

# Field-evaluated Closed Structure Soft Gripper Enhances the Shelf Life of Harvested Blackberries

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**Abstract**—Soft robotic grippers are intrinsically delicate while grasping objects, and can rely on mechanical deformation to adapt to different shapes without explicit control. These characteristics are particularly appealing for agriculture, where items of produce from the same crop can vary significantly in shape and size, and delicate harvesting is among the first concerns for fruit quality. Various soft robotic grippers have been proposed for harvesting different produce types, however their employment in field testing has been extremely limited. In this paper we developed the first closed structure soft gripper for the harvest of blackberries. We adapted an existing gripper concept, initially testing it on a sensorised raspberry physical twin. Then, followed grower-guided protocols to pick blackberries in farm polytunnels, and to evaluate the shelf life in comparison with berries picked by professional human pickers. Our results with ten experimental varieties showed a picking success rate of 95.4% demonstrating the capability of a closed structure gripper to adapt mechanically to fruit-shape variability. Moreover, a shelf life assessment on seven measured traits reported greatly improved shelf life of between 30 and 150%, across all traits for gripper harvested blackberries. Our study demonstrates the potential of soft grippers for delicate fruit harvesting, and indicates how to increase the impact of robotics in agriculture.

## I. INTRODUCTION

Agricultural robots have seen a rapid increase in interest and development in recent years [1]. In the UK alone, shortages of seasonal labour and rising labour costs have led to a high demand for automated solutions for the horticulture sector [2]. This trend is present worldwide due to the large proportion of labour costs in the production of fresh produce, among other concerns for sustainability, resources management, and population increase [3]. In many horticultural crops, harvesting is one of the most complex tasks and the most labour intensive. For soft fruit and top fruit, wages account for 37.4% of revenue compared to 17% across the rest of the horticultural sector [4]. It is therefore unsurprising that the robotics community increasingly pursue harvesting robots [5], [6], [7], [8], [9], [10]. Among several challenges involved with harvesting high-value soft fruits (e.g. strawberries, raspberries, blackberries etc.), delicate

handling and adaptability to crop variation are critical factors undermining the deployment of robotic harvesters.

Soft robotic grippers, with their intrinsic delicacy and adaptability, are envisioned as a technological breakthrough for autonomous harvesting. Several innovative grippers have been developed specifically for agriculture, and recent surveys on soft grippers for agri-food applications highlight the strong synergies between soft and agricultural robotics [11], [12], [13], [14], [15]. However, the employment of soft grippers for actual field deployment is surprisingly limited, despite the clear potential and the relatively low cost of technology. The advantages of soft grippers have been rarely proven beyond testing on lab replicas of their target crop [15], with a high number of solutions tested only on a single fruit, often in the lab. Studies demonstrating that soft grippers can be employed to effectively grasp varied produce items or different cultivars with a minimal set of sensors and control are, to the authors' knowledge, currently lacking.

In this paper we report testing of our proposed soft gripper on physical-twin berry simulator and real berries, across a range of blackberry varieties on a research farm, and a commercial soft fruit farm. Using farmer and plant science informed guidelines, we also assessed harvest-induced damage to the berries. Our work focuses specifically on blackberries, a model crop for robotic harvesting that poses significant challenges to traditional systems. Blackberries are harvested by pulling the berry itself, contrary to other soft fruits for which cutting the stem is possible [16], [17], and they are extremely fragile and prone to druplet damage [18]. Only a few attempts have been directed toward the realisation of soft grippers for blackberry harvesting. A sensorised glove has been used to measure fingers' grasping force during human picking actions [19], and later to inform the design of tendon-driven soft fingers to replicate the picking actions [20], [21]. A different approach employs a soft-walled tube with rigid extremities and an external spring to wrap around the berry, by a twisting movement of the tube [15].

In our study we developed a pneumatically actuated encapsulating gripper described here as a closed structure gripper [22]. Our gripper wraps around the berry with four air cushions. Our solution aims to ensure no rigid elements interact with the crop, substantially reducing rigid elements compared with [15], and ensures a higher contact area with fruit than [21] and less control demand than designs developed in [20]. The gripper was extensively tested on commercial and research farms, to harvest ten different varieties of blackberries and then to harvest more than 100 berries for comparative shelf life assessment.

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## II. MATERIALS AND METHODS

### A. Design

The gripper design is inspired by the structure of the 'STIFF-FLOP module', a soft surgical manipulator well known in the soft robotics field [23]. In this case the soft cylinder is enlarged, retaining wall thickness, to create a cavity large enough to engulf a blackberry. The pneumatic channels are inverted and realigned to direct pressure and resulting actuation inwards into the cavity. When the channels are inflated with air pressure, the inner walls of the cylinder expand around targeted objects, providing a distributed grasping force. An additional pneumatic channel is included to account for increased size of the cylinder and provide greater contact area with the grasped object. To contain the outside layer of the gripper and prevent any potential inflation on the outer surface of channels, the cylinder is wrapped in a thin layer of in-extensible polypropylene film. The resulting closed structure gripper design is optimized and used for the first time for the purpose of fruit harvesting [22].

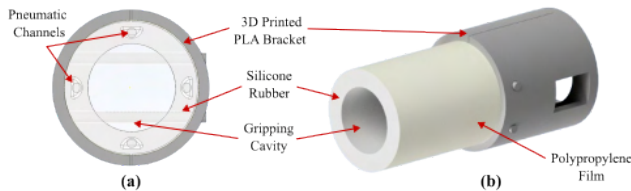


Fig. 1. Gripper design and components illustrated with (a) cross section and (b) CAD assembly.

The dimensions of a closed structure gripper restrict the maximum size of target. Therefore when considering the task of blackberry harvesting, the characteristics of the largest varieties such as 'Karak Black' were considered to inform gripper dimensions. These berries can grow upwards of 5cm in length 3cm in width. For berries smaller than this maximum size, the gripper can be further inflated to provide grasping force. The fully soft and deformable structure of the gripper which interacts with the crop is designed to reduce the risk of damage to nearby untargeted and unripe fruit.

### B. Fabrication

The silicone moulding/fabrication process is also inspired by the process to create a single STIFF-FLOP module [23], however all mould components are redesigned with unique dimensions to form the gripper. The chosen elastomer for casting the gripper body is Smooth-on Inc Ecoflex™ 00-50 for its favourable properties in pneumatic applications [24]. The mould components were all 3D printed using rPLA with Ultimaker S5 FDM 3D printers. The mould shown in Fig. 2c. was filled with degassed liquid silicone and cured to yield Fig. 2d. A second stage moulding then sealed one end of the channels resulting in Fig. 2e. Finally flexible 3mm tubing was glued into the open ends of the four channels using Loctite® Power Flex Glue and a simple bracket was press fit into the two holes left by the dowels in Fig. 2c. The silicone was also wrapped in polypropylene film.

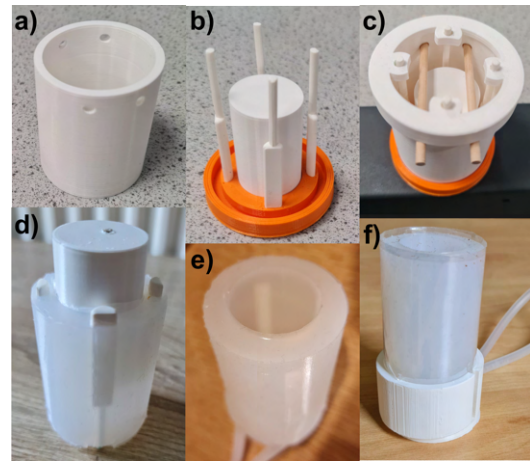


Fig. 2. Fabrication stages a) The outer shell of the gripper mould. b) Inner mould components including channel moulds and cavity mould. c) Fully assembled mould. d) First stage silicone casting. e) Fully cast silicone structure. f) Final gripper with outer sleeve and bracket attached.

### C. Design of Experiments

A user-focused approach was decided upon in order to involve growers and fruit science experts in all stages of the design process. Therefore to validate the initial gripper concept, the majority of experiments were designed around real fruit and actual blackberry farm environments. For all experiments the gripper was actuated using a Programmable-Air open source hardware kit. All harvesting for the scope of this paper was conducted by manually localising the gripper to the fruit, as the focus is on the end effector performance only.

## III. EXPERIMENTS

### A. Concept validation

In order to evaluate the grasping forces applied by the gripper in comparison with a human hand, the gripper was initially evaluated using the sensorized raspberry physical twin [25], a physical simulator of a raspberry, developed to train a harvesting robot [26]. Similarities to raspberries in size and harvesting methods motivate the use of this physical twin to validate the concept of the gripper, and benchmark its ability in comparison with a human harvester.

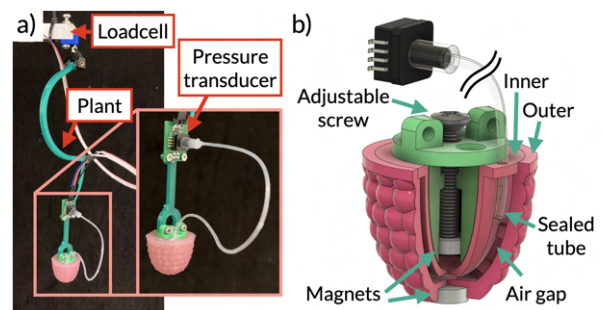


Fig. 3. The sensorized raspberry physical twin. a) Labeled picture of the measurement setup. b) Schematic of the fruit with an updated design from [25].

Fig. 3a shows the physical twin setup where the sensorized fruit is hung from a loadcell via a physical twin of the plant. The loadcell measures the pulling force of the harvest, while compression force is measured by an NXP absolute pressure transducer connected to an air chamber within the fruit. The design of the fruit is improved from the original version [25] by removing the silicone tube used as the air chamber, and instead using two silicone pieces sealed using silicone epoxy as shown in Fig. 3b. While functionally equivalent, this design allows for greater flexibility in tuning the stiffness of the fruit in future works. This design also reduces the size of the receptacle to better mimic the real fruit, further closing the reality gap.

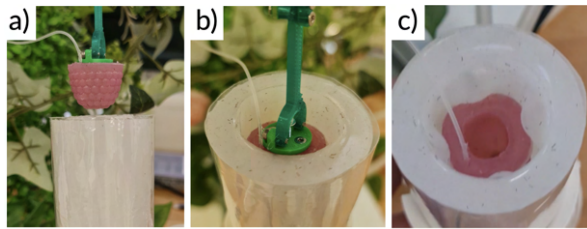


Fig. 4. Images to show the harvesting steps of the fruit: alignment, grasping, and harvest; shown by a), b), and c).

The gripper was used to harvest the berry twin with three increasing values of inflation pressure: 120kPa, 130kPa, and 135kPa. For each gripper-pressure a total of 10 trials were conducted to evaluate grasping success and determine an appropriate inflation pressure. In this test, the gripper was manually operated while grasping to detach the fruit. To compare the robot's harvesting quality, the fruit was also manually harvested by a human for 20 trials. Fig. 4a-c. show the gripper being used to harvest the twin in three steps: alignment, grasping, and harvest.

### B. Grasping versatility

One of the greatest advantages of compliant soft robots is the potential to create in-built tolerance and adaptability to uncertain parameters. Therefore it was hypothesised that the gripper would be able to successfully grasp a wide range of blackberry sizes and shapes by varying inflation and adapting to unknown shapes with deformable materials. To test this we used the gripper to attempt picking of experimental blackberry varieties developed by the fruit breeding team at the National Institute of Agricultural Botany, UK. These varieties are non-commercial research cultivars, developed for cross-breeding and plant/fruit trait experimentation. They present non-uniform shapes and a range of properties making them more challenging to successfully grasp and harvest as highlighted in Fig. 5. Although these fruit are grown in low numbers, an experiment was proposed in which any varieties with five or more ripe blackberries available would be picked with the gripper, recording detachment success rate and qualitative observations. Ten varieties were identified and between five and ten ripe berries were targeted for each variety. The varieties are numbered from H51 to H61 with H53 being excluded due to not enough ripe fruit being

available on the day of picking. The inflation pressure of the gripper was set to 137kPa due the smaller sizes of experimental varieties vs farmed varieties.



Fig. 5. Three experimental blackberry varieties showing non-standard fruit: a) A blackberry with non-uniform drupelet size (H58). b) Blackberries with oversized drupelets (H59). c) Very small blackberries (H60).

### C. Blackberry detachment force

In this experiment we sought to determine the value of force required for a gripper or human picker to successfully detach and harvest farmed blackberries. Data was collected for blackberry detachment force using a PCE Instruments PFG 50 force gauge to harvest blackberries across 14 farm polytunnels shown in Fig. 6. The peak force (N) required for detachment from the blackberry canes was recorded using a 3D printed attachment designed to fit around the top surface of a blackberry shown in Fig. 6, and to apply force to separate the berry from the peduncle (stem).



Fig. 6. Left: Force gauge with blackberry attached. Right: Blackberry farm polytunnels

Factors such as temperature and humidity can affect the picking of blackberries, therefore it was important to consider the location of berries within the polytunnels when collecting data. The 14 polytunnels were segmented into five areas as seen in Fig. 7. and picking was distributed evenly across the five segments with 50 berries being picked and recorded in each section of the map. The outside temperature on the at the time of data collection was between 21 and 23°C and all berries were of the variety Driscoll's® Victoria™.

### D. Shelf life comparison of human-picked and gripper-picked blackberries

The main experiment conducted in the validation of the gripper was the picking and handling of several punnets of real supermarket quality blackberries in the farm environment. Six punnets of blackberries were harvested using the prototype gripper at the same time as professional human pickers harvested six punnets by-hand with standard industry techniques. The gripper-inflation pressure was set 135kPa for

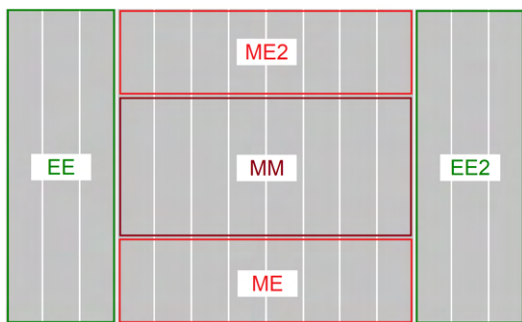


Fig. 7. Representation of the fourteen polytunnels and the segments where detachment force data were collected

this experiment informed by the 100% grasping success in experiment A. In total, 115 berries were picked with the gripper and 120 were picked by human pickers. Following this, the punnets were subjected to a week-long shelf life assessment involving refrigerated storage for 6 days at 4°C and 1 day in a humidity controlled shelf life cabinet at 18°C and 75% humidity (MMM Climacell 707 climactic cabinet). At the end of the 7th day a sample of 10 blackberries was taken from each punnet and the traits listed in Table I were evaluated and scored. The scores can be used to compare the shelf life performance of gripper-picked and human-picked berries to assess the impact of picking using the gripper.

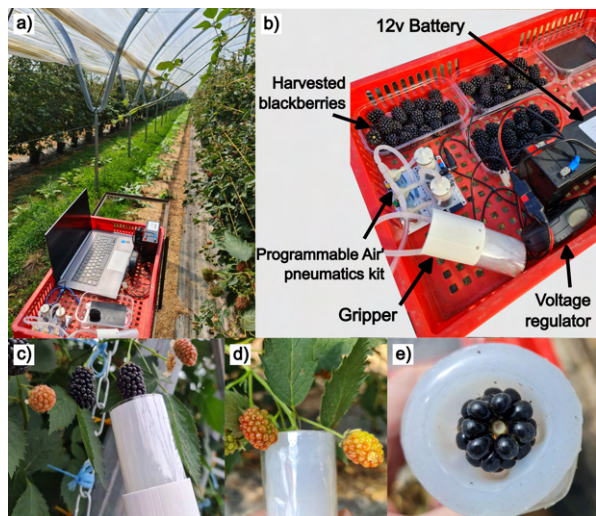


Fig. 8. Picking of blackberries in farm polytunnels: a) A row of blackberry plants inside a polytunnel with a trolley supporting equipment. b) Equipment used to pick blackberries with the gripper. c) Gripper approaching a blackberry. Gripper engulfing blackberry with nearby unripe fruit. e) A blackberry inside the gripper cavity.

## IV. RESULTS AND DISCUSSION

### A. Fabrication Results

The fabrication process for the gripper yielded repeatably detailed and functional silicone castings. Three grippers were cast using the mould without any major defects or issues de-moulding, the grippers have a mass of 122g each. Improvements could be made and it must be noted that the

TABLE I  
TRAIT SCORING IN SHELF LIFE ASSESSMENT

Trait	Scoring
Skin Strength	No. of berries passing surface friction test
Texture of Berry	No. of berries with normal firm texture 1-10
Rots	No. of berries without rots 1-10
Bleeding	No. of berries without bleeds 1-10
RDR	No. of berries without RDR 1-10
Uniformity of Colour	Punnets scored 1-5 (x2) on overall colour
Brightness	Punnets scored 1-5 (x2) on shine/brightness

alignment of the channel moulds is crucial for a high quality picking head. If the channels are not parallel with the cavity of the gripper, then uneven inflation can occur along the channel when actuated. Evidence of this issue is seen in Fig. 8e. where one of the channels is inflating outside of the gripper and pressing against the outer sleeve. This issue could be improved by more precise alignment of the pneumatic channel closer to the inner cavity. The 3D printed bracket at the base of the gripper was not used to attach the gripper to a manipulator arm for the scope of this work. While functional, the bracket should be developed further for arm interface in future work. The gripper inflates in 1.1 seconds. The limiting factor for this is the speed of the compressor in the 'Programmable Air' kit used for actuation. The gripper could be actuated by any compressor/tank or other source of compressed air more quickly if desired.

### B. Concept Validation

Fig. 9. shows the raw time series signals of the concept validation of the gripper using the raspberry physical twin. The top four plots reflect the compression force ( $F_c$ ) on the berry, and can be used as an approximate measure of handling quality. The bottom four plots are the pulling force ( $F_p$ ) recorded by the loadcell. The blue and red lines reflect a successful and unsuccessful harvest respectively. The trial with 120kPa of inflation pressure mostly resulted in unsuccessful harvest (30% success), when increased to 130kPa the success rate is at 80%, and finally at 135kPa the success rate is 100%. This result was used to inform gripper-inflation pressure for later experiments in the study. The negative values of  $F_c$  is a result of changes in volume when the twin is released from the receptacle (described in [25]). Table II reports the mean and standard deviation of the maximum compression and pulling forces,  $\max(F_c)$  and  $\max(F_p)$ , of for the four trial groups. Most notably  $\max(F_c)$  recorded by the gripper is comparable to that of the human harvester. Comparing the human harvester to the robot at 135kPa inflation pressure (where the success rates are equal), the robot applies approximately 11% larger force than the human. However mean values fall within each other's standard deviation range making them highly comparable. In fact, by lowering the inflation pressure to 130kPa, sacrificing some accuracy, the mean  $\max(F_c)$  is lower than the human. This validation experiment concludes the simulated success in using this gripper for raspberry

harvesting, a similar task; and demonstrate its similarities in harvesting compression compared to that of a human.

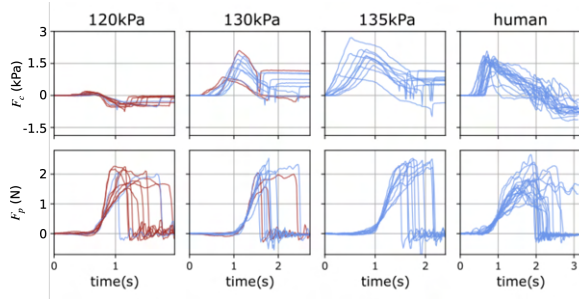


Fig. 9. Raw sensor readings from the sensorized raspberry physical twin. Top figures show compression forces and bottom figures show pulling forces. The four columns show the gripper at 120kPa, 130kPa, and 135kPa; and a human harvester. Blue and red lines indicate successful and failed harvests.

TABLE II  
MEAN(STANDARD DEVIATION) OF THE  $\max(F_c)$  AND  $\max(F_p)$   
MEASURED BY THE PHYSICAL TWIN

	120kPa	130kPa	135kPa	Human
$\max(F_c)$ (kPa)	0.22 (0.10)	2.8 (0.93)	3.6 (0.9)	3.3 (0.7)
$\max(F_p)$ (N)	1.93 (0.23)	2.07 (0.24)	2.36 (0.09)	1.82 (0.345)

### C. Grasping versatility

The experimental varieties picked were mostly smaller in size when compared with farmed blackberries ranging in size from the smallest variety (H60) to the largest (H56). (H60 average height 18.6mm, width 18.2mm. H56 average height 31.2mm, width 23.8mm). The number of grasping attempts was limited by the availability of ripe fruit with some varieties only 5 or 6 blackberries could be picked. All berries were harvested with a pressure of 135kPa and Table III shows the numbers of successful and unsuccessful detachments using the gripper with only one attempt made per berry. Grasping success is defined as total detachment of the blackberry from the cane without obvious visual damage caused. In total only four detachment failures were recorded. these failures included the largest (H56) and smallest (H60) varieties picked. In three instances the gripper slipped off the targeted berry and in one instance a protruding berry druplet was torn and damaged by the gripper. Although the amount of data collected is quite small, the overall result of 95.4% picking success indicates that the gripper deformability can be used to account for a variety of shapes and sizes in blackberries and indicates the ability to harvest berries with non-uniform surfaces. This result is clear evidence of intrinsic soft robotic adaptability and tolerance to unknown shapes without the need for feedback and control.

### D. Detachment force

In total, 250 measurements of detachment force for ripe blackberries were collected across a field with 14 polytun-

TABLE III  
GRASPING SUCCESS RATES FOR EXPERIMENTAL BLACKBERRY  
VARIETIES

Variety number	Grasping attempts	Detachment success	Detachment failure	Success rate
H51	10	9	1	90%
H52	10	10	0	100%
H54	5	5	0	100%
H55	10	10	0	100%
H56	10	9	1	90%
H57	6	6	0	100%
H58	10	10	0	100%
H59	10	10	0	100%
H60	6	5	1	83.3%
H61	10	9	1	90%
Total	87	83	4	95.4%

TABLE IV  
MEAN BLACKBERRY DETACHMENT FORCES BY POLYTUNNEL LOCATION

Area Key	EE	EE2	MM	ME	ME2
Detachment Force (N)	9.14	8.31	7.78	8.93	9.12

nels. The average detachment forces shown in Table IV were higher than expected [20], [21], and indicated a difference in force dependent on whether blackberries are picked in an edge location or in the centre of the field (Fig. 7). An analysis of variance ( $F=3.11$ ,  $p=0.0159$ ) confirms a significant difference between the results, and the Tukey's HSD (Fig. 10.) test reports a significant difference for the centre of the field (MM) and the edge areas (EE and ME2). No significant difference is reported for the remaining areas. This initial data set collected should be expanded with further investigation to evaluate the significance of location, including factors such as temperature, humidity and growth stage of the blackberry canes. These results show that when designing robotic harvesting systems, it is important to consider that variability in fruit is significant enough that fruit-informed engineering specifications should be based on a significantly large and varied set of data.

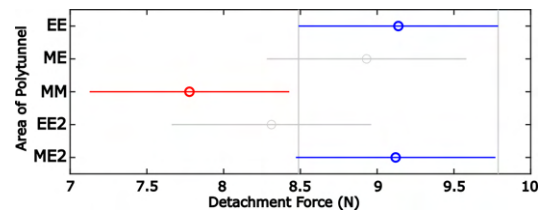


Fig. 10. Tukey's HSD test among the areas of the polytunnel. Two groups (Blue) have means significantly different from the centre (Red).

### E. Shelf life assessment

In total 115 blackberries were picked with the gripper across 14 polytunnels. A total of 121 picking attempts were made with six failures recorded, three of which were due to grasping under-ripe berries after closer inspection. Given the

observed difference in force required to pick an underripe berry this could inform future work in using detachment force thresholds to enhance ripeness detection in automated blackberry picking systems. Overall the results yield a total grasping success rate of 95.0% for the gripper manually operated in the farm environment. This figure is high for a robotic gripper and demonstrates the potential of this end effector to be taken forward for implementation with robot arms and a vision system. Despite the high grasping success rate, a limitation of this experiment was the single pressure used for grasping, future work will investigate using sensor feedback to set the pressure. The berries picked with the gripper were packed into six single-layer punnets with lids and soaker pads. Six punnets of human picked berries were randomly selected from punnets picked at the same time across the same field. The berries were subject to a 7 day shelf life assessment as detailed in section III D. The results of the shelf life are presented in Fig. 11.

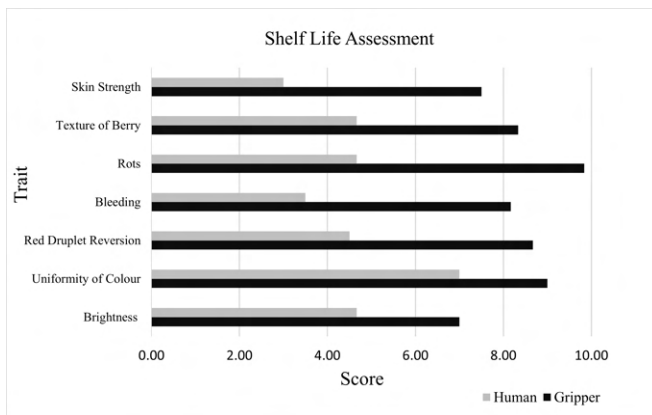


Fig. 11. Shelf life assessment results for gripper-picked vs human-picked blackberries.

The shelf life assessment reveals a statistically significant improvement for the gripper-picked berries across all measured traits compared to the human-picked berries. Significance was tested with Mann-Whitney U test (Table V) for each metric on normalised data.

TABLE V  
MANN-WHITNEY U TEST FOR SIGNIFICANCE OF HARVEST METHOD  
EFFECTING MEASURED TRAITS

Trait	W	p-value
Skin Strength	35.5	0.005849
Texture of Berry	36	0.003993
Rots	36	0.003353
Bleeding	36	0.004551
RDR	36	0.004624
Uniformity of Colour	31.5	0.02392
Brightness	33	0.01338

For traits that were scored by counting defects, such as the no. of berries without rots, bleeds and Red Druplet Reversion (RDR) the difference was very large. An average of 8.7 berries per 10 sampled showed no evidence of RDR for

gripper-picked vs only 4.5 for human picked berries. Likewise, 8.2 gripper-picked berries out of 10 had no damaged bleeding drupelets while only 3.5 out of 10 human picked berries were free from bleeding drupelets. Finally, the gripper-picked berries showed almost no evidence of rotting with score of 9.8 berries free from rots. In fact only 1 berry out of 60 sampled was rotten, compared with an average of 5.3 berries per punnet of human-picked berries.

One possible explanation for such a substantial improvement in shelf life could be the way pressure is distributed around the surface of the berry. While Fig. 9. shows that the force applied to a berry at 135kPa is similar to that of the human hand picking the sensorized berry, the compressive force applied by human fingers is concentrated in small contact areas. The gripper however, is able to distribute force over a much larger contact area along the whole length of the berry (Fig. 8). This is notable in blackberry harvesting vs the raspberry physical twin due to the longer, less rounded shape of farmed blackberries. Another contributing factor may be the handling of blackberries by the human pickers. Pickers work at high speeds, grasping blackberries quickly and dropping them into punnets rather than placing them. While this handling may not cause immediate visual damage it likely explains some of the berry quality reduction seen at the end of the shelf life assessment [18]. A limitation of this study was that the gripper performance was only compared with a single random human picker. Experiments could be repeated with multiple pickers to avoid comparison biased with a single picker's performance.

## V. CONCLUSION

To address the growing societal and economic needs for automation in harvesting we have presented a closed structure soft gripper for harvesting of blackberries. Through evaluation of this gripper in lab based tests on a berry simulator, and in field tests with over 200 berries, the harvesting success, adaptability and shelf-life improvement was demonstrated. The harvesting success is higher than typical robotic solutions, but the key notable result was the improved shelf-life recorded. This indicates that the soft gripper could have a significant impact to reduce waste and spoilage in addition to enabling automated harvesting. Further work is now required to investigate more extensively why the force distribution and properties of the gripper positively affect the shelf life, and to further optimize the gripper to improve the harvesting success with pressure sensor feedback. Longer term, integrating this with computer vision and robotic arms would enable more extensive field tests, and would represent a move towards a deployable solution for harvesting blackberries.

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