Tendon-Driven Soft Robotic Gripper for Blackberry Harvesting

Anthony L. Gunderman, Jeremy A. Collins, Andrea L. Myers, Renee T. Threlfall, and Yue Chen

***Abstract*—Global berry production and consumption have significantly increased in recent years, coinciding with increased consumer awareness of the health-promoting benefits of berries. Of those consumed, fresh-market blackberries are primarily harvested by hand to maintain postharvest quality. However, the forces applied during hand harvesting can result in major losses of marketable berries to red drupelet reversion (RDR). What is more, manual harvesting is a costly endeavor that accounts for up to 50% of the person-hours involved in berry production. Herein, we present a novel, tendon-driven soft robotic gripper with active contact force feedback control, which leverages the passive compliance of the gripper to allow the gentle harvesting of berries. The versatile gripper can generate a desired force as low as 0.5 N with a mean error of 0.046 N. Field test results indicate that the robotic gripper is capable of harvesting berries with 16% RDR while maintaining a harvesting reliability of 95.24% at a harvesting rate of approximately 4.8 seconds per berry.**

***Index Terms*—Soft robot, agricultural automation, soft grippers.**

I. Introduction

BERRY production and consumption have increased globally in recent years. According to the United States Department of Agriculture report, the U.S. berry market reached a value of $7.5 billion in 2020 [1]. The global market is expected to grow an additional 9.3% by 2025 [2]. This rise in berry consumption is associated with the health-promoting benefits of berries [3], [4], which contain antioxidants [5]–[7] that mitigate conversion of cellular macromolecules to specific reactive, oxidized forms [6], a primary cause of chronic diseases [8].

Blackberries are a delicate, aggregate fruit comprised of drupelets surrounding a soft tissue torus [9]. Consequently, harvesting methods for fresh-market blackberries are constrained to hand-harvesting approaches to prevent yield loss and surface berry damage. As a result, blackberry harvesting is an inherently labor-intensive operation, requiring a massive deployment of laborers, contributing up to 50% of the total hours spent on the crop annually [10]. These costly high-intensity harvesting periods are short, consisting of a 31-day annual harvesting window. This labor demand contributes substantially to the average seasonal cost per blackberry tray (4.5 pounds) of $6.25 [11]. However, failure to harvest meticulously can be detrimental to product quality, often resulting in berry damage or disorders such as red drupelet reversion (RDR) in blackberries [12]. Damage to the berries can cause decay and leakage in fruit, whereas RDR is a postharvest disorder where drupelets change color from black to red, which can affect up to 85% of the harvested crop [12] and negatively impact marketability [3], [4]. Consequently, handling consistency is of paramount importance, but it is often intractable due to the immense variance in skill and speed between harvesters.

Current methods of automated harvesting in agriculture rely on rough handling of the fruit by either (1) cutting the stem [13], (2) shaking the fruit off of the plant [14], (3) picking the fruit with rigid components [15], [16], or (4) using compliant plastic grippers to pick the fruit [17], [18]. For example, blueberries are harvested by shaking, whereas strawberries, oranges, apples, plums, and peppers are harvested using methods (1), (3), or (4). However, these methods inevitably damage the surface of less robust berries, such as blackberries.

Soft robotics provides an alternative option to the conventional automated harvesting methods [19], [20]. This is a departure from the rigid harvesting methods due to the inherent compliance of elastic materials used in the robotic body (rubber, silicone, etc.). These soft robotic systems are ideally suited for grasping [21], [22] and manipulating delicate objects with complex shapes [23], [24], enabling task versatility that is not found in traditional robotic systems. Current industry-based soft robotic grippers include the mGrip and mGripAI, which are used commonly in food automation [25]. However, the implementation of soft robotic grippers for the harvesting of delicate blackberries has yet to be explored, motivating the development of a novel harvesting framework (Fig. 1).

In this letter, we present a custom-designed, tendon-driven, soft robotic gripper for fresh-market blackberry harvesting that utilizes accurate force feedback to generate consistent handling forces. The tendon actuation provides a more compact actuator than pneumatically or hydraulically driven soft robots [26]–[28]. The gripper's tendon retraction was actively controlled with the feedback from the force sensors at the fingertips, ensuring harvesting consistency that surpasses the capabilities of the human hand. This robotic gripper was extensively validated through several metrics in benchtop settings, as well as field

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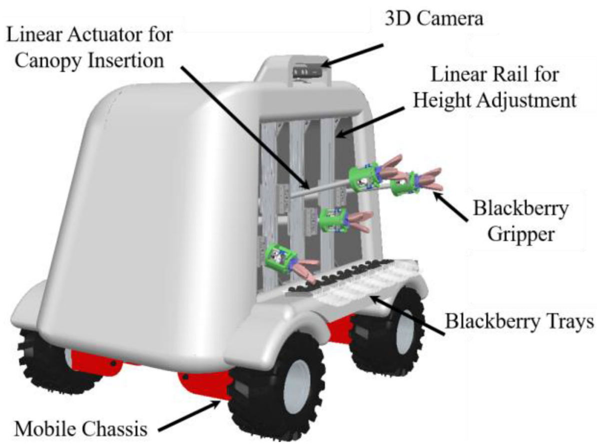

Fig. 1. Proposed soft robotic system for autonomous blackberry harvester. The soft gripper is implemented on a mobile chassis, which can identify, reach for, and grasp ripe berries. Note that multiple grippers can be used to obtain optimized harvesting efficiency vs. cost.

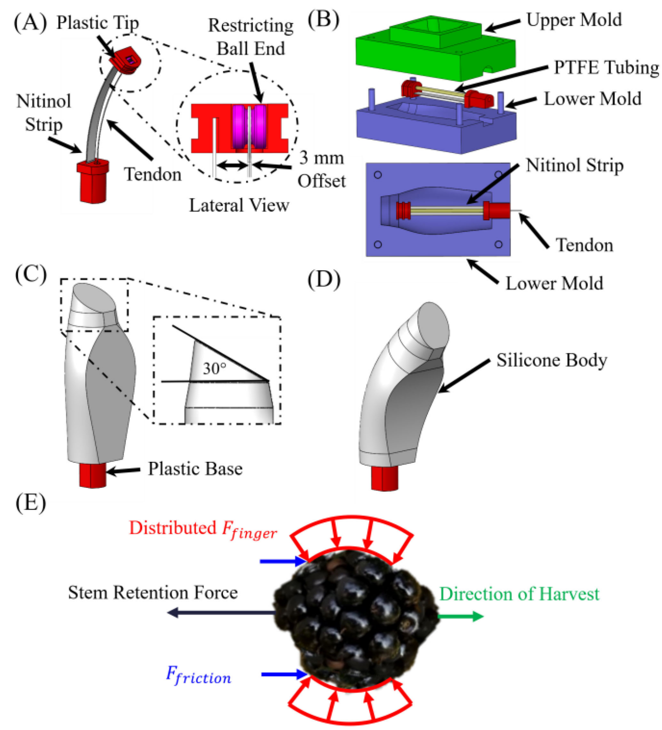

Fig. 2. (A) The internal components of the finger in the retracted configuration. The ball end of the guitar string was restricted by interference in the plastic tip as shown in the detailed section view. (B) An enhanced view of the molding process for the finger body with the finger backbone can be seen with a top view of the lower mold beneath it. Note that the nitinol strip provides the rigidity necessary to ensure the plastic tip and plastic base are in line. (C) The casted finger in its straight and (D) Tendon retracted configuration. (E) Force distribution (red) on the berry surface to overcome the stem retention force (black) during harvest.

tests, in which 240 Sweet-Ark^{TM} Caddo blackberries were harvested at a commercial grower. Due to the complexity associated with cane/berry localization, this work only focuses on gripper efficacy. Consequently, the gripper placement is performed manually at this early stage and future work will explore the system level integration of the soft gripper and robotic arm for autonomous harvesting [29]–[31]. Postharvest analysis with a focus on RDR was conducted on these berries for a comparative study. The rest of this letter is organized as follows: Section II of this letter describes the soft gripper design, fabrication and prototyping, sensor integration, finger configuration, and the force feedback control method. Section III provides the experimental methods. Section IV elaborates on the results and a discussion of the preliminary field tests. The letter is concluded in Section V.

II. Methods and Materials

A. Design Objectives

Robotic grippers are generally designed with the goal of optimizing their performance to a specific task. In this letter, our gripper aims to outperform the human hand with respect to the specific task of fresh-market blackberry harvesting. By limiting the scope of functions strictly to berry harvesting, the gripper design aims to overcome the limitations associated with hand harvesting by adhering to the following constraints:

1) Current berry damage associated with hand harvesting has up to an 85% loss of marketable berries due to red drupelet reversion (RDR) [12]. In this preliminary study, it is desired to obtain similar or less berry damage percentages compared to that of hand-harvesting methods.
2) In this preliminary study, we aim to design a gripper that maintains a harvesting reliability of at least 75%, similar to preliminary studies for other small fruit [13], [17], [32].
3) Previous research on blackberries showed that blackberries can vary in size and shape with lengths of up to 5 cm [3], [33] Therefore, the gripper must be able to reliably handle a large range of berry diameters and shapes (∼1.5 to 5 cm) while possessing a small cross-sectional footprint to increase dexterity for navigation within the berry canopy and avoid neighboring unripe berries.

B. Finger Design and Fabrication

The soft finger was fabricated by casting the finger body out of a two-part silicone (Model: Dragon Skin FX Pro, Brand: Smooth-On). Dragon Skin FX Pro was the optimal material selection amongst the Smooth-On family as it (1) minimized cure time (40 minutes) while (2) maximizing pot life (12 minutes). This allowed (1) the fastest prototype turnover and (2) the longest handling time for pouring the two-part mixture into the mold. The two-part silicone provided inherent passive compliance. This compliance is described by a finger stiffness of only 0.025 N/mm and 0.067 N/mm for bending in the direction of desired flexure and transverse direction, respectively. However, this property also leaves the fingers susceptible to disturbances from external loads, such as collisions with the plant canes. To combat this drawback, a 0.3 mm thick nitinol strip was used due to its super-elastic properties as an internal backbone to increase stiffness, as shown in Fig. 2A. This strip mildly increased stiffness in the direction of desired flexure, requiring a maximum tendon actuation force of only 20 N at 9 mm of tendon retraction, but increased the stiffness in the transverse direction 134 ×.

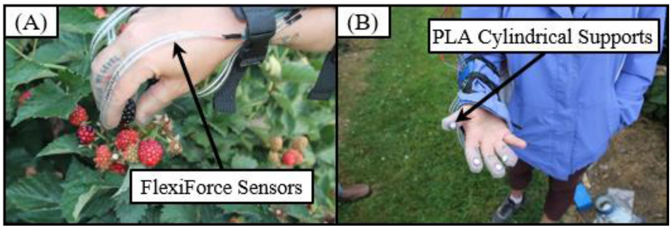

Fig. 3. (A) Force-sensing apparatus for manual blackberry harvesting. (B) Sensors were oriented to maximize contact with the berry surface during harvesting. Data recording and processing were conducted in a portable water-resistant case.

TABLE I
AVERAGE FORCES PER FINGER FOR MANUAL HARVESTING BLACKBERRIES

Finger	Thumb	Index	Middle	Ring
Force [N]	0.782	0.191	0.397	0.065

The finger molding process began with the assembly of the internal structure (Fig. 2A). The nitinol backbone was adhered to a plastic tip and base using cyanoacrylate. Polytetrafluoroethylene (PTFE) tubing was also attached to the plastic tip and base using cyanoacrylate to create a channel for the tendon to slide through within the silicone cast. The tendon was a guitar string (36-gauge, Ernie Ball, CA USA) that was terminated in the upper plastic component with a 3 mm lateral offset from the nitinol strip. This offset eccentrically loads the finger, resulting in inward bending during tendon retraction.

The internal structure was placed in the lower mold and held in place by clamping the upper mold to the lower mold (Fig. 2B). Silicone was poured through the opening in the upper mold. After the silicone was cured (∼40 min.), the finger was removed, and the excess silicone was severed from the finger body with a blade. The mold casted the fingertip at a 30-degree offset to the plane orthogonal to the longitudinal axis. This offset increased surface contact of the fingertip to the berry surface when the finger is in its retracted configuration (Fig. 2C and D) and resulted in a fingertip contact area of $\sim 3\ \mathrm{cm}^2$ for each finger. Fig. 2E depicts the force distribution on the berry surface during harvest.

C. Finger Configuration

Based on feedback from the growers, laborers typically use three or four fingers for berry harvesting depending on the laborer's hand size. Consequently, quantitative analysis was conducted to determine if the ring finger of a laborer with smaller hands applied a non-negligible force. A custom-made force sensing system was developed to detect the forces applied by the fingertips of an experienced laborer using FlexiForce A301 resistive force sensors, as shown in Fig. 3A. A total of 1440 blackberries were harvested at a private pick-your-own berry farm in Fayetteville, AR using this system, quantifying the average force applied by each finger during the manual harvesting process. Several cultivars of different size and shape of blackberries were harvested. These results can be seen in Table I.

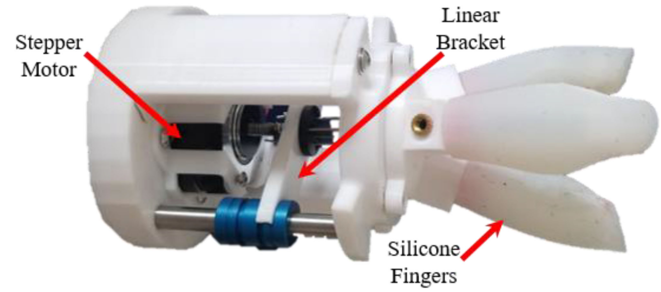

Fig. 4. The gripper assembly without the force sensors.

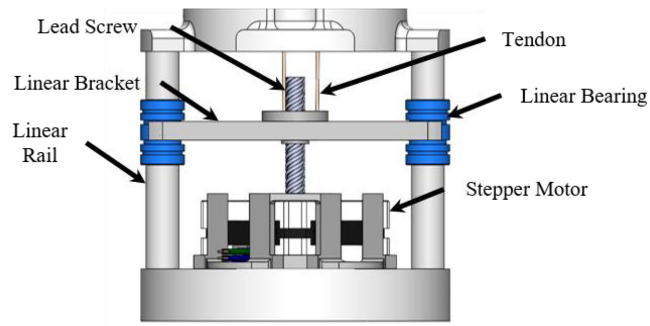

Fig. 5. The custom-designed lead screw mechanism was designed to mount beneath the fingers, providing a method for retracting the tendons.

Table I indicates the ring finger applies a negligible contact force when compared to the other three fingers. It should be noted that the thumb had the highest average force of 0.782 N, followed by the middle finger with a value of 0.397 N. This can be explained by the anatomical opposition of the thumb to the middle finger when gripping small objects. Considering that a common mode of blackberry damage is drupelet deflation, axis-symmetric spacing of the fingers was used to equally distribute the fingertip contact force onto the berry surface (Fig. 4). For the gripper design, the fingers were 6.45 cm long and spaced 120° around the circumference of the palm. The fingers were offset by an angle of 20° from the vertical axis, providing a maximum gripping diameter of 5.5 cm, which accommodated the largest perceivable blackberry size of 5 cm and ensured that the outsides of the fingertips were within the compact mounting base profile.

D. Control System

A NEMA 17 stepper motor (17HS08-1004S, StepperOnline Inc., NY, USA) was used to perform tendon retraction via a lead screw, which converted the rotational motion of a stepper motor to linear translation through a linear bracket. The three-finger tendons were each terminated below the linear bracket via knots located at the end of the tendons. The linear bracket extended radially to two linear rails and was affixed to two linear bearings, enabling low-friction translation (Fig. 5).

The fingertip-berry contact force feedback was achieved by adhering a FlexiForce resistive force sensor (A301, Tekscan) to each fingertip using cyanoacrylate. According to the integration recommendation of Tekscan, a thin cylindrical support (9.50 mm OD, 1.00 mm thick) was additively manufactured out of

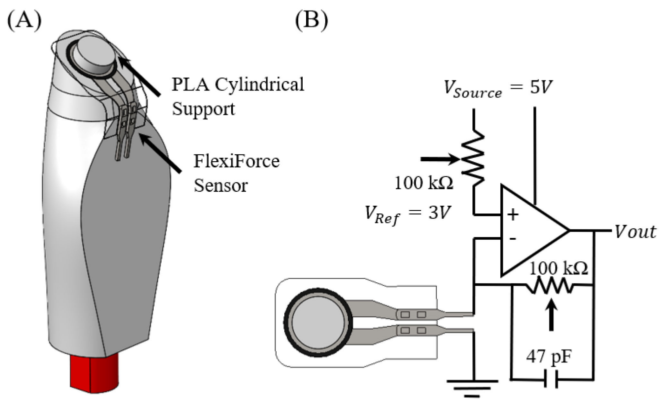

Fig. 6. (A) The finger can be seen with the FlexiForce sensor attached to the tip with cyanoacrylate. Note the PLA cylindrical support attached to the sensing area of the FlexiForce sensor per the user manual of the FlexiForce sensor. (B) The amplifying circuit can be seen with the FlexiForce sensor connected to the inverting terminal of the operational amplifier.

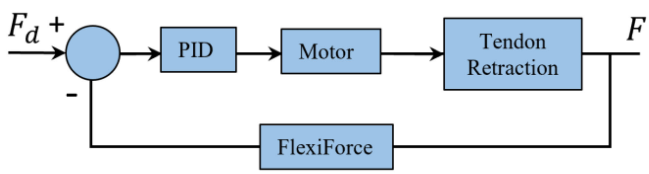

Fig. 7. The block diagram of the control system with $K_P = 4000$, $K_I = 0$, and $K_D = 125$. The sensor value from each finger was checked and the maximum measured value was used for the feedback.

polylactide (PLA) and attached to the sensing area of each FlexiForce sensor with double-sided tape. This support was used to ensure the force was fully transmitted to the sensing area of the sensor. The sensor data was amplified via an MCP6004-I/P operational amplifier, as shown in Fig. 6 [34]. The circuit had an operating output voltage range that was dependent on the linear relationship between the applied load to the FlexiForce sensor and the reference voltage (3V $\propto$ 0N) and the source voltage (5V $\propto$ 3.9N).

The contact force control algorithm (Fig. 7) was implemented with an Arduino Mega 2560 using a global timer interrupt ensuring 10 kHz communication for analyzing the fingertip contact force data and controlling the stepper motor. A proportional-integral-derivative (PID) controller was used to control the stepping speed of the stepper motor based on the difference between the desired fingertip contact force and the measured force value from the Flexi-Force sensor. To reduce power consumption the motor is shut off when the measured error difference is within a tolerance of 0.025 N, at which point the contact force value is maintained by the non-back-drivable lead screw.

III. Experimental Methods

A. Force Control Accuracy

Berry damage is primarily caused by excessive handling loads during manual harvesting. Evaluation of the PID controller's performance was done to validate the gripper's ability to maintain proper fingertip-berry contact force. The gripper was tested at eleven different desired fingertip contact force values

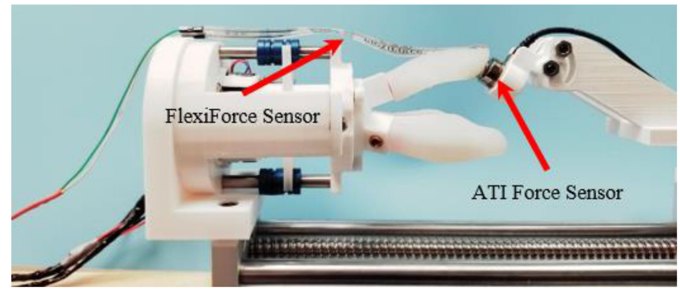

Fig. 8. The experimental setup to test the accuracy of the PID controller. Note that the ATI force sensor was constrained such that it was approximately parallel to the FlexiForce sensor after finger retraction.

ranging from 0.50 N to 1.45 N. The desired fingertip contact force applied by the controller was compared to the measured force of a high-resolution ATI force sensor (P/N: 9230-05-1311, ATI). The ATI sensor was constrained to a linear table and was positioned such that it was approximately parallel to the finger's force sensor in the finger's curved configuration, as shown in Fig. 8. Each test was repeated eleven times for each force value, resulting in a total of 121 data points.

B. Fingertip Contact Force Characterization

The normal component of the fingertip contact force of soft robotic grippers is influenced by the joint space input, finger geometry and stiffness, and object size and shape, often requiring computationally intensive analysis to estimate. We aim to develop an experimental procedure that creates a tractable approach for empirically characterizing the normal component of a gripper's fingertip contact force across a variety of joint space inputs (tendon retraction) and object diameters. This approach will permit an efficient method of comparing future grippers across a common metric.

Contact force analysis begins with simplifying the grasped object to axis-symmetric geometry around the longitudinal axis, reducing grasping complexity and analysis. A cone was chosen for this experiment to enable a continuous method of analyzing the fingertip contact force relationship across a range of object diameters. Using the cone, the object diameter grasped by the gripper is a function of linear translation l from the cone tip and the draft angle θ of the cone, as shown in (1).

$$D\left(l\right) \ = \ 2l * tan\left(\frac{\theta}{2}\right) \tag{1}$$

By attaching a force sensor to the center of the base of the cone, the force required to insert F_{push} and remove F_{pull} the cone from the gripper's grasp can be measured. Knowing the push and pull force at some distance l from the tip of the cone, the relationship between input tendon retraction (joint space input), grasping object diameter, and the normal component of the fingertip contact force F_{finger} can be calculated. By considering the free body diagrams and summing the forces with respect to the coordinate system shown in Fig. 9, (2) and (3) are obtained.

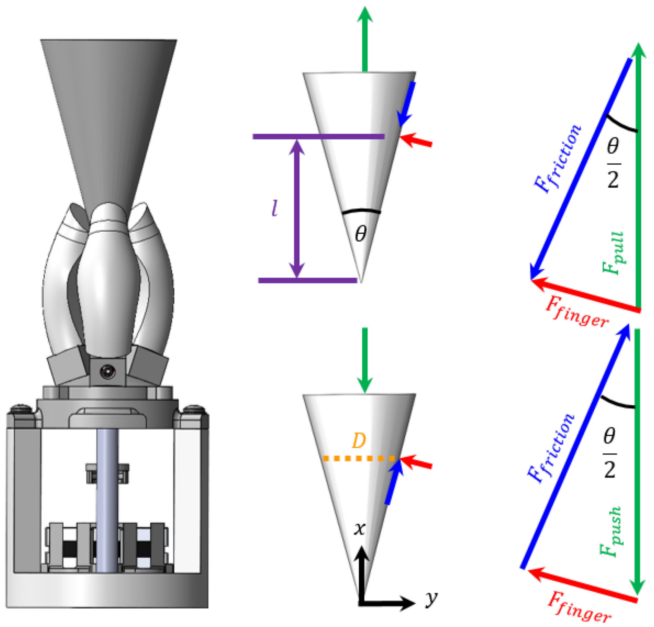

Fig. 9. A 2D representation of the free body diagram. The blue and red arrows are the frictional and normal components of the fingertip contact force, respectively. The green arrow is the force required to insert or remove the cone from the gripper (measured). The coordinate system (black) can be seen with respect to the conical tip.

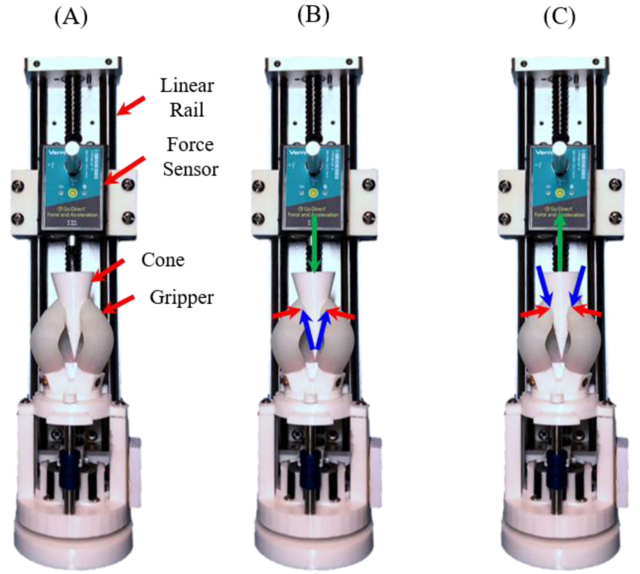

Fig. 10. (A) The experimental setup used for the fingertip contact force characterization. The direction of forces for (B) the cone insertion and (C) retraction procedure can be seen. The green arrow represents F_{push} or F_{pull} for (B) and (C), respectively, the blue arrow represents $F_{friction}$, and the red arrow represents F_{finger} from Fig. 9.

$$\sum F_{x,pull}: \; F_{pull} = n\left(\mu F_{finger}\cos\left(\frac{\theta}{2}\right) - F_{finger}\sin\left(\frac{\theta}{2}\right)\right) \quad (2)$$

$$\sum F_{x,push}: \; F_{push} = n\left(F_{finger}\sin\left(\frac{\theta}{2}\right) + \mu F_{finger}\cos\left(\frac{\theta}{2}\right)\right) \quad (3)$$

where μ is the coefficient of kinetic friction and n is the number of fingers in contact with the conical surface. By adding (2) and (3), the unknown variable μ is eliminated, solving for F_{finger} as:

$$F_{finger}(D,T) = \frac{F_{push}(D,T) - F_{pull}(D,T)}{2n * sin\left(\frac{\theta}{2}\right)} \quad (4)$$

where D and T are the object diameter and tendon retraction at point l along the x-axis on the conical surface.

The normal component of the contact force was characterized using a 3D printed cone with a 15° draft angle. The cone was inserted into and retracted from the gripper's fingers at 1 mm/s. Insertion was achieved using a linear sliding table that utilized an SFU1605 ball screw driven by a NEMA 23 stepper motor (Fig. 10). The base of the cone was attached to a force sensor (Go Direct Force and Acceleration Sensor, Vernier), which was constrained to the linear table. The gripper assembly was fixed to the end of the linear rail using an additively manufactured bracket. Pushing and pulling procedures were conducted at tendon retractions ranging from 5 to 9 mm in 0.5 mm increments. The 9 mm tendon retraction was conducted first, and the tip of the cone was placed at the tips of the fingers, which were in contact with each other at this joint space configuration. The lead screw position corresponding to this configuration was set as $l = 0$ for all tests conducted. Linear translation data and force data were recorded synchronously, providing the relationship between object push/pull force and object diameter.

C. Grasping Versatility

Although the gripper was designed specifically for berry harvesting, it also has potential to be used to handle objects of activities of daily living (ADL). As a result, gripper versatility was tested on a wide variety of object sizes, geometries, and material properties. This included a variety of fruits and vegetables, glass and plastic bottles, and other rigid and non-rigid objects. This was done by simply placing the object to be tested within the gripper's workspace and retracting the tendons of the gripper until an adequate amount of force was applied to prevent the object from falling.

D. Field Test (Harvest Reliability, Speed, and Damage)

The final evaluation of the gripper's efficacy was a field test that involved harvesting an additional 240 Sweet-Ark™ Caddo blackberries at a private pick-your-own berry farm in Fayetteville, AR. The blackberries were roughly 8 g each with a length of 30 mm and a width of 21 mm. In this study, the gripper was manually positioned and oriented, and the berry was harvested once it was within the workspace of the gripper. Three different desired fingertip contact force thresholds were used based on our preliminary harvesting data. Sixty berries were harvested at a desired fingertip contact force value of 0.59 N, 0.69 N, and 0.78 N, respectively and compared to berries

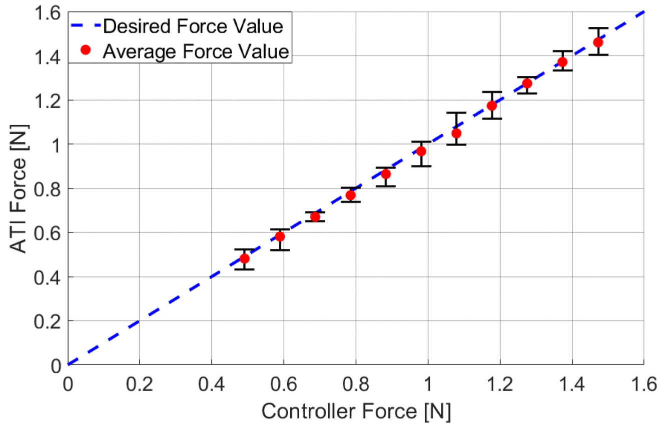

Fig. 11. The experimental fingertip contact force values (red dots) overlaid on the desired fingertip contact force line (hyphenated blue lines) can be seen with their corresponding error bars (black).

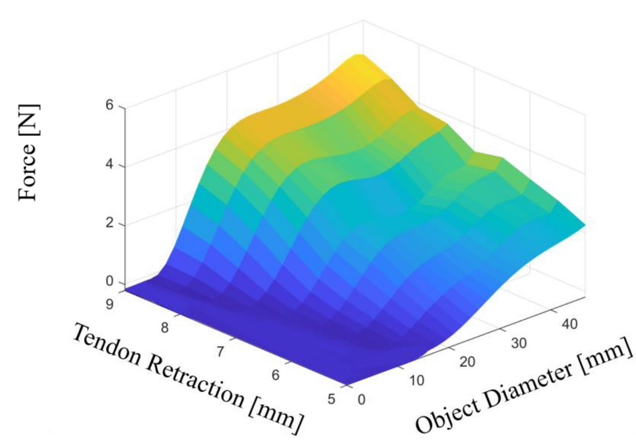

Fig. 12. The calculated normal components of the fingertip contact force values can be seen with respect to tendon retraction lengths of 5-9 mm and object diameters of 0-47 mm.

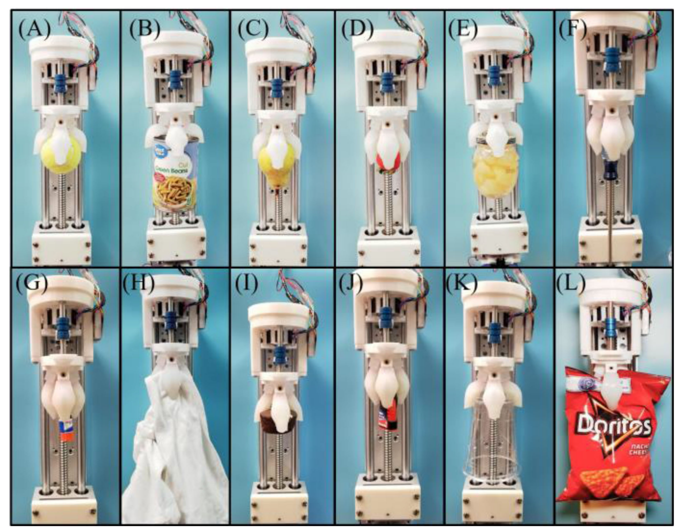

Fig. 13. Shown is the gripper handling various objects. These objects are a tennis ball (A), a can of beans (B), a pear (C), a strawberry (D), a jar of pears (E), a screwdriver (F), a glue stick (G), a t-shirt (H), a pastry (I), a container of super glue (J), an upside-down plastic cup (K), and a bag of chips (L).

harvested manually. For each tip force level, the blackberries were harvested and placed in plastic, vented clamshell containers (20 berries per clamshell), then stored at 2 °C for 21 days to evaluate RDR.

IV. Results and Discussion

A. Force Control Accuracy

For each desired force value, the force from the ATI force sensor was recorded for the 11 trials. A plot of the desired fingertip contact force (hyphenated blue line) and the resulting average force values for each trial (red dots) of the experimental results can be seen in Fig. 11, where deviation in the vertical direction (black error bars) corresponds to error from the desired fingertip contact force value. Due to the novelty of robotic blackberry harvesting, there remain many unknown design constraints, such as the required force accuracy to prevent berry damage. However, the average error between the desired force and the applied force to the ATI force sensor was 0.046 N, indicating the controller can successfully prevent excessive handling loads. Additionally, the average standard deviation resulting from the manual harvesting experiment (Section II-C) was 0.702 N. Conversely, the average standard deviation resulting from the gripper experiment was 0.027 N, providing a 26$\times$ reduction in handling variability.

B. Fingertip Contact Force Characterization

The fingertip contact force characterization experiment was successful at empirically characterizing the normal component of the fingertip contact force across a variety of gripping diameters and tendon retractions. This framework provides an efficient method of comparing the capability of soft robotic grippers developed in the future across a common metric. Experimental results from the cone produced continuous data at gripping diameters ranging from 0 to 47 mm. The results were processed in MATLAB. The fingertip contact force was a function dependent on object diameter and tendon retraction (4). A curve was fit to the calculated fingertip contact force and its corresponding object diameter at each tendon retraction. These 2D plots were then meshed, creating a knitted 3D plot, as seen in Fig. 12. The maximum normal component of the fingertip contact force was determined to be 4.92 N at an object diameter of 47 mm and a tendon retraction of 9 mm. It was found that objects with diameters less than 10 mm are not sufficiently grasped by the gripper. Note that at 9 mm and 5 mm of tendon retraction, the object must be at least 6 mm and 10 mm in diameter, respectively, to be effectively grasped. However, the average blackberry diameter is above 2 cm (21 mm as listed in Section III-D), indicating that the gripper is suitable for the harvesting of blackberries.

C. Grasping Versatility

The grasping versatility of the gripper is illustrated by the handling of objects that are a part of activities of daily living as seen in Fig. 13. These objects were selected to provide a variety in geometry, stiffness, weight, and compliance for testing the

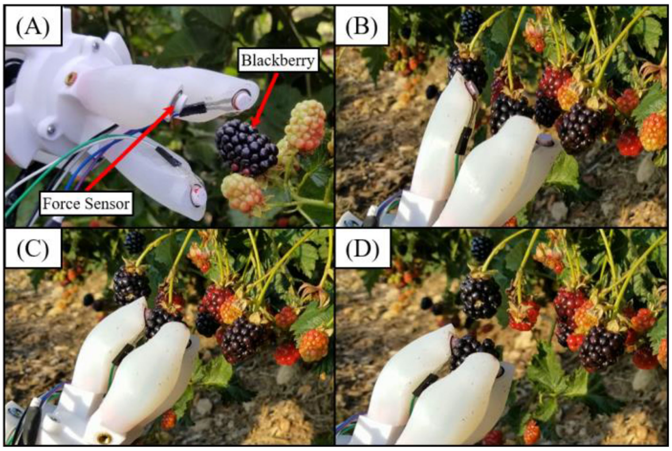

Fig. 14. (A) Soft robotic gripper prior to harvesting a ripe blackberry. Note the wide initial opening angle and the straightness of each finger. (B) The gripper is aligned so that the berry is within the gripper's workspace. (C) The gripper has been actuated and is using the force feedback to delicately handle the berry. (D) The berry has been removed from the stem.

TABLE II
RESULTS OF HARVESTING FRESH-MARKET BLACKBERRIES WITH VARYING FORCE FEEDBACK

Parameter	Test 1[i]	Test 2	Test 3	Hand[ii]
Fingertip Force [N]	0.59	0.69	0.78	N/A[iii]
Reliability [%]	77.92	86.96	95.24	100.00
Harvest Time [s]	8.10	7.30	4.80	1.40
Red Drupelet Reversion [%]	0.00	8.00	16.00	0.00

i. Tests 1-3 were performed by the gripper with force feedback.
ii. Test labeled "Hand" corresponded to berries harvested manually. This included 4 cultivars ('Sweet-Ark™ Caddo', 'Natchez', 'Osage' and 'Prime-Ark® Traveler').
iii. N/A – not applicable.

efficacy of the gripper. The ability of this gripper to delicately grip soft objects is represented by Fig. 13I, where the gripper is used to hold a pastry. Conversely, the strength of the gripper is displayed by its ability to hold a can of beans and a jar of pears as shown in Fig. 13B and E, respectively. Finally, the ability of the gripper to hold compliant objects is verified by the handling of the T-shirt in Fig. 13H and the bag of chips in Fig. 13L.

It should be noted that the internal plastic tip used to terminate the tendon within the silicone fingers provided useful mechanical advantage as illustrated in Fig. 13B and E. For these objects, the gripper fingers are forced into an angle greater than the initial offset angle of 20°, which could potentially cause an unstable grasp; however, as the tendons are retracted, the internal plastic component wraps around the lip of the can and the lid of the jar, creating an inherent mechanical advantage. This is analogous to the way that human fingers can curl around a small object, reducing the need to rely on frictional grasping.

D. Field Harvesting Test

The results of the field harvesting test (Fig. 14) can be seen in Table II. In conjunction with the berries harvested by the gripper (Test 1-3), 60 berries were also harvested manually (Hand) to provide a control group. The metrics of comparison were RDR, reliability, and harvest time. Red drupelet reversion (RDR) was the percentage of 60 berries that had RDR after they were harvested and stored in clamshells (20 berries/clamshell) at 2 °C for 21 days. Reliability was the number of berries harvested, in this case 60 per test, divided by the total number of harvesting attempts. The harvest time refers to the amount of time required to approach a berry, grasp it, remove it from the plant, and place it in a nearby clamshell.

In the force feedback tests, RDR and reliability were proportional to the desired fingertip contact force, while harvesting time was inversely proportional. This is to be expected. With a higher fingertip contact force, the normal component of the fingertip contact force increases, causing the frictional component of the force value to also increase. This results in a more stable grasp during the harvesting procedure, increasing reliability. However, because of a higher force being applied to the berry surface, the likelihood of RDR increases. This implies that there is an optimal fingertip contact force value that minimizes RDR while maintaining sufficient reliability. Nonetheless, in Test 3, where the fingertip contact force value was 0.78 N, the RDR was only 16%, with a reliability of 95.24%. It should be noted that the harvest time for the robot in Test 3 was ∼3.4 times slower than harvesting by hand. This is primarily due to the slow response time of the gripper's actuation procedure. Harvest time can be improved by tuning the PID gains to decrease response time. Additionally, in the current configuration, only the force at the fingertips is considered in the feedback loop. In future work, we will include berry diameter, which will allow the gripper to be closer to its desired task space configuration during placement, minimizing actuation time once the berry is in the workspace.

V. CONCLUSION

This letter presents a novel tendon-driven gripper for the harvesting of delicate, plant-ripened fresh-market berries, as well as objects used in ADL. Force feedback was provided through the implementation of a flexible resistive force sensor and an operational amplifier. As a result, each finger was able to apply a desired force as low as 0.50 N to as high as 1.45 N with an average error of 0.046 N. Field harvesting tests indicated that this gripper can perform comparably to manual harvesting, with RDR as low as 0%. It was found that reliability and RDR increase proportionally due to the coupled nature between fingertip contact force and berry damage. In our future work, we will perform further testing to identify an optimum fingertip contact force that maximizes reliability while minimizing RDR. All force feedback levels maintained a harvesting speed of under 9 seconds per berry, where improvements can be made by 1) further tuning of the PID gain values to increase the system response time as well as 2) optimizing the home position of each finger prior to gripping.

Future work includes mapping joint space force to task space force, i.e., estimating fingertip force indirectly by measuring the tension in the tendons to reduce potential berry damage caused by the plastic cylindrical force sensor supports attached to the gripper's fingertips [35]. We will also optimize the fingertip geometry to enable efficient grasping and dexterity. Additionally, the gripper's response to external forces, such as canes and leaves, will be investigated to develop a more robust system. The end goal will be to attach the gripper to a custom-made mobile robot chassis that utilizes simultaneous localization and mapping to autonomously harvest blackberries using the integration of novel image processing into the system.

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