A biologically inspired compliant gripper for kiwifruit harvesting

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Abstract

This gripper was designed taking inspiration from the technique agricultural workers use to pick kiwifruit, and designing the fingers of the gripper similar to that of a humans, with optimised dimensions through SolidWorks Simulations. Validating the gripper included testing for Fruit Detachment Force (FDF) and Fruit Contact Pressure (FCP). The FDF tests involved testing kiwifruit over a variety of input pressures (0-0.7 MPa) to see at what point slippage, i.e. failure occurred. This was conducted over a range of differently sized gold and green kiwifruit, resulting in input pressures between 0.3-0.55 MPa achieving the required FDF of 30.074 N. The FCP tests involved applying the same range of input pressures to force gauges on specialised rigs (one to represent a small kiwifruit and one for large) to find at what input pressure, the output pressure exceeded the critical pressure (0.216 MPa) at which kiwifruit would be damaged. From this we found the maximum FCP (at our operating input pressure of 0.6N – rounded up from our maximum FDF input pressure of 0.55N) to be 0.09 MPa, which is much less than the critical damaging pressure of 0.216 MPa. By then manipulating the faces to account for a variety of differently shaped kiwifruit by extending out the location of the force gauges one at a time, the results were largely affected. The majority of the results remained below the critical pressure, with a few rare situations causing failure, specifically when face 4 was protruded a further 3 mm, and face 2 by just 1 mm for the large kiwifruit situation and 3 mm for the small. To further validate this gripper, it was compared to two existing grippers, one rigid, and one compliant. FDF testing was found to be achieved for all sizes of fruit tested for this gripper and the existing compliant gripper, however the existing rigid gripper failed to pick smaller kiwifruit. In regards to FCP testing, all grippers were comfortably under the critical damaging pressure, with our gripper having a slightly higher pressure then the existing grippers.

1. Introduction

The need for automation in the kiwifruit harvesting industry is ever present with the supply of labour diminishing (University of Waikato, n.d.. Automation can be incorporated into the industry to combat this problem in a number of different ways, including developing robots that move down the rows of kiwifruit, programming image detecting cameras to recognise and locate kiwifruits location on a vine, and the end-effector (gripper) that successfully picks the fruit without damaging it, which is the aspect this article is specifically focusing on (Williams et al., 2019). This was investigated by designing and testing a biologically inspired compliant gripper and comparing it to both a rigid, and a compliant kiwifruit gripper (ScienceDirect, n.d.).

Reducing damage to the kiwifruit is a critical part of the harvesting process. Damage can occur through picking, handling, storage, and transportation of the fruit – in which this article is looking specifically at the picking aspect. It is estimated that through manual picking of kiwifruit – the damage rate is around 8% (Dbhynds, 2011). Given the 2024 export value of kiwifruit from New Zealand being $3.1 billion, it highlights the scale of the operations and the importance of minimising wastage through damaged kiwifruit (Origin Capital Partners, n.d.).

Lots of the other grippers that have aimed to address this issue have had a similar approach, by using a two-fingered gripper relying on a soft contacting surface to prevent damage to the fruit while maintaining sufficient gripping force. While these do not replicate the humans picking process, the fingers they have designed can handle fruit delicately, and approach fruit differently to how this research project does. However a key limitation is that the majority of these grippers are designed without multiple joints, making them less conforming to the fruit. We aim to see how our biologically inspired approach, with multiple joints and a high degree of conformity, compares to these existing approaches.

This paper presents the design for a biologically inspired articulated finger which successfully picks a wide variety of kiwifruit without damaging them. The gripper is evaluated and compared to two existing grippers, one rigid and one compliant. The existing compliant gripper is a two fingered SLS nylon mechanism with resin sleeve pads, that grips the fruit vertically, as shown below in figure 1. The existing rigid is also a two fingered mechanism with resin sleeve pads, but instead made out of a mixture of PLA and various fittings, as shown below in figure 2.

Figure 1 – Existing Compliant Gripper approaching fruit vertically

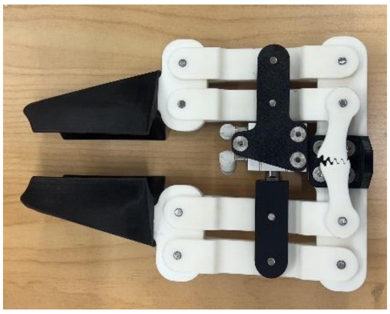

Figure 2 – Existing Rigid Gripper

Inspiration was taken for this design by how an agricultural worker typically picks a kiwifruit, as shown below in figure 3 (Tebbutt, 2024). This was simplified to a two fingered ABS mechanism with soft foam pads that grips the fruit horizontally, as shown below in figure 6. Key measurables for this project included fruit detachment force (FDF) and fruit contact pressure (FCP), the existing compliant mechanism has known data for these criteria, which this new gripper was designed to sufficiently surpass in order to be successful in practice.

Figure 3 – Traditional kiwifruit picking technique

2. Related Work

Related work used for this article primarily comes from the internal testing of the existing compliant and rigid gripper by two different colleagues, which included an in-depth analysis of the physical properties of gold and green kiwifruit, as well as the optimal fruit detachment force (FDF) and fruit detachment angle (FDA). The FDF for the existing compliant gripper was found by picking a range of fruit at different angles as summarized by table 1 below, with a FDF of 27.34 N at an angle of 60 degrees found to be the most effective picking angle in terms of minimizing FDF and fruit slippage. This study adopted the 60-degree angle for the testing process, and used a safety factor of 1.1 so that the FDF required for this study would be 30.074 N. This relatively low safety factor of 1.1 was chosen, as 27.34 N was previously found to be the maximum FDF required over 240 samples, which makes it very unlikely that it would be exceeded.

Table 1 – FDF relative to Angle

		Maximum required gripping force	
Angle (°)	Maximum FDF (N)	F_{O1} (N)	F_{O2} (N)
0	61.76	45.68	45.68
15	64.73	61.68	82.83
30	66.95	73.7	116
45	42.36	49.32	86.53
60	27.46	31.58	60.37
75	23.94	25.57	53.27
90	13.42	12.31	27.31

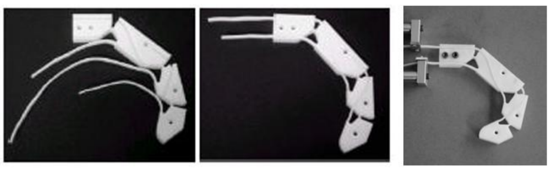

Figure 4 – Compliant Finger Inspiration

Another internally conducted study found the FCP to be 0.24 MPa as a worst-case scenario. This was found by doing a 5s flat plate compression hold on the kiwifruit with the lowest firmness from a sample of 46 fruit, at just 60.5 N. For this study, we decreased this to 0.216 MPa, using a safety factor of 1.1. This relatively low safety factor was used due to the previous study already having found a worst case scenario pressure, therefore there not being much need to make it a further worst case. It was found at the start of the kiwifruit season, fruit had firmness up to 95 N, and 60.5 N was the lowest fruit firmness found at the very end of the season, which further validates that 240 kPa is worst case scenario, and the vast majority of the season this gripper would be picking much more firm kiwifruit.

There are a variety of existing grippers, designed for different purposes, such as conforming to a range of geometries, hardness of objects, and other different requirements. The vast majority of these grippers approach the object vertically via between two to four fingered mechanisms using a pneumatic to actuate the gripper, with a mixture of either compliant or rigid mechanisms. Examples of these mechanisms include fin-ray mechanisms, mechanisms using inflation chambers to move, and slider crank mechanisms. This studies design took inspiration from an existing biologically inspired finger design (Lotti & Vassura, 2003), as shown in figure 4. This finger took strong inspiration of that of a human finger, and was made of machined PTFE, which has a yield strength of 23 MPa similar to that of ABS at 18.75 MPa, and a higher stiffness, at approximately 2800 MPa, compared to ABS at just 1307.76 MPa. This gives ABS a stiffness to yield strength ratio of 69.7, and PTFE a ratio of 121.7, these values are important in material selection, as it is very desirable with compliant mechanisms to have a low ratio. This design prioritized having a low stiffness to yield strength ratio, as well as being reliable, cheap, and easy to manufacture, which led to ABS being used, especially due to its easy accessibility and rapid prototyping by 3D printing it given the resources available for this project.

Looking specifically at soft grippers, there were a variety of different approaches used to maximize contact area and minimize contact pressure. The majority of them approached the fruit vertically with two or three fingered mechanisms. Methods of having a large and soft contact area on the fruit included having silicone pads over top of the fingers that were curved to the shape of the fruit, making use of the fin ray structure (Chen et al., 2022) which naturally conforms to the shape of the fruit, having molded silicone fingers actuated through inflation chambers (Zhang et al., 2023), and finally fingers with a solid backbone, primarily composed of silicone on the faces, actuated through string running through to a DC motor (Manti et al., 2015). Having a soft contacting area significantly increases conformity, which in turn decreases pressure. It can also be an effective way to transition between a hard gripper, like the ones using the silicone pads over top of the fingers, while still maintaining a soft interface. This gripper takes inspiration from all these techniques, by using hard ABS to create a finger that conforms well around the kiwifruit, with soft foam pads on the contacting surface to further increase surface area and decrease pressure.

3. Experimental Design and Methodology

3.1 Articulated Gripper

This gripper consists of two compliant fingers, each with four links connected by compliant joints, as shown in Figure 5. The fingers of the gripper were designed and optimized using SolidWorks to ensure what was initially a stress safety factor of 1.5 (stress within the finger) using 3D printed nylon, however due to accessibility issues in the prototyping phase, the switch was made to 3D printed ABS which had similar material properties and was very accessible. The SolidWorks Simulations still showed a safety factor above 1.5, however this was using the default material properties from SolidWorks, which later turned out to be different from the actual ABS properties of the material being used, when test results had come back on the material properties. This led to a safety factor of just 1.03, which while low, still does not theoretically cause the finger to yield. This was found after testing was completed, so as part of the future work of this project the finger would be minorly altered to increase the safety factor, and testing would be conducted again, however it is unlikely this heavily affected the results from this project. The fingers are made from 3D printed ABS with 100% infill, with a yield strength of 18.75 MPa, a stiffness of 1307.76 MPa, and a stiffness to yield strength ratio of 69.7, which is almost double that of the original Nylon material at a ratio of 33.3.

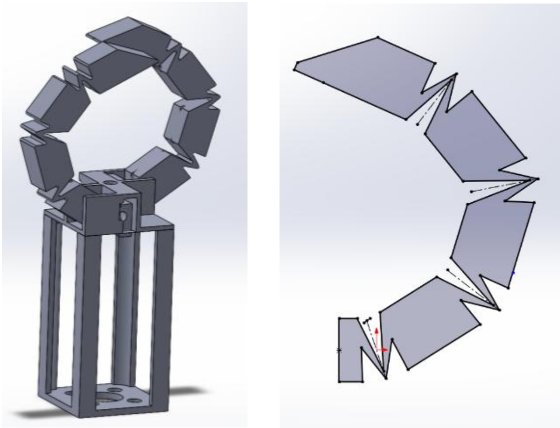

Figure 5 – 3D CAD model of gripper & 2D model of finger

A 0.65 mm nylon cord runs internally through each link to act as a tendon to close each finger. No extensor tendon is required due to the compliant nature of the joints, and the finger naturally returns to its neutral state once the tension is released from the cord. The fingers are attached to a housing, with an integrated pneumatic cylinder with a bore of 20 mm, and a stroke of 30 mm, as pictured in Figure 6.

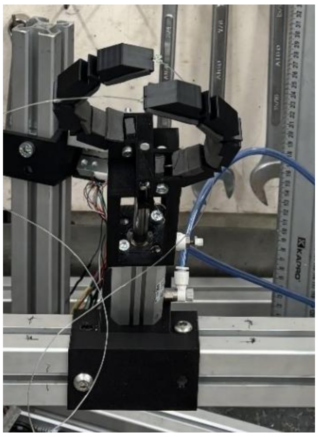

Figure 6 – Gripper designed in this study

3.2 Fruit Detachment Force Testing

FDF was tested on a variety of sized green and gold kiwifruit using the test rig shown in Figure 7. The rig consists of a force gauge mounted to a rail system, which applies a load to the kiwifruit which is held by the gripper.

The gripper was mounted to the bottom aluminium member of the rig, angled at 60 degrees to the vertical plane. The slack in the nylon cord was removed before testing. To allow a load to be applied to the kiwfruit, the fruit was punctured with an M4 x 75 mm bolt, with a washer at either end, and secured with a nut. A string was attached to the end of the bolt, and then tied to the hook attachment of the force gauge.

Tests were performed at a pressure range of 0.1 to 0.6 MPa, increments of 0.1 MPa, for a total of seven different pressures. The force gauge was moved upwards using the crank mechanism to apply an external load to the fruit, until the first sign of slippage was observed, at which point the force reading was recorded. There were seven green kiwifruit tested which ranged in size with heights between 42-49 mm, widths between 60-69 mm, and lengths between 62-69 mm. There were four gold kiwifruit tested which ranged in size with heights between 51-55 mm, widths between 51-58 mm, and lengths between 71-83 mm.

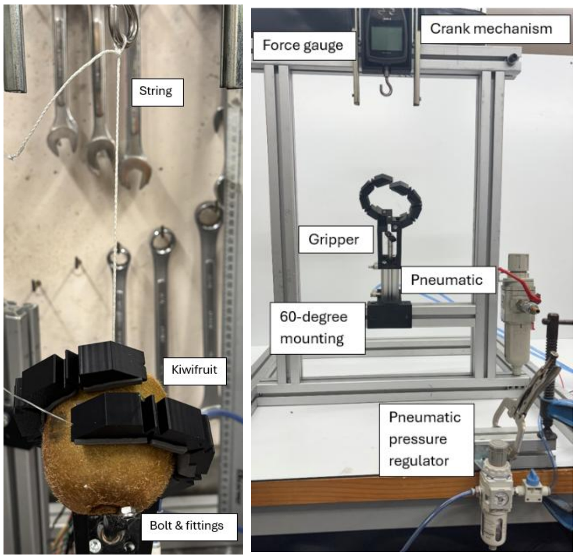

Figure 7 – FDF testing rig

3.3 Fruit Contact Pressure Testing

FCP was tested using the rig in Figure 8.

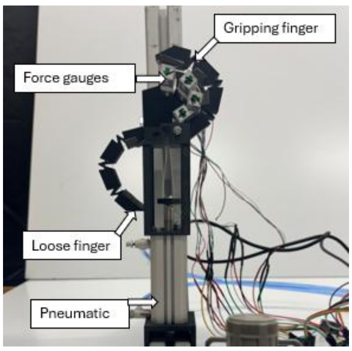

Figure 8 – Labelled test rig used for FCP testing

In the FCP testing, the force gauges read force values, which by finding the contacting area of each face, can be converted into a pressure value. To find the areas, permanent marker was used to apply to a finger, as shown below in figure 9, and manually wrapped around the fruit to leave imprints on it, which were then measured. This occurred across all the fruit tested, with the smallest areas from each face used in the pressure calculations to give the worst-case scenario.

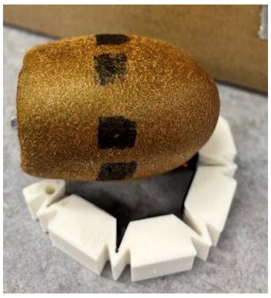

Figure 9 – Contact Area Calculation

The following method was used:

1) Before testing, remove the majority of the slack from the nylon string in the finger by tensioning it.
2) Position gripper and large force gauge rig so that the bottom force gauge is just above the palm of the gripper. Ensure only the finger that will be contacting the force gauges is in upright position so the other finger doesn't interfere.
3) Open the Arduino code on connected computer and wait for results to start showing. While pressure is not applied the results should be showing zero.
4) Increase the pressure to 0.1 MPa and record the reading when the results have adjusted and are steady.
5) Repeat step 4 for increasing pressures of 0.1 MPa increments, up to 0.6 MPa
6) Run a short bolt through the underside of the furthermost threaded hole from the rig in the top force gauge (corresponding to face 1 on the finger), continue threading the bolt until it is extending from the force gauge by 1 mm. Repeat steps 4 and 5 for this new scenario and record the results.
7) Repeat steps 4 to 6, each time increasing the distance the bolt sticks out by 1 mm between the range 1mm– 3mm.
8) Repeat steps 4-7 for each force gauge individually.
9) Repeat steps 2-8 using the small force gauge rig instead of the large. These represent the smallest case kiwifruit and the largest respectively.

The 1mm, 2mm and 3mm extension of the faces mentioned in the method above are referred to as manipulations to the face throughout the course of this report.

4. Results and Discussion

4.1 Fruit detachment force testing

A summary of the FDF results on the different tested kiwifruit is shown below in table 2 and figure 10 respectively.

The FDF test results clearly show that all the tested kiwifruit achieved FDF at an input pressure of between 0.3-0.55 MPa, with the exception of kiwifruit 8 and 9 which failed due to the bolt shearing through the kiwifruit. The gold kiwifruit achieved FDF between 0.4-0.5 MPa, while the green kiwifruit were between 0.45-0.55 MPa (with the exception of the extreme outlier of 0.3 MPa from kiwifruit 5), which shows a weak relationship between the type of kiwifruit, and the pressure required to achieve FDF, with gold typically requiring a lower input pressure. It is also important to note the gold kiwifruit were typically much larger in regards to height and length compared to green kiwifruit. This data leads into the next set of testing, where we aim to see how the input pressure affects the fruit contact pressure. The input pressures required to achieve FDF were also higher than expected, which can be explained by the internal friction of the string running through the finger.

In regards to comparing these results to the two existing grippers, the compliant gripper conducted initial experiments to find the FDF, which it achieved at 27.34 N. The rigid gripper on the other hand, was found to comfortably achieve forces above an FDF of 30.074 N (27.34 N with 1.1 safety factor applied) when operating on large kiwifruit at an input pressure of 0.4 MPa, however failed to achieve FDF at any point with smaller kiwifruit, coming as close as 20 N at 0.5 MPa. This goes to show the gripper designed in this study did well relative to other grippers regarding ability to achieve FDF, especially of smaller fruit.

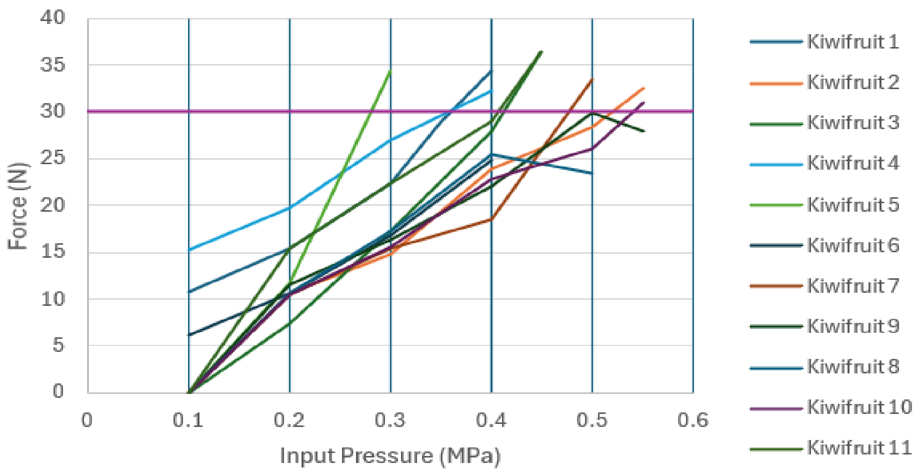

Figure 10 – FDF vs Input Pressure

Table 2 – Summary of FDF test results

Kiwifruit #	Height (mm)	Width (mm)	Length (mm)	Type	Max FDF (N)	Input Pressure to achieve FDF (MPa)
1	45	64	66	Green	34.43	0.45
2	42	60	62	Green	32.52	0.55
3	52	51	71	Gold	36.36	0.45
4	55	55	73	Gold	32.22	0.4
5	48	63	68	Green	34.34	0.3
6	54	58	83	Gold	34.68	0.5
7	51	55	74	Gold	33.42	0.5
8	46	68	66	Green	[1]25.5	0.4
9	49	64	67	Green	[1]29.9	0.4
10	48	66	69	Green	32.01	0.5
11	44	69	68	Green	33.92	0.55

[1] Kiwifruits 8 & 9 failed due to the bolt piercing the skin of the kiwifruit and pulling through prior to reaching sufficient FDF.

4.2 Fruit contact pressure testing

Key findings included the fact none of the tests performed on face 1 and face 3 ever exceeded the FCP of 0.216 MPa. However, face 2 and face 4 did fail under specific conditions for both small and large kiwifruit, as entailed in figures 11-14 below, with the operating pressure of 0.6 MPa highlighted in yellow. It was also noticed that only the face manipulated ever failed, which shows the significant effect this has on the likelihood of damaging the fruit. In summary, this means that this gripper would not be able to successfully harvest fruit when the fruit is 1 mm or greater in size in the direction of the second face on the largest kiwifruit tested for in this study, and 3 mm or greater for the smallest kiwifruit, and 3 mm or greater for the smallest and largest kiwifruit in the direction of face 4. Out of the 26 different cases tested in the FCP testing (the normal cases for both small and large kiwifruit, as well as the 1, 2 & 3 mm manipulations on each face), FCP only exceeded the critical 0.216 MPa on 5 occasions, and only 3 times at an input pressure of 0.6 MPa. All of these occasions would rarely occur in practice, more so the further they're manipulated, which goes to show this gripper would successfully be able to pick the vast majority of kiwifruit without damage.

This goes to show that the gripper distributes pressure well on the largest and smallest kiwifruit, however begins to significantly favour pressure distribution in face 4 and especially face 2 when a kiwifruit happens to be abnormally larger in that specific direction.

In regards to comparing this gripper to the other two grippers, the maximum output pressure exerted from this gripper at 0.6 MPa input pressure (rounding up from the 0.55 MPa found in the FDF section) was 0.09 MPa (without any manipulation to the force gauges), which is well below the maximum allowable FCP used in this study of 0.216 MPa. The existing compliant and rigid grippers compared to the gripper in this study as summarized in table 3 below, which shows that our gripper has a relatively higher pressure output compared to the two existing grippers, at 0.034 MPa for the compliant gripper, and 0.025 MPa for the rigid, however despite this our gripper is still 2.4 times less than the maximum allowable pressure of 0.216 MPa. Another notable point is that the rigid grippers FCP was reasonably similar between different sized kiwifruits, as opposed to the gripper designed in this study, where FCP varied slightly between different sizes as investigated in sections 4.3 and 4.4 of this report.

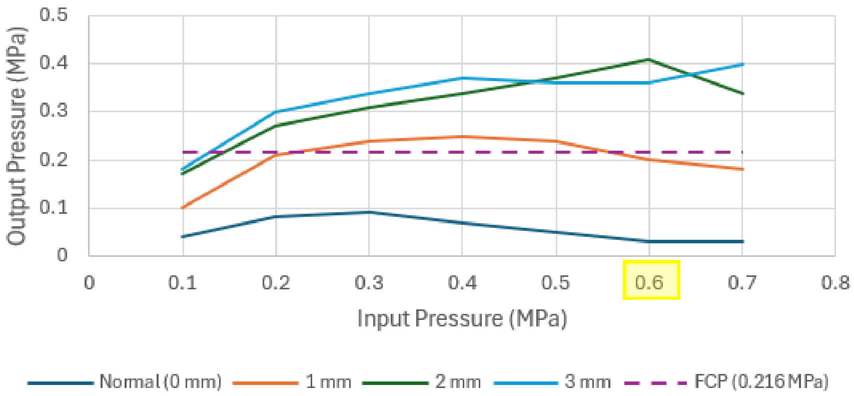

Figure 11 – Input vs Output Pressure for varying displacements on face 2 of a large fruit

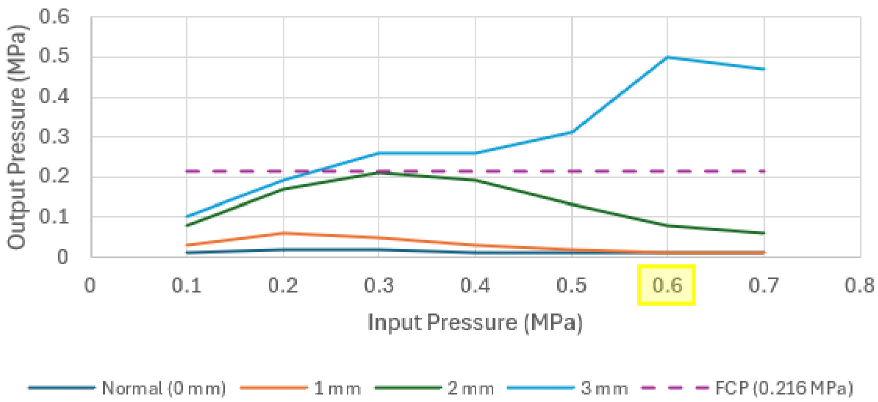

Figure 12 – Input vs Output Pressure for varying displacements on face 2 of a small fruit

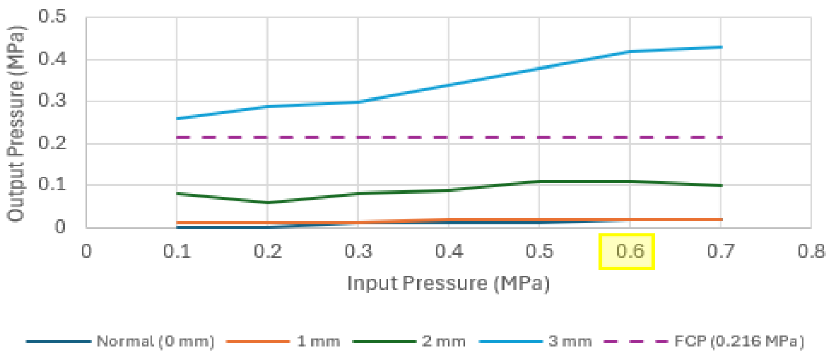

Figure 13 – Input vs Output Pressure for varying displacements on face 4 of a large fruit

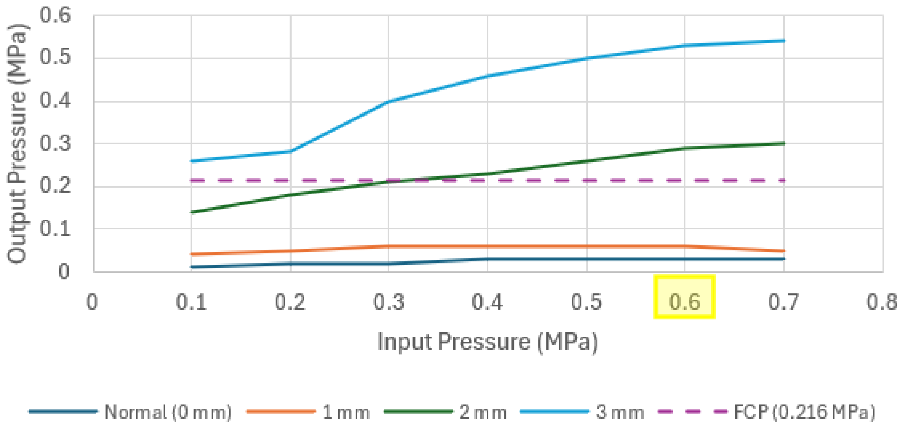

Figure 14 – Input vs Output Pressure for varying displacements on face 4 of a large fruit

Table 3 – FCP Comparison

	Existing Compliant Gripper	Existing Rigid Gripper	This Studies Gripper	Maximum Allowable
Gripping Force (N)	60.37	44.56	N/A	N/A
Contacting Area[3] (m^2)	0.0018	0.0018	0.000416	N/A
Output Pressure (MPa)	0.034	0.025	0.09	0.216

[3]Found using the same method used in figure 9

4.3 Large kiwifruit

The effect of input pressure on the output pressure of the different faces was investigated. Shown below in figure 15 is this relationship for the largest kiwifruit. As expected, it shows a relatively linear increase in output pressure as input pressure increases for faces 1, 3 and 4, with face 1 being affected the most, followed by face 3 and face 4. Face 2, on the other hand, displays much different results, as it steadily increases from the beginning to peak at an input pressure of 0.3 MPa, and the joint highest output pressure at 0.09 MPa, before steadily decreasing down to 0.03 MPa output pressure. This can likely be explained by the face getting closer and applying more pressure to the force gauge between input pressures 0.1-0.3 MPa, before slowly being wedged away from the face as the faces either side of it, 1 and 3, continuously increase, forcing face 2 away from the force gauge as a result. This would be caused by a small amount of slipping along faces 1 and 3, but a negligible amount to be further investigated for potential damage. An example of this is detailed below in

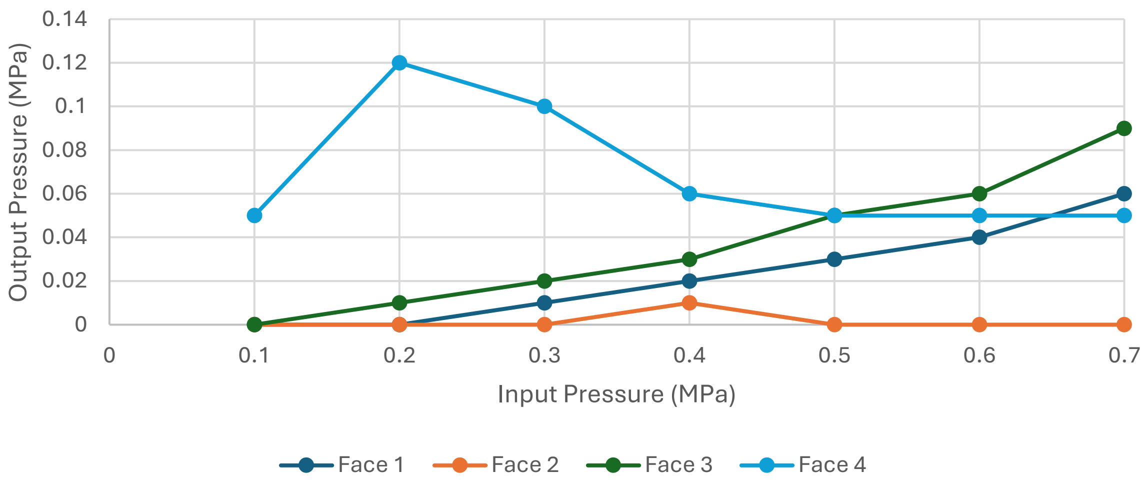

Figure 15 – Input vs Output Pressure for large kiwifruit

figure 16 – with low pressure being well conforming, and high pressure having faces 2 and 3 wedging away.

Another interesting point to note is that across all the different tests, the highest pressure was always found on the face that was being manipulated bar one case, which shows the effect the difference in shape of the fruit has on the pressure it experiences.

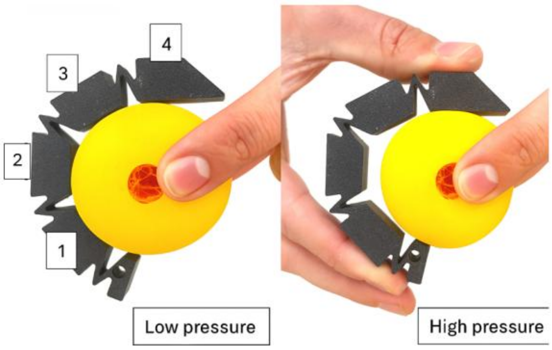

Figure 16 – Wedging effect on finger

4.4 Small kiwifruit

Shown below in figure 17 is this relationship for the smallest kiwifruit. Again, as expected, face 1 and 3 show a relatively linear increase between input and output pressure, with face 3 being steeper than face 1, showing it is affected greater to a change in input pressure, which is contradictory to the results from the large kiwifruit. The results from face 2 were nearly negligible, only registering an output pressure of 0.01 MPa at 0.4 MPa input pressure. Face 4 displayed a similar behaviour to face 2 in the large kiwifruit testing, by peaking at 0.2 MPa, registering the highest output pressure at 0.12 MPa, before rapidly decreasing and then steadying out 0.05 MPa. This again can likely be explained by the steady increases in pressure in faces 3 and 4 wedging face 1 and 2 away from the force gauges, an example of which detailed in figure 16 above.

4.5 Comparison

In regards to how other faces react to manipulation of a face, we found that manipulations in face 2 and face 4 had little to no effect on any of the other faces. Meanwhile manipulations in face 3 generally led to decreased pressures in faces 2 and 4, while manipulations in face 1 led to increased pressures in face 3 and 4. It is also notable that face 1 was very persistent with results, hardly being affected by manipulations in other faces, while the other faces were much more sensitive. None of these manipulations led to any of the other faces having output pressures above the critical FCP value of 0.216 MPa, therefore further discussion is not important.

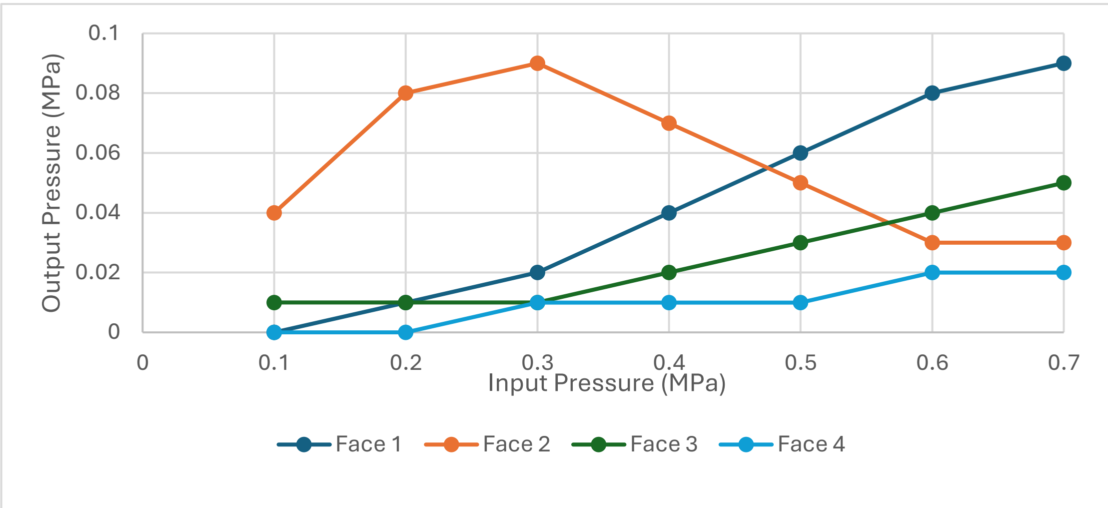

Figure 17 – Input vs Output Pressure for small kiwifruit

5. Conclusion

The comparative study conducted in this article makes it clear the unique approach of this gripper, approaching the fruit horizontally and developing a biologically inspired compliant design, lead to great success regarding the objectives of this paper. Key findings included this design being able to achieve FDF for a greater variety of sized fruits than the rigid gripper and have a slightly higher FCP (0.09 MPa for the normal case), compared to both the rigid and compliant gripper, at 0.025 and 0.034 MPa respectively, all of which are comfortably under the critical FCP of 0.216 MPa. Through the FCP testing, it was also found this gripper remained resilient with its FCP results across a variety of sized kiwifruits, with few exceptions (only exceeding the critical FCP value on 3 out of 26 occasions, all of which very rarely occurring), which was a point of difference in regard to testing compared to similar studies, as they only tested for one uniform size. Another key finding was that FCP didn't increase linearly across all faces as expected. Instead, face 2 for the large kiwifruit and face 4 for the small kiwifruit experienced a wedging effect, where they peaked at 0.1 MPa and 0.12 MPa respectively, while all the other faces steadily increased as input pressure increased.

Future work would involve adjusting the geometry of the finger to better distribute pressure between the faces and minimise the extreme values that surpassed the critical 0.216 MPa pressure. This could be done through iterative testing of different geometries using critical thinking as to how pressure could be reduced. Friction within the finger should be minimised to reduce losses, and hence reduce the required input pressure.

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