 mm	0.00342	17544	
Gyroid 0.5 mm	0.0125	4800	
Gyroid 0.7 mm	0.027	2222	2473
Gyroid 1.0 mm	0.06	1000	1751

Note:

- Structure does not show constant compressive stress for a range of displacement / strain.
- Structure shows constant compressive stress for a range of displacement / strain. But the required surface area to maintain constant stress is much higher than the actual fruit contact area when applied load is 60 N. Hence this is not considered.
- Structure shows constant compressive stress for a range of displacement / strain. But the required surface area to maintain constant stress is slightly higher than the actual fruit contact area when the applied load is 60 N. Hence this is not considered.
- Structure shows constant compressive stress for a range of displacement / strain. Required surface area to maintain constant stress is less than the actual fruit contact area when applied load is 60 N. Hence this is considered.

Among all the specimens with different infills, it is considered that the required surface area by gyroid 0.7 is 2222 mm^2 and the actual surface area it has is 2473 $mm^{2,}$ and for gyroid with 1 mm, the required area is 1000 mm^2 and the actual surface area is 1751 mm^2 which means that these two maintain constant stress and is less than the actual fruit contact area when applied load is 60 N. If the actual surface area measured in the surface area test using a kiwifruit exceeds the minimum required surface area, the resulting compressive stress, calculated using Equation 4.2 remains within the constant compressive stress range. For example, the Gyroid

1.0 mm structure demonstrates a constant compressive stress of 0.06 MPa (Table 4.3) within a compressive strain range of 0.20–0.38. According to the surface area test, the actual surface area obtained for this structure is 1751 mm² and a compressive displacement of 3.0 mm under a 60 N load. Using Equation 4.3 the compressive stress corresponding to the 60 N load is calculated as 0.034 MPa (60 N/1751 mm²) and corresponding compressive strain of 0.28 (Equation 4.4). These compressive stress and strain values remain within the constant compressive stress and corresponding strain range (Figure 4-12:).

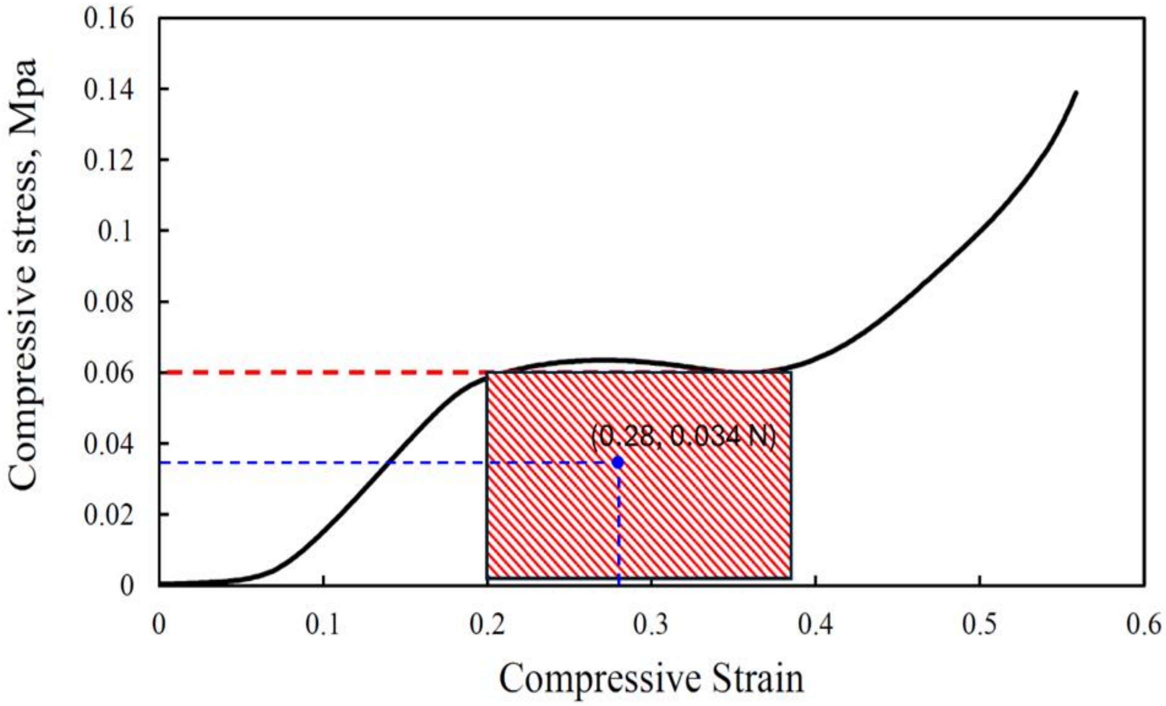


Figure 4-12: Shows constant compressive stress-strain of gyroid 1 mm

4.4 The Final Rubber Gripper Fingers

Based on the experiments and parameters explored previously, soft gripper fingers were designed and 3D printed in different shapes to match the mechanism and functionality of the existing compliant gripper structure developed at the University of Waikato. After considering the material, geometrical design and functionality, the two shaped fingers were designed and printed to compare the specifications. One of these designs featured an oval shape, which closely matches the natural shape of the kiwifruit. The finger was slightly curved to conform to the kiwifruit's shape, ensuring a better grip.

Several key parameters were considered during the design process, including strength, stiffness, surface texture, and the required surface area. The finger needed to conform to kiwifruits of varying sizes, remain flexible and adaptable, and handle the fruit under pressure without causing damage. Additionally, the design ensured precise control over the processes of picking, handling, and placing the kiwifruit.

The dimensions of the oval-shaped gripper finger were 70 mm in length and 52 mm in width. The surface area of the finger was 2907 mm², which was sufficient for securely grasping a kiwifruit. The gyroid infill pattern used in the finger had a thickness of 10 mm with 1 mm wall thickness.

After testing grippers with various infill patterns, it was observed that grippers incorporating gyroid unit cells demonstrated high durability and could be used repeatedly.

Figure 4-13: 3D-printed curved round fingers

Figure 4-13 shows the 3D-printed curved finger based on the parameters and previous experimentations. The gripper has a thickness of 10 mm, with gyroid infill unit cells that provide a combination of softness and stiffness, minimising fruit damage. However, the curved gripper lacks side walls, which increases pressure on the infill gyroid cells, damaging the unit cells near the outer edges. The surface area of the gripper is 3038 mm², significantly exceeding the required contact area for grasping a kiwifruit.

Figure 4-14: Shows the finger based on parameters

Figure 4-14: illustrates a finger designed based on the parameters, including kiwifruit dimensions, gripper geometry, required gyroid stiffness, and the surface area needed for effective and damage-free fruit gripping. This finger is tailored to the gripper's geometry. The distance between the two fingers is 60 mm, with each finger measuring 74 mm in length. The finger thickness tapers from 30 mm at the bottom to 20 mm at the top. Each finger weighs 62 grams and features a gyroid infill pattern with a 1 mm wall thickness.

The total surface area of the gripper is 3095.32 mm^2, while the kiwifruit requires a surface area of 1751 mm^2 for grasping. After testing grippers with various infill patterns, it was observed that the grippers with gyroid unit cells are durable and suitable for repeated use. A 3 mm-wide support is incorporated in the middle of the finger, extending 1 mm into the gyroid structure to enhance durability. However, this finger is thicker and heavier compared to designs based on nylon. If the gripper were made of steel or metal, thinner designs would be achievable.

In comparison, both finger designs feature gyroid infill with a 1 mm thickness. However, when the round gripper was tested, gripping the fruit exerted higher pressure on the sides due to its curved shape. The absence of outer walls in the cover resulted in the breakdown of the gyroid sidewalls under stress.

4.4.1. Experiment using Fake Kiwifruit and the Rubber Gripper

To characterise the soft finger and evaluate the viability of the proposed approach, a series of experiments were conducted using fake kiwifruits and the 3D-printed rubber gripper with a 1 mm infill gyroid. First, static experiments were performed to measure the physical properties of the fake kiwifruit, including its length, diameter, and the dimensions and weight of the soft gripper. The experimental setup in Figure 4-15, illustrates the grasping of a fake kiwifruit using two soft fingers to determine the contact surface area of the grippers.

The grasping tests were conducted using two artificial kiwifruits made of rubber, each measuring 68.60 mm in length and 56.50 mm in diameter. The experiment involved the use of white powder (silica silylate), adhesive (Fevistick), and a scale. The process began by applying powder to the rubber covers of the gripper, followed by adhesive application to the fake kiwifruit. Using a compressor and air hose, the gripper grasped the kiwifruit, transferring powder from the 3D-printed cover onto the fruit. Images of the contact surface area were then captured from above. To ensure precise surface area calculations, the gripper was placed under microscopic observation, and measurements were marked and analysed using the Essentials

Olympus Stream software with a 10 mm scale. Each test was performed five times, and the mean value was recorded to improve accuracy.

Figure 4-15: Shows the grasping fake kiwifruit with a rubber gripper

The minimum required surface area for the 1 mm infill gyroid specimen was 1750.84 mm². The total surface area of the 3D gripper was 3095.32 mm², with the area covered by each finger during fruit grasping measured as 1984.69 mm² (left finger) and 2048.04 mm² (right finger), as shown in Figure 4-16. These measurements indicate that the gripper effectively distributes pressure, as a larger contact area reduces the pressure exerted on the fruit. n contrast, the solid finger, with a surface area of 3095.32 mm², covered only 1503.48 mm² when grasping the fake kiwifruit. This result suggests that the solid finger would require greater grasping force to pick up the kiwifruit, increasing the risk of damage.

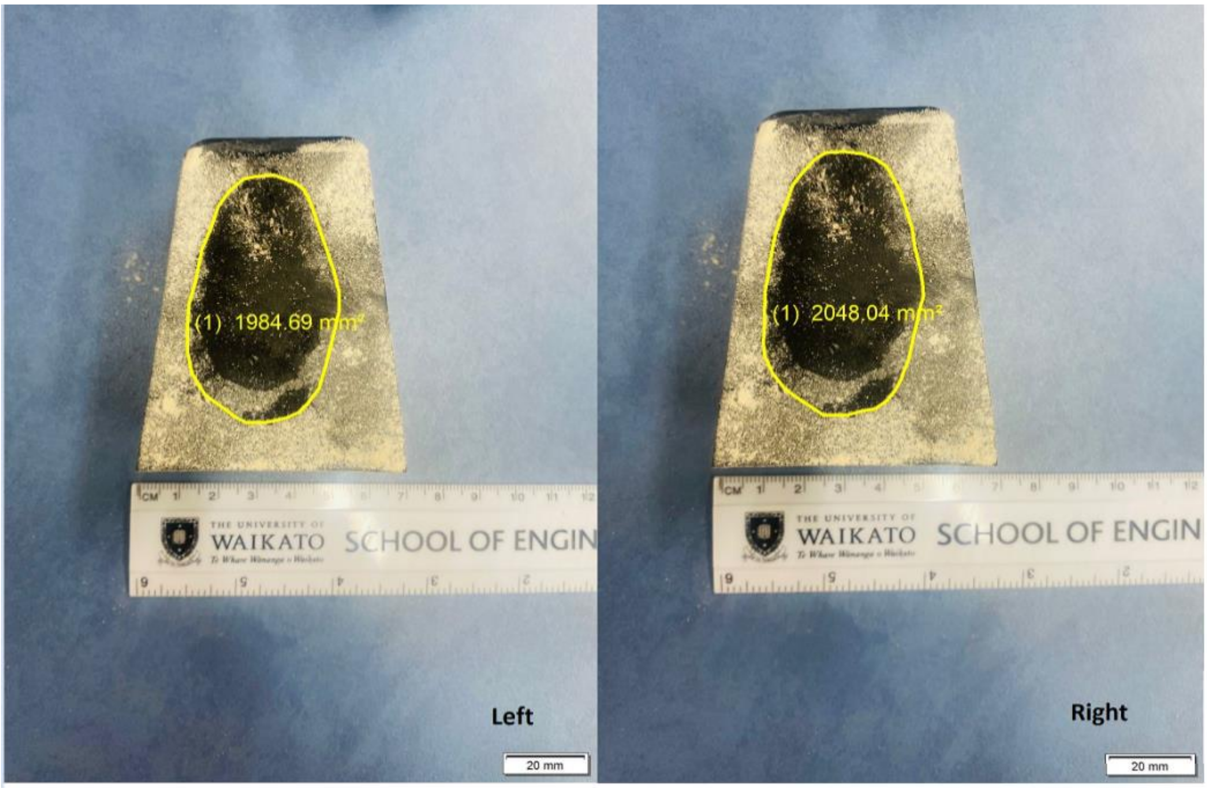


Figure 4-16: Shows the obtained surface area by the 1 mm infill gyroid infilled fingers

The solid finger, with a total surface area of 3095.32 mm², only achieved a contact area of 1503.48 mm² when grasping the fake kiwifruit. This limited contact area indicates a need for higher grasping force, which increases the likelihood of damage to the fruit. Thus, the gripper design with infill lattices offers a clear advantage in handling fragile items safely and efficiently.

Chapter 5: Conclusion

As the demand for automation in agriculture grows, the robotics industry must develop innovative problem-solving approaches to meet this need promptly. While technology is progressing towards full automation, an interim stage involving soft fruit harvesting remains essential for bridging the gap between manual and fully automated processes. The literature review highlighted significant gaps in existing products and knowledge, particularly regarding the creation of lightweight, soft end-effectors designed to harvest delicate fruits like kiwifruit.

This thesis has described the development and manufacture of a customised, 3D-printed soft robotic gripper finger designed to handle and manipulate soft produce effectively in horticultural applications. Handling delicate produce, such as kiwifruit, remains challenging due to the rigidity of conventional robotic grippers. Mimicking the most effective method of grasping—human hands—requires numerous actuation sources and sensors, even to achieve a basic grip. This study demonstrated how lattice structures and material selection could significantly enhance gripper performance while simplifying mechanical design and reducing cost.

The findings revealed that rubber is superior to other materials due to its inherently high coefficient of friction and ability to provide a gentle yet firm grip. This makes it ideal for applications where a secure hold is required without excessive pressure, such as picking kiwifruit. Rubber’s ability to conform to the shape of the object enhances the contact surface area and gripping effectiveness while minimising the risk of slippage. Additionally, rubber's versatility in being moulded into different shapes and textures further optimises its suitability for gripping the unique contours of kiwifruit.

In contrast, silicone, while flexible, has a lower coefficient of friction than rubber, making it less effective in applications requiring high frictional forces. Its softness results in less effective deformation to match the fruit's contours, compromising grip quality and durability.

Although nylon exhibits thermoplastic rigidity with excellent wear and tear resistance, its significantly lower coefficient of friction compared to rubber makes it less suitable for a soft gripper designed for kiwifruit harvesting. Nylon's rigidity may exert excessive pressure on the fruit, increasing the risk of skin damage.

Additionally, the study observed that rough or textured surfaces enhance gripper performance by increasing the contact surface area, which, in turn, raises the frictional force during grasping. Textured grippers effectively prevent slippage, contributing to better handling of kiwifruit.

Compression tests conducted using the Instron machine determined the mechanical properties of different lattice structures. The gyroid structure demonstrated superior stiffness, flexibility, and durability, making it ideal for the soft gripper. Conversely, other lattice structures, such as honeycomb, primitive Schwarz, diagonal simple cubic, and FCC, displayed failure behaviours under testing. The honeycomb structure, while the second stiffest, primarily failed due to the buckling of its unit cells under load.

The soft robotic gripper discussed in this research drew inspiration from robotics using soft materials. The gripper's finger cover features a gyroid infill pattern with a 1 mm wall thickness, providing the required surface area to grasp kiwifruit securely without causing damage. Future designs could include thinner, lightweight, flexible grippers to optimise performance further. While current experiments yielded promising results, adjustments—such as internal reinforcements within the finger design—are necessary to improve its grasping capabilities.

Through comparative testing with rigid rubber resin and infill-patterned specimens, it was evident that the latter outperformed due to their enhanced deformability, and superior adaptability to irregular surfaces. . Specifically, the contact surface area for the rigid specimen was measured at 913.09 mm^2, covering only a fraction of what the infill-patterned specimens achieved. This difference is attributed to the flexible and deformable nature of the infill designs, which allow for better conformity to kiwifruit of uneven shape, which states the grippers with infill lattice structures are very superior than rigid grippers.

Overall, it can be concluded that research has contributed to agricultural robotics by designing and testing innovative, adaptable 3D-printed gripper fingers. By introducing gyroid lattice infills and evaluating the role of material properties and textures, this thesis addresses key gaps in existing knowledge.

5.1 Future Work

This thesis primarily focused on the performance of a soft lattice-structured gripper finger to increase friction, improve grasping, and reduce fruit damage. To build on this foundation, the following areas warrant further investigation:

- Exploring thinner and more intricate infill patterns to enhance softness and flexibility.
- Reducing the size and weight of gripper fingers to improve dexterity and energy efficiency.
- Designing customised grippers for varying fruit sizes and shapes to reduce material usage and production costs.
- Conducting extensive field testing to validate laboratory findings under real-world conditions.
- Investigating alternative materials beyond F80 resin, such as biodegradable or composite materials, for enhanced performance and sustainability.

Future advancements should also focus on integrating AI-driven decision-making algorithms for adaptive control and optimising texture designs for both delicate and heavy objects. With continued research, soft grippers will play an increasingly critical role in the agricultural and automation industries, bridging the gap between manual labour and full automation.

This research lays the groundwork for creating efficient, cost-effective solutions, enabling a transformative impact on horticulture and fostering sustainable advancements in agricultural robotics.

Chapter 6: References

[1] K. Chen *et al.*, "A soft gripper design for apple harvesting with force feedback and fruit slip detection," *Agriculture,* vol. 12, no. 11, p. 1802, 2022.

[2] S. Bano and F. Scrimgeour, "New Zealand kiwifruit export performance: market analysis and revealed comparative advantage," 2011.

[3] D. Wagner, "The issue of biosecurity in New Zealand. A case study of the PSA epidemic on the kiwifruit industry," 2013.

[4] S. Bano and F. Scrimgeour, "The export growth and revealed comparative advantage of the New Zealand kiwifruit industry," *International Business Research,* vol. 5, no. 2, pp. 73-82, 2012.

[5] M. Guenther, J. T. Saunders, and T. Driver, "Emissions targets of New Zealand's agricultural export competitors–," 2022.

[6] M. Beverland, "Creating value through brands: the ZESPRITM kiwi fruit case," *British Food Journal,* vol. 103, no. 6, pp. 383-399, 2001.

[7] N. K. Meena, M. Baghel, S. Jain, and R. Asrey, "Postharvest biology and technology of kiwifruit," *Postharvest biology and technology of temperate fruits,* pp. 299-329, 2018.

[8] M. Kilgour, C. Saunders, F. Scrimgeour, and E. Zellman, "The key elements of success and failure in the NZ kiwifruit industry," 2008.

[9] F. Scrimgeour and S. Locke, "Review of Kiwifruit New Zealand," *Available at SSRN 3286701,* 2015.

[10] J. Prochazkova, "Foreign seasonal workers in New Zealand horticulture: An ethnographic account of the Nexus of labour and immigration policies and employment practices," University of Otago, 2013.

[11] J. Davidson, S. Bhusal, C. Mo, M. Karkee, and Q. Zhang, "Robotic manipulation for specialty crop harvesting: A review of manipulator and end-effector technologies," *Global Journal of Agricultural and Allied Sciences,* vol. 2, no. 1, pp. 25-41, 2020.

[12] L. Jin, Z. Wang, S. Tian, J. Feng, C. An, and H. Xu, "Grasping perception and prediction model of kiwifruit firmness based on flexible sensing claw," *Computers and Electronics in Agriculture,* vol. 215, p. 108389, 2023.

[13] Y. A. AboZaid, M. T. Aboelrayat, I. S. Fahim, and A. G. Radwan, "Soft Robotic Grippers: A Review on Technologies, Materials, and Applications," *Sensors and Actuators A: Physical,* p. 115380, 2024.

[14] K. Liu, W. Chen, W. Yang, Z. Jiao, and Y. Yu, "Review of the research progress in soft robots," *Applied Sciences,* vol. 13, no. 1, p. 120, 2022.

[15] C. Armanini *et al.*, "Soft robotics for farm to fork: applications in agriculture & farming," *Bioinspiration & Biomimetics,* vol. 19, no. 2, p. 021002, 2024.

[16] Z. Xu *et al.*, "Research Progress on Low Damage Grasping of Fruit, Vegetable and Meat Raw Materials," *Foods,* vol. 12, no. 18, p. 3451, 2023.

[17] Y. Liu, J. Hou, C. Li, and X. Wang, "Intelligent soft robotic grippers for agricultural and food product handling: A brief review with a focus on design and control," *Advanced Intelligent Systems,* vol. 5, no. 12, p. 2300233, 2023.

[18] H. Williams *et al.*, "Improvements to and large-scale evaluation of a robotic kiwifruit harvester," *Journal of Field Robotics,* vol. 37, no. 2, pp. 187-201, 2020.

[19] E. Vrochidou, V. N. Tsakalidou, I. Kalathas, T. Gkrimpizis, T. Pachidis, and V. G. Kaburlasos, "An overview of end effectors in agricultural robotic harvesting systems," *Agriculture,* vol. 12, no. 8, p. 1240, 2022.

[20] J. Hemming, B. van Tuijl, W. Gauchel, and E. Wais, "Field test of different end-effectors for robotic harvesting of sweet-pepper," in *XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014): 1130*, 2014, pp. 567-574.
[21] C. B. Campos, M. M. Arteche, C. Ortiz, and Á. V. Fernández, "Technologies for robot grippers in pick and place operations for fresh fruits and vegetables," *Spanish Journal of Agricultural Research,* vol. 9, no. 4, pp. 1130-1141, 2011.
[22] F. Longsheng, Z. Fanian, G. Yoshinori, L. Zhen, W. Bin, and C. Yongjie, "Development and experiment of end-effector for kiwifruit harvesting robot," *Nongye Jixie Xuebao/transactions of the Chinese Society of Agricultural Machinery,* vol. 46, no. 3, 2015.
[23] J. Chen, H. Wang, H. Jiang, H. Gao, W. Lei, and G. Dang, "Design of end-effector for kiwifruit harvesting robot," *Nongye Jixie Xuebao(Transactions of the Chinese Society of Agricultural Machinery),* vol. 43, no. 10, 2012.
[24] A. J. Scarfe, "Development of an autonomous kiwifruit harvester: a thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Industrial Automation at Massey University, Manawatu, New Zealand," Massey University, 2012.
[25] K. Elgeneidy, "Towards a more controllable sensorised soft gripper: a data-driven approach," Loughborough University, 2019.
[26] S. Sheikholeslami, "Soft Gripper Driven by a Solenoid Actuator," 2019.
[27] Z. Wang, S. Hirai, and S. Kawamura, "Challenges and opportunities in robotic food handling: A review," *Frontiers in Robotics and AI,* vol. 8, p. 789107, 2022.
[28] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The International Journal of Robotics Research,* vol. 35, no. 1-3, pp. 161-185, 2016.
[29] L. Birglen, T. Laliberté, and C. M. Gosselin, *Underactuated robotic hands*. Springer, 2007.
[30] S. Xiang, J. Li, Y. Zhang, Y. Yang, J. Liu, and Z. Liu, "Adaptive Wrapping with Active Elastic Band-based Gripper for Stable In-Hand Manipulation," *Sensors and Actuators A: Physical,* p. 115743, 2024.
[31] J. R. Amend, E. Brown, N. Rodenberg, H. M. Jaeger, and H. Lipson, "A positive pressure universal gripper based on the jamming of granular material," *IEEE transactions on robotics*, vol. 28, no. 2, pp. 341-350, 2012.
[32] A. M. Nasab, A. Sabzehzar, M. Tatari, C. Majidi, and W. Shan, "A soft gripper with rigidity tunable elastomer strips as ligaments," *Soft robotics,* vol. 4, no. 4, pp. 411-420, 2017.
[33] J. Pi, J. Liu, K. Zhou, and M. Qian, "An octopus-inspired bionic flexible gripper for apple grasping," *Agriculture,* vol. 11, no. 10, p. 1014, 2021.
[34] L. Zhou, L. Ren, Y. Chen, S. Niu, Z. Han, and L. Ren, "Bio-inspired soft grippers based on impactive gripping," *Advanced Science,* vol. 8, no. 9, p. 2002017, 2021.
[35] P. Polygerinos *et al.*, "Soft robotics: Review of fluid-driven intrinsically soft devices; manufacturing, sensing, control, and applications in human-robot interaction," *Advanced engineering materials,* vol. 19, no. 12, p. 1700016, 2017.
[36] B. Zhang, Y. Xie, J. Zhou, K. Wang, and Z. Zhang, "State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: A review," *Computers and Electronics in Agriculture,* vol. 177, p. 105694, 2020.
[37] A. L. Gunderman, J. A. Collins, A. L. Myers, R. T. Threlfall, and Y. Chen, "Tendon-driven soft robotic gripper for blackberry harvesting," *IEEE Robotics and Automation Letters,* vol. 7, no. 2, pp. 2652-2659, 2022.

[38] R. Mishra, T. Philips, G. W. Delaney, and D. Howard, "Vibration improves performance in granular jamming grippers," *arXiv preprint arXiv:2109.10496*, 2021.
[39] A. Jaiswal and B. Kumar, "DESIGN CONSTRAINTS OF VACUUM GRIPPER OF ROBOTS–AS A PICK AND PLACE OPERATING TOOL," *Int J Sci Technol*, vol. 6, no. 4, pp. 26-35, 2016.
[40] S. Davis, J. Gray, and D. G. Caldwell, "An end effector based on the Bernoulli principle for handling sliced fruit and vegetables," *Robotics and Computer-Integrated Manufacturing*, vol. 24, no. 2, pp. 249-257, 2008.
[41] A. Koivikko, D.-M. Drotlef, C. B. Dayan, V. Sariola, and M. Sitti, "3D-printed pneumatically controlled soft suction cups for gripping fragile, small, and rough objects," *Advanced Intelligent Systems*, vol. 3, no. 9, p. 2100034, 2021.
[42] A. Petterson, T. Ohlsson, D. G. Caldwell, S. Davis, J. O. Gray, and T. J. Dodd, "A Bernoulli principle gripper for handling of planar and 3D (food) products," *Industrial Robot: An International Journal*, vol. 37, no. 6, pp. 518-526, 2010.
[43] Y. Liu, J. Zhang, Y. Lou, B. Zhang, J. Zhou, and J. Chen, "Soft bionic gripper with tactile sensing and slip detection for damage-free grasping of fragile fruits and vegetables," *Computers and Electronics in Agriculture*, vol. 220, p. 108904, 2024.
[44] Z. J. Zhou Jun and Z. S. Zhu ShuPing, "Slippage detection in gripping fruits and vegetables for agricultural robot," 2013.
[45] J. H. Shin, J. G. Park, D. I. Kim, and H. S. Yoon, "A universal soft gripper with the optimized fin ray finger," *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 8, pp. 889-899, 2021.
[46] C.-n. Ting, "Comparison between selective and non-selective kiwifruit harvesters for economic viability," The University of Waikato, 2018.
[47] D. Yilmaz and I. Yildirim, "Effects of different storage techniques on rupture properties of kiwifruits," *Journal of Food Measurement and Characterization*, vol. 10, pp. 539-545, 2016.
[48] A. Subeesh and C. Mehta, "Automation and digitization of agriculture using artificial intelligence and internet of things," *Artificial Intelligence in Agriculture*, vol. 5, pp. 278-291, 2021.
[49] V. Paradkar, H. Raheman, and K. Rahul, "Development of a metering mechanism with serial robotic arm for handling paper pot seedlings in a vegetable transplanter," *Artificial Intelligence in Agriculture*, vol. 5, pp. 52-63, 2021.
[50] Y. Wang, X. Wu, D. Mei, L. Zhu, and J. Chen, "Flexible tactile sensor array for distributed tactile sensing and slip detection in robotic hand grasping," *Sensors and Actuators A: Physical*, vol. 297, p. 111512, 2019.
[51] M. Ryo, "Explainable artificial intelligence and interpretable machine learning for agricultural data analysis," *Artificial Intelligence in Agriculture*, vol. 6, pp. 257-265, 2022.
[52] Z. Zhang, J. Zhou, B. Yi, B. Zhang, and K. Wang, "A flexible swallowing gripper for harvesting apples and its grasping force sensing model," *Computers and Electronics in Agriculture*, vol. 204, p. 107489, 2023.
[53] H. Abdullayev and E. Huseynzade, "ROBOTIC GRIPPERS IN FOOD INDUSTRY: A SHORT REVIEW," 2025.
[54] M. Dadkhah, Z. Zhao, N. Wettels, and M. Spenko, "A self-aligning gripper using an electrostatic/gecko-like adhesive," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2016: IEEE, pp. 1006-1011.
[55] J. Zhou, S. Chen, and Z. Wang, "A soft-robotic gripper with enhanced object adaptation and grasping reliability," *IEEE Robotics and automation letters*, vol. 2, no. 4, pp. 2287-2293, 2017.

[56] J. Langowski, P. Sharma, and A. L. Shoushtari, "In the soft grip of nature," *Science Robotics*, vol. 5, no. 49, p. eabd9120, 2020.
[57] Z. Jiang, M. Shen, Y. Ma, J. Che, and H. Li, "Design and fabrication of a gecko-inspired surface for improving the grasping ability of a humanoid dexterous hand," *Science China Technological Sciences,* vol. 66, no. 3, pp. 784-792, 2023.
[58] K. Xu, P. Zi, and X. Ding, "Learning from biological attachment devices: Applications of bioinspired reversible adhesive methods in robotics," *Frontiers of Mechanical Engineering,* vol. 17, no. 3, p. 43, 2022.
[59] Y. Hao and Y. Visell, "Beyond soft hands: Efficient grasping with non-anthropomorphic soft grippers," *Frontiers in Robotics and AI*, vol. 8, p. 632006, 2021.
[60] C. Glowania, L. van Dam, E. Brenner, and M. Plaisier, "Smooth at one end and rough at the other: influence of object texture on grasping behaviour," *Experimental Brain Research,* vol. 235, pp. 2821-2827, 2017.
[61] C. Linghu *et al.*, "Universal SMP gripper with massive and selective capabilities for multiscaled, arbitrarily shaped objects," *Science Advances,* vol. 6, no. 7, p. eaay5120, 2020.
[62] T. Hao, H. Xiao, J. Wang, X. Wang, S. Liu, and Q. Liu, "Friction Enhancement Through Fingerprint-like Soft Surface Textures in Soft Robotic Grippers for Grasping Abilities," *Tribology Letters,* vol. 72, no. 2, p. 47, 2024.
[63] J. Rong *et al.*, "Development and evaluation of a watermelon-harvesting robot prototype: vision system and end-effector," *Agronomy,* vol. 12, no. 11, p. 2836, 2022.
[64] J. Gao *et al.*, "Development and evaluation of a pneumatic finger-like end-effector for cherry tomato harvesting robot in greenhouse," *Computers and Electronics in Agriculture*, vol. 197, p. 106879, 2022.
[65] C. W. Bac, J. Hemming, B. Van Tuijl, R. Barth, E. Wais, and E. J. van Henten, "Performance evaluation of a harvesting robot for sweet pepper," *Journal of Field Robotics,* vol. 34, no. 6, pp. 1123-1139, 2017.
[66] W. Xiao, C. Liu, D. Hu, G. Yang, and X. Han, "Soft robotic surface enhances the grasping adaptability and reliability of pneumatic grippers," *International Journal of Mechanical Sciences,* vol. 219, p. 107094, 2022.
[67] Z. Li, J. Liu, and P. Li, "Relationship between mechanical property and damage of tomato during robot harvesting," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 26, no. 5, pp. 112-116, 2010.
[68] F. Zhang *et al.*, "Research on flexible end-effectors with humanoid grasp function for small spherical fruit picking," *Agriculture,* vol. 13, no. 1, p. 123, 2023.
[69] H. Li, P. Zhou, S. Zhang, J. Yao, and Y. Zhao, "A high-load bioinspired soft gripper with force booster fingers," *Mechanism and Machine Theory,* vol. 177, p. 105048, 2022.
[70] B. N. Peele, "Imparting dexterity, touch, and visual expression in soft robotics," Cornell University, 2018.
[71] M. Helou and S. Kara, "Design, analysis and manufacturing of lattice structures: an overview," *International Journal of Computer Integrated Manufacturing,* vol. 31, no. 3, pp. 243-261, 2018.
[72] L. E. Murr *et al.*, "Next-generation biomedical implants using additive manufacturing of complex, cellular and functional mesh arrays," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* vol. 368, no. 1917, pp. 1999-2032, 2010.
[73] V. S. Deshpande, N. A. Fleck, and M. F. Ashby, "Effective properties of the octet-truss lattice material," *Journal of the Mechanics and Physics of Solids,* vol. 49, no. 8, pp. 1747-1769, 2001.

[74] S. Hyun, A. M. Karlsson, S. Torquato, and A. Evans, "Simulated properties of Kagomé and tetragonal truss core panels," *International Journal of Solids and Structures,* vol. 40, no. 25, pp. 6989-6998, 2003.

[75] M. G. Weir, M. R. Knecht, A. I. Frenkel, and R. M. Crooks, "Structural analysis of PdAu dendrimer-encapsulated bimetallic nanoparticles," *Langmuir,* vol. 26, no. 2, pp. 1137-1146, 2010.

[76] S. Mitra and T. M. Sinclair, "Output fluctuations in the G-7: An unobserved components approach," *Macroeconomic dynamics,* vol. 16, no. 3, pp. 396-422, 2012.

[77] J.-H. Park and K. Park, "Compressive behavior of soft lattice structures and their application to functional compliance control," *Additive Manufacturing,* vol. 33, p. 101148, 2020.

[78] D. W. Abueidda, M. Bakir, R. K. A. Al-Rub, J. S. Bergström, N. A. Sobh, and I. Jasiuk, "Mechanical properties of 3D printed polymeric cellular materials with triply periodic minimal surface architectures," *Materials & Design,* vol. 122, pp. 255-267, 2017.

[79] D. Li, W. Liao, N. Dai, and Y. M. Xie, "Comparison of mechanical properties and energy absorption of sheet-based and strut-based gyroid cellular structures with graded densities," *Materials,* vol. 12, no. 13, p. 2183, 2019.