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A Hybrid Three-Finger Gripper for Automated Harvesting of Button Mushrooms

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Abstract: Button mushrooms (*Agaricus bisporus*) grow in multilayered Dutch shelves with limited space between two shelves. As an alternative to conventional hand-picking, automated harvesting in recent times has gained widespread popularity. However, automated harvesting of mushrooms faces critical challenges in the form of growing environment, limited spaces, picking forces, and efficiency. End effectors for picking button mushrooms are an integral part of the automated harvesting process. The end effectors developed so far are oversized, bulky, and slow and thus are unsuitable for commercial mushroom harvesting applications. This paper introduces a novel three-finger hybrid gripper with rigid and soft parts, specifically designed for harvesting button mushrooms in automated systems even on narrow shelves. It discusses the design, fabrication, force analysis, and picking performance of the gripper in detail for both individual and clustered mushrooms. The results indicate that the gripping force depends on mushroom density and size. The inclusion of textured soft pads on gripper fingertips performs better compared with plain soft pads by reducing force by up to 20% and improving picking time. The gripper achieved a 100% picking success rate for single-grown mushrooms and 64% for clusters, with reduced picking times compared with existing end effectors. However, harvesting clustered mushrooms led to increased damage, suggesting the need for future improvements.

Keywords: automated harvesting; end effectors; hybrid gripper; electro-mechanical systems

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1. Introduction

The button mushroom (*Agaricus bisporus*) is a popular edible fungus extensively cultivated globally in a controlled environment. It has two common color variations, namely, white and brown, commercially available in the market. These mushrooms are low in calorie, fat, cholesterol, and sodium levels; however, they offer rich nutritional value through their high dietary fiber, protein, vitamins, and essential mineral contents like copper, manganese, selenium, and zinc [1]. Mushroom harvesting generally refers to picking a mushroom from the bed, cutting the stem, and collecting the caps. Recent studies have shown that the discarded stem also offers good nutritional value in the form of protein and fiber [2]. Furthermore, dry stem powder can be utilized in various applications like animal feed [3]. Because of their exceptional nutritional benefits and texture, they are gaining more popularity, especially among fitness enthusiasts and vegetarian people. According to the 2023 report by Global Market Insights, the global market for button mushrooms is USD 25 billion with a CAGR (compound annual growth rate) of 6.6% [4]. In 2022, button mushrooms contributed to 80% of the total mushroom consumption in

the world [4]. The traditional harvesting practice involves skilled human workers hand-picking mushrooms, cutting the stem, and sorting the mushroom caps based on their sizes. However, the labor-intensive nature of this work, along with labor shortages and rising expenses, negatively impacts the profitability of the mushroom harvesting industry. Therefore, in recent times, several research works have been conducted on automated mushroom harvesting as a potential alternative to manual harvesting.

One of the critical components of the automated harvester is the end effector. The end effector is attached to the manipulator and is responsible for grabbing a mushroom, picking it from the growth bed, and securely holding the mushroom while transporting it to the collector. Many end effectors are available both commercially and in the literature that are designed to pick up soft organic objects like fruits and vegetables [5–7]. Although some of these end effectors have also been experimented on mushrooms, they are not suitable for commercial mushroom harvesting mostly because of the following three reasons: the nature of mushroom growth pattern, the growing environment, and picking performance. In commercial mushroom production, mushroom beds are arrays of multi-level Dutch shelves made up of wood or aluminum. For traditional wooden shelves, the average gap available between the mushroom cap and ceiling is 170 mm, and for aluminum shelves, it is 280 mm, as shown in Figure 1 [8]. The dimensions for the wooden shelves are considered regarding the mushroom farm studied in this project. These shelves offer very limited space for the manipulator and the end effector during harvesting. Some of the aluminum shelves can be designed to accommodate the gantry that runs through the rails on the shelves. However, they are expensive and very difficult to establish in already existing farms [9]. The average picking time for a skilled human worker for a single mushroom is 3 s [10]. Thus, another critical challenge in the end effector design is to match the picking time with a similar success rate compared to a human picker.

Most end effectors used in mushroom harvesting are either vacuum suction cups or grippers. Vacuum cups use negative pressure actuation to grab a mushroom at the top. These end effectors are effective in picking most of the mushroom as they hold the mushroom from its exposed cap [10,11]. Although these end effectors do not cause instant injuries, bruises are reported after a few days of picking as they require significant force to hold the mushroom [11]. They also need a sophisticated actuation mechanism, which makes the overall mechanism bulky and slow. These end effectors rely on bending and twisting mechanisms to pick the mushroom, which may not be possible if the neighboring mushrooms are too close [10–14]. Therefore, the use of a finger-like gripper structure has been at the center of research in recent times. Most of these gripper mechanisms are inspired by the analysis of the hand-picking method [15]. This includes three-finger gripper mechanisms that mimic the thumb, index, and middle finger used by a human picker to pick mushrooms. Gripper research works are mostly focused on developing soft grippers and a combination of rigid and soft parts [6,8]. A three-finger grasper was developed to pick shiitake mushrooms; however, it was not reported whether this grasper worked well in the picking environment of button mushrooms [16]. The primary objective of soft grippers is to develop a flexible structure that can conform to the shape and size of a mushroom, while the softness also provides a cushion against potential damages. These types of soft grippers are slow and cannot exert sufficient force to pick a mushroom [8,15,17]. The rigid–soft gripper has a standard rigid shape that provides mechanical support; however, it also uses soft pads to provide cushioning to the mushroom to avoid injuries.

The grippers developed so far in this category are mostly closed grippers that work for mushrooms of limited size, and the actuation mechanism is also complicated [6,8]. Some of these are too big to use with multi-level shelves [11,12,15]. There are also studies that focus on two-finger grippers as a potential solution [18]. These research works focus on the analytical performance of the gripper and not its actual picking performance. Some of the works were performed on the gripper used to pick a specific stage of a mushroom, like bud thinning, which was incapable of picking fully grown mushrooms [19]. All grippers grab a mushroom from multiple sides with their fingers or closed structure to securely hold

the mushroom. However, they fail to pick a mushroom when the mushrooms are close to each other and grow in a cluster. At the current stage of mushroom harvesting, there is an urgent need for a gripper that is lightweight, compact, fast, and can also pick from a cluster.

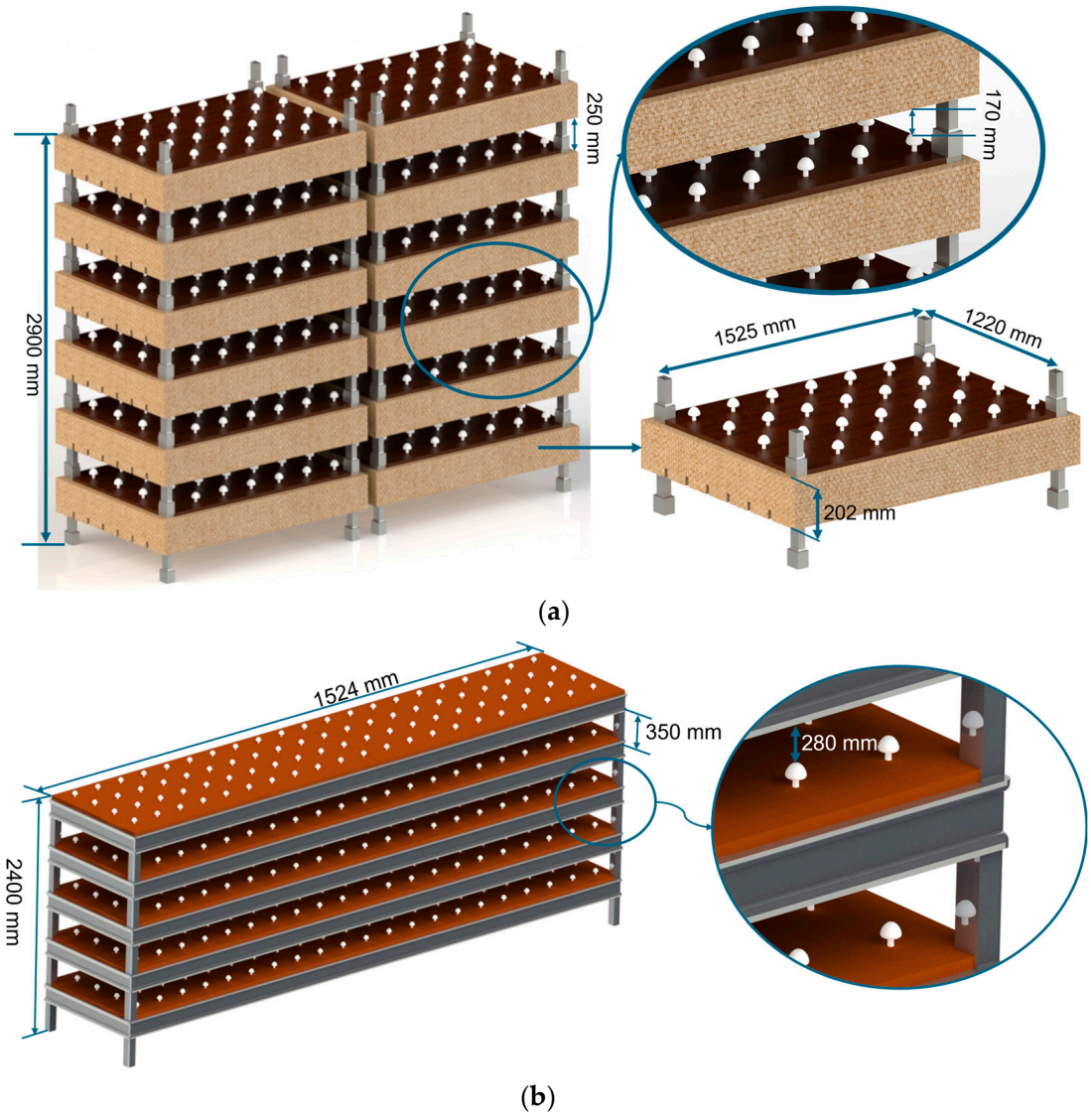


Figure 1. Model and dimensions of Dutch shelves for mushroom growing: (**a**) wooden shelves and (**b**) aluminum shelves.

In this paper, we present the design details, force analysis, and picking performance of a compact gripper, as well as a comparison with the existing end effectors. This is a type of three-finger hybrid gripper with rigid and soft parts.

2. Materials and Methods

2.1. Analysis of the Mushroom-Picking Mechanism

The mushroom-picking method involves applying either or all the following forces on the mushroom cap: bending, twisting, and lifting, as shown in Figure 2. In the conventional hand-picking method, a worker uses the combination of the thumb, index, and middle finger to apply these forces. The correct application of these forces depends on the mushroom's size, orientation, and growing environment. A lifting mechanism is a must to pick the mushroom up and transfer it to the collector.

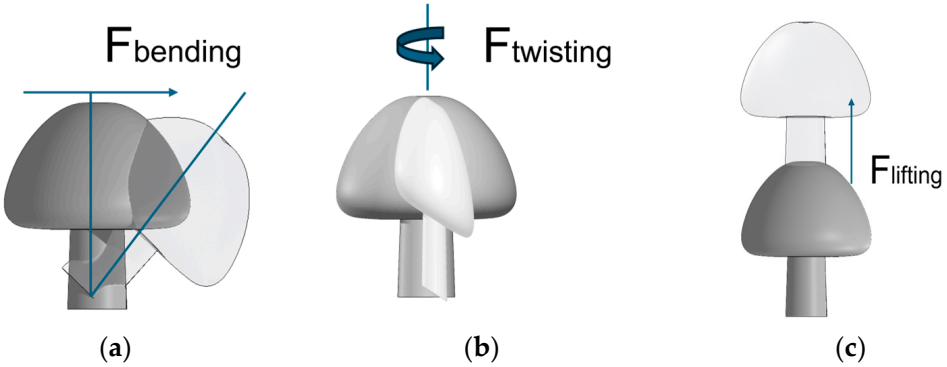


Figure 2. Mushroom-picking methods using different forces: (**a**) bending, (**b**) twisting, and (**c**) lifting.

However, the other two mechanisms (bending and twisting) depend on the gripper's design, the actuation method, and mushroom growth conditions. Especially, when picking from a cluster, the gripper does not have space to apply the twisting and bending motions, as this would cause dislocation of the neighboring mushrooms or even injuries. In such a case, the picking must be performed using the lifting process. The force required to grip and pick the mushrooms was taken from previous studies on mushroom end effectors using vacuum suction cups and finger grippers. Also, the total thickness of each gripper finger was minimal so that the fingers could go inside the cluster even with little space.

2.2. Mushroom Growing Environment

A commercial mushroom farm was studied to understand the picking environment and the constraints that need to be considered in the design. The shelf dimensions, mushroom heights, clusters, and single-grown mushroom size, shape, and orientation were also studied, as shown in Figure 3. For this design, the wooden shelf dimensions were considered as they have much less space available and pose more challenges. Room temperature and moisture level were also taken into consideration as these might affect the materials, electronics, and sensors used in the gripper. The average operating temperature and moisture level were recorded as 60–70 F and 90% RH, respectively. The mushrooms were categorized as small, medium, and large if their cap diameter was less than 37 mm, between 37 and 61 mm, and larger than 61 mm, respectively.

2.3. Gripper Design

Mushroom caps are irregular and different in shape and cannot be generalized. Therefore, for each size category, multiple mushroom CAD models with different shapes were implemented. The gripper finger curvature was designed to have a maximum contact surface on different mushroom cap shapes and sizes modeled in CAD.

The gripper has three circular and symmetrical fingers; however, these fingers are not designated as a thumb, index, or middle finger, unlike the other grippers mentioned in the literature. Each of these fingers can work independently with the help of one servo motor because when the space is limited, only two fingers must be used.

In this hybrid gripper, the finger is the rigid part that provides mechanical strength and support, while the soft pad is also attached to the interior side of the finger to provide cushion during mushroom gripping. For the soft pad, both plain and irregular textured profiles were studied to understand the gripping performance, as shown in Figure 4. On the top of the soft pads, force-resistive sensors (FSRs) are installed to measure the gripping force and to control the servo motor motion. Figure 4 shows the CAD design of the gripper, its dimensions, the finger profile, and soft pads.

For this project, the gripper was analyzed using only the lifting mechanism to examine the possibility of using just one mechanism to pick mushrooms. Hence, a slider–crank mechanism was also designed to lift the gripper set in the vertical direction. The target location was performed manually by moving the gripper above the target mushroom.

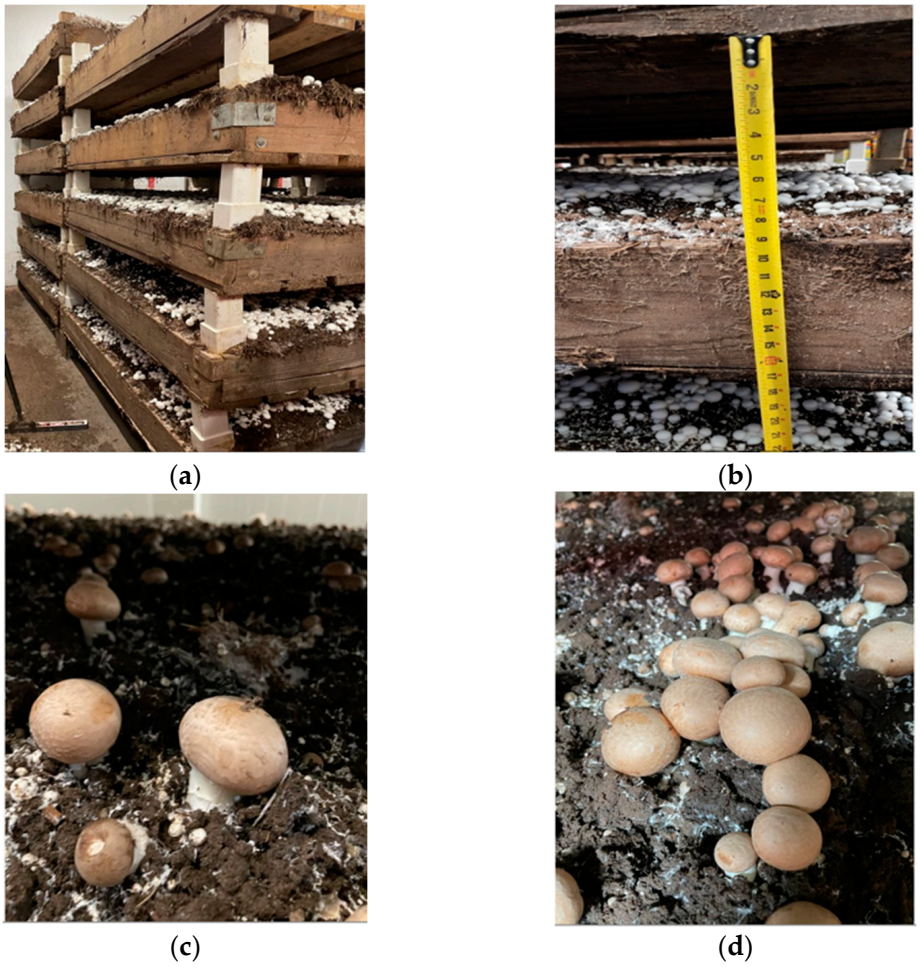


Figure 3. Images of the mushroom growing environment taken in the mushroom farm: (**a**) wooden shelf arrangement, (**b**) clearance between wooden shelves, (**c**) a single-grown mushroom, and (**d**) a cluster of mushrooms.

2.4. Gripper Analysis

At a point of contact, P, on the mushroom cap, three fingers may apply different forces given by F_1, F_2, and F_3. In this analysis, only F_1 is considered because the effect of the other two forces is similar. The force applied is from the servo motor rotation at angle θ with respect to a horizontal on a fixed-point O, as shown in Figure 5a. This fixed point can be considered at the root on the soil or at the point of contact between the stem and cap, as shown in Figure 5a. The horizontal components of this force, $F_1 \times Cos\ \theta$, is responsible for the gripping, bending, and twisting actions; however, this component also causes dents and bruises on the mushroom. The vertical component, $F_1 \times Sin\ \theta$, acts in the opposite direction of the lifting force and adds up the weight component, which must be compensated in the lifting force. This also causes dislocation, breaking, and damage to the mushroom.

The moments caused by these two components of force in the horizontal and vertical directions on the mushroom (M_{H1} and M_{V1}) are given in Equations (1) and (2), respectively.

$$M_{H1} = d_1 \times F_1 \times Cos\ \theta, \tag{1}$$

$$M_{V1} = r_1 \times F_1 \times Sin\ \theta, \tag{2}$$

where d_1 is the vertical distance from a fixed-point O to the point of contact P, and r_1 is the horizontal distance from O to P.

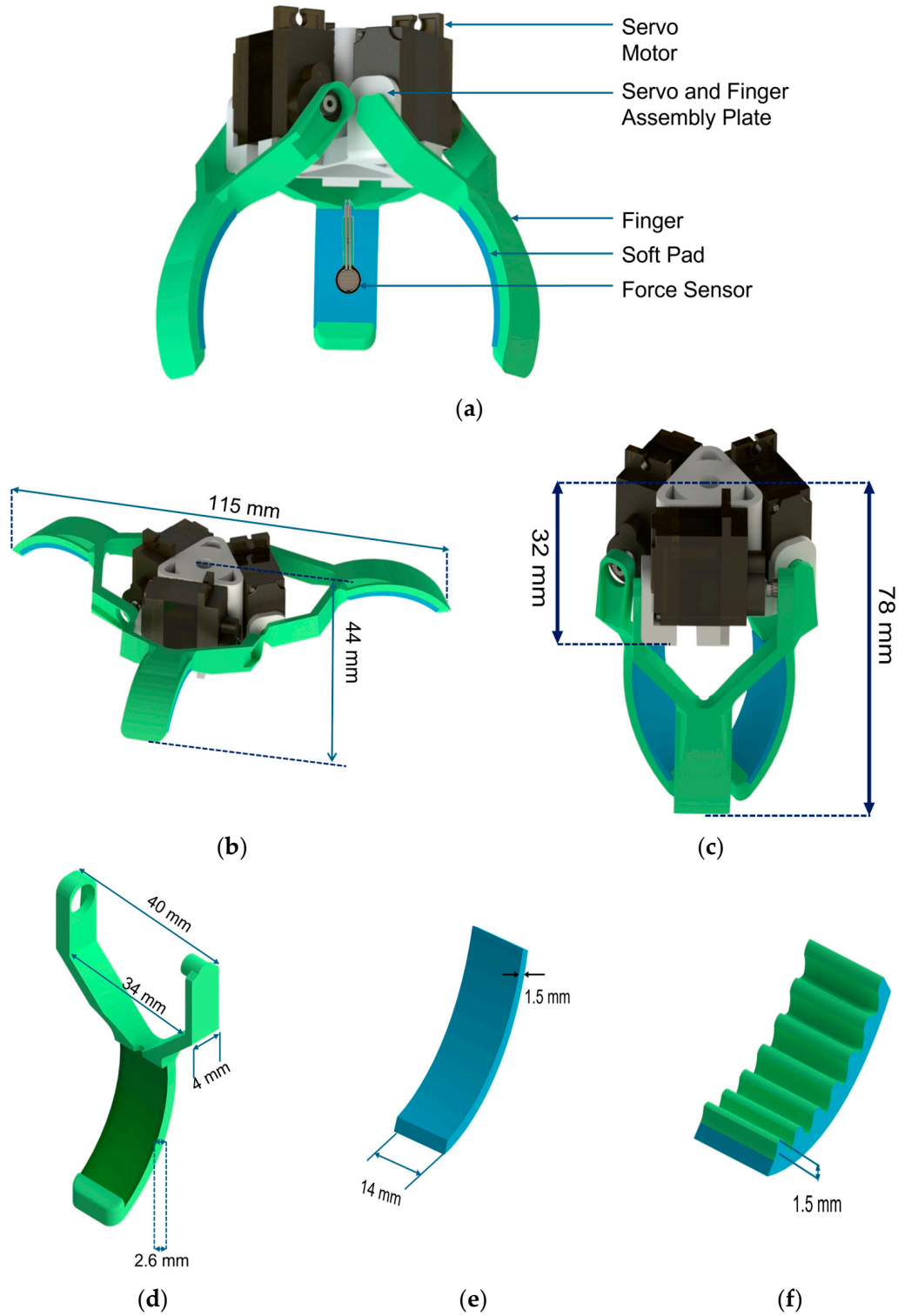


Figure 4. CAD model of the gripper: (**a**) assembled gripper, (**b**) fully open fingers, (**c**) fully closed fingers, (**d**) finger design, (**e**) plain soft pad, and (**f**) textured soft pad.

These moment equations show that as the distance in both the vertical and horizontal directions from a fixed-point O increase, the effect of moment is more significant. This means that the force for different categories of mushrooms must be different to minimize the effect of moment. Similarly, on the gripper, the horizontal component of force acts as a compression force. This compressive force is absorbed by the soft pads and has a minimum effect on the rigid part of the gripper and the gripping force. However, the

moment generated by these rectangular components must be considered in the selection and programming of the servo motors.

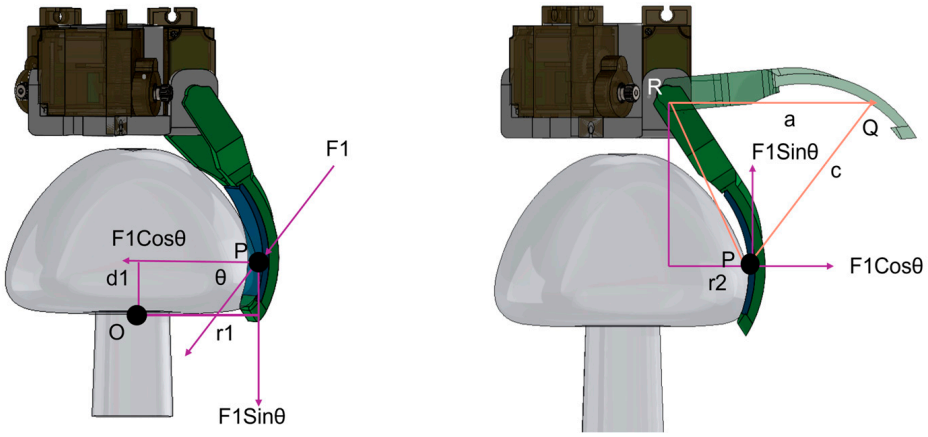


Figure 5. Force diagram: (**a**) force exerted by the gripper on a mushroom contact point and (**b**) the reaction force on the finger contact point.

The moment components in the horizontal and vertical directions accounts for the torque applied from the servo motor at point R, as shown in Figure 5b.

$$M_{H2} = d_2 \times F_1 \times Cos\,\theta, \tag{3}$$

$$M_{V2} = r_2 \times F_1 \times Sin\,\theta, \tag{4}$$

$$M = \left[(M_{H2})^2 + (M_{V2})^2\right]^{1/2}, \tag{5}$$

where M is the total moment; the motor must apply force F_1. Here, the friction factors and motor inconsistency are not considered.

The transient analysis for a gripper finger was performed in Ansys to verify the stress and deformation throughout the gripping time. The CAD modeled from Solidworks was imported into Ansys and necessary boundary conditions were imposed. A gripping force varying over time at the point of contact with the mushroom was applied, and maximum deformation and stress were analyzed using finite element analysis. Figure 6 shows the variable force with respect to time, stress, and deformation over time. The figure shows that the soft pads do not transfer significant stress to the gripper; moreover, the deformation is negligible. The material properties of PLA and the silicone soft pad are shown in Table 1.

Table 1. Material properties of PLA and silicone rubber used in the gripper analysis.

Material	Density [g/cc]	Tensile Yield Strength [MPa]	Modulus of Elasticity [GPa]	Poisson's Ratio
Polylactic acid (PLA) [20,21]	1.3	15.4	2.1	0.35
Silicone rubber [22]	1.23	10.4	0.0167	0.47

2.5. Materials and Fabrication Methods

The CAD model of all the parts was designed using SolidWorks, including the mushroom models of different sizes and shapes and soft pads. MG90S servomotors were used to control the fingers. The speed and stall torque at 5 V for this servo motor were 0.12 s per 60° at no load and 6.5 Kgf·cm, respectively. The maximum torque was 9 Kgf·cm at 8.4 V with a speed of 0.07 s per 60°. Even at 5 V, this torque was enough to apply the gripping force

discussed in Section 2.4. A RP-C resistance type force sensor was used to measure force and control the servo motors. These force sensors can be used in the mushroom growing environment discussed in Section 2.2. The force sensors were calibrated and installed on the soft pads at various forces. The Arduino voltage and force relationship for forces larger than 2 N was established, which was later used to calculate the gripping forces mentioned in Section 3. Equation (6) shows the linear relationship between the Arduino voltage drop and gripping force for forces larger than 2 N. Smaller forces were not considered as the forces were not strong enough to pick the mushrooms. The equation was established using linear regression with an R-squared value of 0.97. The test was performed in a controlled temperature and humidity environment, as discussed in Section 2.2.

$$Force = 3.3 \times Voltage - 5.45, \quad (6)$$

For the soft pads, platinum crystalized silicone rubber, Smooth-on Ecoflex 00-50, was used. The material is soft, strong, and bio-friendly, and it is commonly used in prosthetics. The fingers, servo motor housings, and lifting mechanism parts were 3D-printed using PLA (polylactic acid) material. The mushrooms used in the experiments were mostly fresh mushrooms from the farm and market. However, sponged dummy mushrooms were also used during the preliminary tests. Standard weights were used to counter the lifting force. Arduino was used as a controller to control the servo motors as well as force sensor readings. After the force sensor was calibrated, a threshold gripping force was set as a reference to control the servo motors. The weight and cost of all the gripper parts are summarized in Table 2.

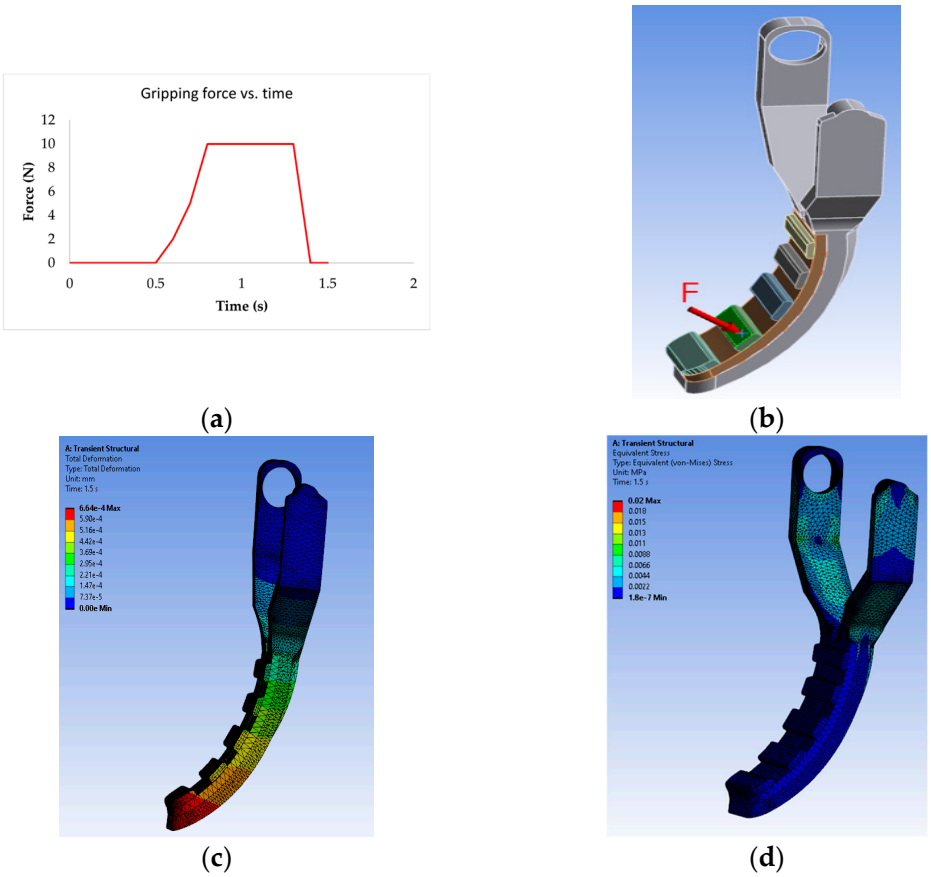


Figure 6. Deformation and stress analysis of the gripper finger at a variable load against time: (**a**) gripping force vs. time, (**b**) application of force on the gripper, (**c**) total deformation, and (**d**) equivalent stress.

Table 2. Weight and cost details of parts used in the gripper.

Parts	Weight (gm)	Cost (USD)
Motor housing	11.2	0.22
Servo motors	41*3	8.2
Fingers	4.2*3	0.25
Soft pads	0.8*3	0.1
Force sensors	-	12.5
Total	164.2	21.27

The weight and cost information for the 3D printed parts were calculated using Creality slicer software v5.1.1.9490. The print quality and infill density were 0.1 mm and 50%, respectively. The cost of servo motors, ecoflex, and force sensors were taken from Amazon.com (accessed on 12 June 2024) [23–25].

3. Results

3.1. Calculation of Gripping Force F_1

The gripping force analysis test was performed on white button mushrooms using both single-grown and cluster mushrooms to find the safe force the gripper needs to apply to securely hold the mushroom while picking and transporting it to the collector. Twenty single-grown mushrooms and a cluster of 10 mushrooms were tested. For single-grown mushrooms, only vertical upright mushrooms were tested, and the inclination of the mushroom at any other angle was not considered. The gripper with soft pads, both plain and with irregular texture, was tested on mushrooms of different size categories. Forces from each gripper were applied at the increment of 1 N until the gripper successfully picked the target mushroom. The success rate was defined as the ratio of total successful picks to the total attempts without considering mushroom damage. For the cluster-grown mushrooms in a limited space, only two fingers were used to pick the mushroom, while all three fingers were used to pick single-grown mushrooms, as shown in Figure 7.



(**a**) (**b**)

Figure 7. Mushroom picking: (**a**) a single-grown mushroom and (**b**) a cluster-grown mushroom.

3.1.1. Gripping Test with Plain Soft Pads

For single-grown mushrooms, no mushrooms could be picked at <2 N force. At 2 N, the gripper could hold the mushroom; however, it failed while picking or lifting the mushroom. The gripper was able to pick some mushrooms at 3 N force, and the success rate increased with increasing force. At 3 N and 4 N forces, the gripper could not hold the mushroom securely against small disturbances like bending and twisting. However, at 5 N, all mushrooms were successfully picked. In contrast, for the cluster mushrooms, the gripper had zero success until 5 N force. At 5 N, the gripper had a small success rate, and all the

target mushrooms were successfully picked at 7 N force. Even though all the mushrooms were picked successfully with this force, many mushrooms were injured during the picking process. The gripping force vs. success rate for single-grown and cluster mushrooms is shown in Figure 8a. Since only two fingers were used to pick cluster mushrooms and the target mushroom was sandwiched between the neighboring mushrooms, the gripping force required from each gripper was slightly high. Although the total force required to pick a cluster mushroom successfully was slightly less than the force required to pick a single-grown mushroom, the gripping force was not significantly different. Single-grown mushrooms have a better connection with the base. Moreover, the neighboring mushroom may be dislodged while picking a mushroom from a cluster. Therefore, the total gripping force to pick a cluster mushroom was slightly less than picking a single-grown mushroom.

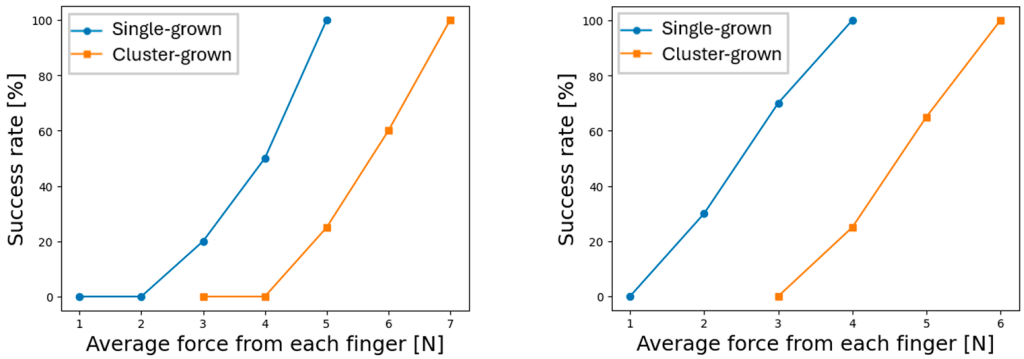


Figure 8. The success rates of picking mushrooms at different gripping forces using (**a**) plain soft pads and (**b**) textured soft pads.

This analysis shows that the gripper force F_1 must be different while picking single-grown mushrooms and from cluster mushrooms. Although 7 N force can pick both types of mushrooms, there are chances of minor injuries, as seen during the picking of cluster mushrooms. Therefore, a different threshold must be set for the force sensor for these two categories.

3.1.2. Gripping Force with Irregular Textured Soft Pads

With the irregular textured soft pads, the gripper showed better grip compared with the plain soft pads. For the single-grown mushrooms, the gripper had a good success rate even at 2 N force. None of the mushrooms were damaged. At 4 N force, the gripper was able to pick all the target mushrooms. Even for cluster mushrooms, the gripper picked up some mushrooms at 3 N force, and at 5 N force, all the mushrooms were picked. However, there were also injuries to the mushrooms while picking from a cluster. This shows that the surface texture of the soft pads plays a great role in improving gripping performance. Using a smaller force can also reduce injuries. The force vs. success rate for single-grown and cluster-grown mushrooms using a textured soft pad is shown in Figure 8b.

3.1.3. Mushroom Damage Analysis

A force analysis test was conducted on real mushrooms to determine the range of forces that cause severe damage and minor injuries and allow safe handling. In this test, single mushrooms were tested against gripping only, and lifting, bending, and twisting mechanisms were not considered. Moreover, only single-grown mushrooms were tested, as cluster mushrooms can be damaged even at a smaller force and thus do not represent the accurate mushroom damage resistance against the gripping force. Over a hundred mushrooms, varying in size from 1 inch to 3 inches in diameter, were tested to assess how size affects the applied force. Each gripper's force data were recorded, noting the maximum and minimum forces exerted.

For white button mushrooms of any size, a force below 9 N from each gripper finger did not cause any damage based on visual inspection. Larger mushrooms began showing minor dents, particularly gripper marks on their caps, at 10 N. As the applied force increased, both the percentage and severity of damaged mushrooms increased. Above 14 N, all the large mushrooms tested were completely damaged.

Medium-sized mushrooms showed slightly better resistance, showing minor dents and bruises at 12 N, with only a few damaged. However, damage to medium mushrooms increased significantly after 15 N, with all being damaged at 16 N. On the contrary, only 20% of the small mushrooms showed defects at 13 N. At 18 N, all mushrooms, regardless of their sizes, were completely crushed. Severe damage occurred to all mushroom sizes above 18 N. This shows the size and force dependency of the mushroom, and during gripping, the force must not exceed 9 N. The damage rate vs. gripping force is shown in Figure 9.

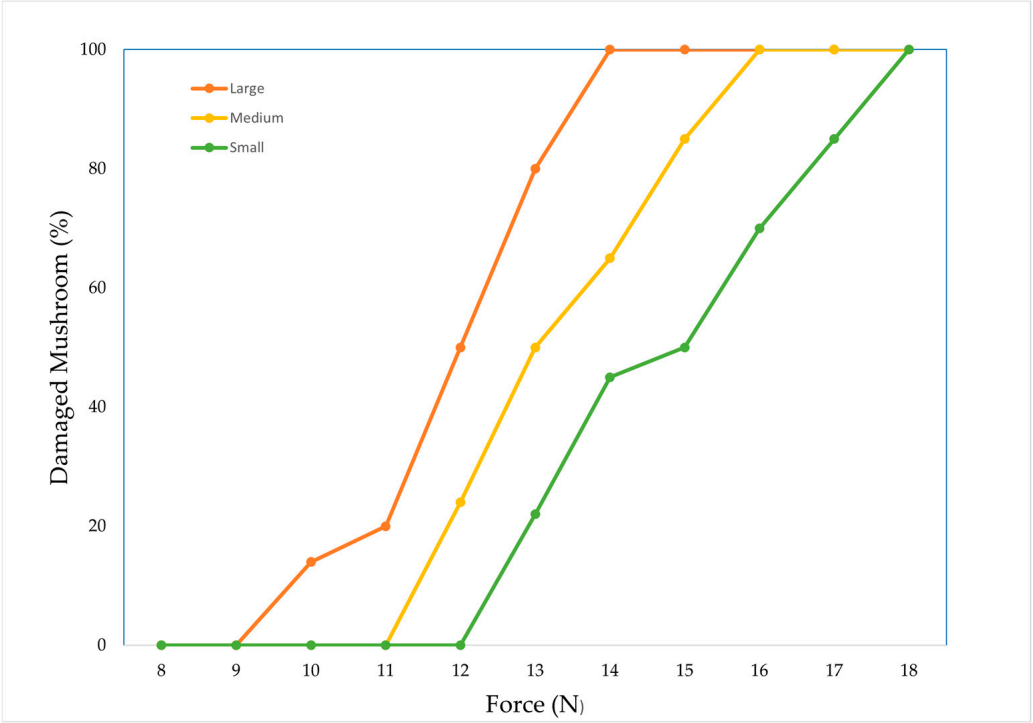


Figure 9. Force resistance against damage for different sizes of mushrooms.

Mushrooms of various sizes (15 large, 15 medium, and 15 small) were visually inspected and analyzed under different force magnitudes to determine the force levels that cause damage. At lower forces, defects primarily included gripper marks, dents, and discoloration. At higher forces, mushrooms either cracked or were completely crushed. Different damages against the gripping force are shown in Figure 10. Smaller mushrooms exhibited greater resistance to gripping force on their caps, likely because of their more compact shape and the reduced distance of the cap edge (or contact point) to the stem (fixed point), which helps distribute the force. The stem also acts as a support, transferring force to the bed. Additionally, larger mushrooms are typically older and have remained in the mushroom bed longer. During the harvesting cycle, very small mushrooms are left to grow into larger ones for the next harvest. In contrast, smaller mushrooms are relatively young and healthier.

3.2. Harvesting Performance

Harvesting performance was analyzed based on picking time and the mushroom damage rate. The net picking time discussed here is the average time taken by the gripper to grip and uproot a mushroom. The time the gripper takes to reach the target mushroom

and bring the mushroom to the designated area or collector is ignored here as it depends on the manipulator used and does not give the gripper speed. The damage rate is the percentage of the number of mushrooms damaged among the total mushrooms picked.



(**a**) (**b**) (**c**)

Figure 10. Different damages seen on a large mushroom at various forces: (**a**) dents from the gripper finger at 10 N, (**b**) cracks at 12 N, and (**c**) crushed at 14 N.

Harvesting was performed using both types of soft pads, i.e., plain and textured, on single-grown and cluster-grown mushrooms. For single-grown mushrooms, all three fingers of the gripper were used to grab the mushroom, while for cluster-grown mushrooms, depending on space availability, only two fingers were used. Table 3 summarizes the comparative picking results. From earlier experiments, the gripping forces required to successfully pick a mushroom using a plain soft pad were 5 N and 7 N for single-grown and cluster-grown mushrooms, respectively. Using the textured soft pads, the gripping force required was 4 N and 5 N for single and cluster mushrooms, respectively. The net picking time with plain and textured soft pads was 1.5 s and 1.2 s, respectively. The textured soft pad gripper was slightly faster at picking as it had a better grip on the mushroom cap.

Table 3. Comparative picking performance of the gripper using plain and textured soft pads.

Soft Pad Type	**Single-Grown**			**Cluster-Grown**		
	Gripping Force [N]	**Picking Time [s]**	**Damage Rate [%]**	**Gripping Force [N]**	**Picking Time [s]**	**Damage Rate [%]**
Plain	5	1.5	0	7	3	40
Irregular textured	4	1.2	0	6	2.8	36

For the cluster mushrooms, with 7 N gripping force and the plain soft pad, the damage rate was 40%. While the damage rate improved slightly to 36% with the textured soft pad, the damage was still significant, suggesting further gripper design improvements for cluster mushrooms. This was evident in the net picking times of 3 s and 2.8 s for the plain and textured soft pad grippers, respectively. The damage to clustered mushrooms varied from displacing adjacent mushrooms to causing minor or major injuries to neighboring mushrooms, as well as minor bruises on the picked mushroom itself.

4. Discussion

The optimal gripping force for mushroom caps depends on factors such as their size, density, and the design of gripper fingers. Utilizing irregular textured soft pads on the gripper fingers enhances gripping performance and reduces the required gripping force by 20% across various mushroom types. This approach also enhances picking quality by minimizing mushroom injuries and absorbing reaction forces during gripping. Previous experiments with soft grippers, and those incorporating both rigid and soft components, have shown similar outcomes. For instance, Galley A. et al. [6] achieved a 100% success rate using 2 mm thick concave PDMS soft pads during gripping tests. Recchia et al. improved picking performance by employing various shapes and thicknesses of compression slots on

the fingertips to improve picking performance by enhancing compression resistance [8]. Additionally, Mbakop et al. [15] utilized a ribbed finger structure made of soft material to achieve over a 90% success rate in picking. All these results highlight the role of soft pads and the structure of soft pads. This demands further research on soft pad designs to improve performance further.

Large mushrooms are more susceptible to damage as their point of contact is far from the fixed connecting point (stem or at the root), and they are also relatively old. This limits the gripping force to pick up the mushroom. The gripping force of 6 N was proven to pick up all single-grown mushrooms without any damage and most of the cluster mushrooms. To improve the harvesting performance of cluster mushrooms, the current gripper needs improvement in the mechanical design and additional mechanisms. An additional mechanism on the manipulator to orient the gripper in the direction of the mushroom orientation can make picking much easier and can eventually improve cluster mushroom harvesting. Although we do not know of any studies that discuss cluster mushroom harvesting in detail, Mavridis et al. highlighted the importance of considering mushroom orientation in their harvester design. This shows a significant research gap on cluster mushrooms and leaves plentiful space to explore in future works.

Regarding picking time, the net picking time of 1.2 s for single-grown mushrooms is comparable to the human picking time mentioned in the experiment by Huang et al. [10]. This result is slightly better than the picking time with other end effectors like the vacuum suction described by Huang et al. with a picking time of 1.7 s with the bending mechanism. The comparative performance of different end effectors is summarized in Table 4. Mbakop et al. and Recchia et al. tested a smaller gripping force; however, the picking time and success rate were not as good and not explored, respectively [8,15]. Vacuum suction cups have achieved an impressive success rate, but the pressure applied is very high, which can damage the mushroom.

Table 4. Comparison of the performance of various mushroom-picking end effectors.

End Effector Types	Authors [Ref]	Gripping Force (Pressure) [N/KPa]	Picking Time [s]	Success Rate	
				Single-Grown [%]	Cluster-Grown [%]
Conventional hand picking	Huang et al. [10]	4 N	3 s	100	100
Vacuum suction	Huang et al. [10]	172 KPa	1.7	100	-
	Yang et al. [12]	9.3 N	3.5	88.2	-
	Zhao et al. [13]	9.2 KPa	-	98.5	-
Soft gripper	Mbakop et al. [15]	1 N	3	85	-
Closed gripper	Galley et al. [6]	18 N	-	-	-
	Recchia et al. [8]	3 N	-	-	-
Three-finger gripper	This work	6 N	1.2	100	64

The impacts of bending and twisting mechanisms were not explored, and these may improve the picking performance as well. As discussed earlier, the geometrical features of the gripper and soft pads can also be improved to enhance harvesting performance. Nevertheless, the gripper discussed in this paper is a better solution with a faster picking time, less force, and an excellent success rate. The results for cluster mushrooms can be improved by incorporating bending and twisting mechanisms. Picking a mushroom with the stem will also be explored in the future.

5. Conclusions and Future Works

A compact hybrid three-finger gripper model with rigid or soft pads was developed for the efficient picking of button mushrooms. Different mushroom harvesting constraints

like growing environment, picking force, size, and picking time were analyzed in detail. The gripper was also tested on cluster mushrooms, and its performance analysis was presented. The key findings of this work can be summarized as follows:

1. A compact lightweight gripper, 44 mm in height and 80.2 g in weight, was designed to accommodate the smallest mushroom shelf. A low-cost and fast gripper was presented, which can be used with any type of manipulator.
2. Compared with plain soft pads, using irregular textured soft pads reduced the gripping force and picking time by 20% for single-grown mushroom picking. For a cluster-grown mushroom, the irregular textured soft pad required 17% less force and was 6.7% faster. A detailed study on soft pads can improve the results further.
3. The gripping force depended on the mushroom's size and density. A force of more than 10 N damaged larger mushrooms, and the safe force to pick both single and cluster mushrooms was 6 N with irregular textured soft pads. An impressive 100% success rate with 0 damage was recorded for single-grown mushrooms. For cluster-grown mushrooms, even with the safe force, a significant damage rate of 36% was observed.
4. For cluster mushroom picking, only two fingers were used when the space was limited. Although the total picking force for cluster mushrooms was less than for single-grown mushrooms, the damage rate was significant, which calls for further improvement.
5. The gripper performance with bending and twisting mechanisms was not studied. The picking performance on mushrooms aligned at an angle besides vertical was also not considered. Furthermore, mushroom picking along with the stem was not performed. These works will be explored in the future.

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References

1. El-Ramady, H.; Abdalla, N.; Badgar, K.; Llanaj, X.; Törős, G.; Hajdú, P.; Eid, Y.; Prokisch, J. Edible Mushrooms for Sustainable and Healthy Human Food: Nutritional and Medicinal Attributes. *Sustainability* **2022**, *14*, 4941. [CrossRef]
2. Banerjee, D.K.; Das, A.K.; Banerjee, R.; Pateiro, M.; Nanda, P.K.; Gadekar, Y.P.; Biswas, S.; McClements, D.J.; Lorenzo, J.M. Application of Enoki Mushroom (*Flammulina Velutipes*) Stem Wastes as Functional Ingredients in Goat Meat Nuggets. *Foods* **2020**, *9*, 432. [CrossRef] [PubMed]
3. Ibrahim, S.; Huda-Faujan, H.S. Potential Use of Underutilised Mushroom Stems in Meat Products and Meat Analogues: A Mini Review. *Malays. J. Sci. Health Technol.* **2023**, *9*, 147–152. [CrossRef]
4. Global Market Insights White Mushroom Market Size. Available online: https://www.gminsights.com/industry-analysis/white-mushroom-market (accessed on 12 June 2024).
5. Rajendran, V.; Debnath, B.; Mghames, S.; Mandil, W.; Parsa, S.; Parsons, S.; Amir, G.-E. Towards Autonomous Selective Harvesting: A Review of Robot Perception, Robot Design, Motion Planning and Control. *J. Field Robot.* **2023**, 1–33. [CrossRef]
6. Galley, A.; Knopf, G.K.; Kashkoush, M. Pneumatic Hyperelastic Actuators for Grasping Curved Organic Objects. *Actuators* **2019**, *8*, 76. [CrossRef]
7. Bachche, S. Deliberation on Design Strategies of Automatic Harvesting Systems: A Survey. *Robotics* **2015**, *4*, 194–222. [CrossRef]
8. Recchia, A.; Strelkova, D.; Urbanic, J.; Kim, E.; Anwar, A.; Murugan, A.S. A Prototype Pick and Place Solution for Harvesting White Button Mushrooms Using a Collaborative Robot. *Robot. Rep.* **2023**, *1*, 67–81. [CrossRef]
9. Mycionics Inc. System and Method for Autonomous Harvesting of Mushrooms. U.S. Patent 11,154,010, 26 October 2021.

10. Huang, M.; He, L.; Choi, D.; Pecchia, J.; Li, Y. Picking Dynamic Analysis for Robotic Harvesting of Agaricus Bisporus Mushrooms. *Comput. Electron. Agric.* **2021**, *185*, 106145. [CrossRef]
11. Huang, M.; Jiang, X.; He, L.; Choi, D.; Pecchia, J.; Li, Y. Development of a Robotic Harvesting Mechanism for Button Mushrooms. *Trans. ASABE* **2021**, *64*, 565–575. [CrossRef]
12. Yang, S.; Ji, J.; Cai, H.; Chen, H. Modeling and Force Analysis of a Harvesting Robot for Button Mushrooms. *IEEE Access* **2022**, *10*, 78519–78526. [CrossRef]
13. Zhao, K.; Li, H.; Ji, J.; Li, Q.; Li, M.; He, Y.; Li, J.; Xing, S. Pressure-Stabilized Flexible End-Effector for Selective Picking of Agaricus Bisporus. *Agriculture* **2023**, *13*, 2256. [CrossRef]
14. Rowley, J. Developing Flexible Automation for Mushroom Harvesting (Agaricus Bisporus): Innovation Report. Ph.D. Thesis, University of Warwick, Coventry, UK, 2009.
15. Mbakop, S.; Tagne, G.; Lagache, A.; Youcef-Toumi, K.; Merzouki, R. Integrated Design of a Bio-Inspired Soft Gripper for Mushrooms Harvesting. In Proceedings of the 2023 IEEE International Conference on Soft Robotics, RoboSoft 2023, Singapore, 3–7 April 2023.
16. Li, J.; Feng, Q.; Ru, M.; Sun, J.; Guo, X.; Zheng, W. Design of Shiitake Mushroom Robotic Picking Grasper: Considering Stipe Compressive Stress Relaxation. *Machines* **2024**, *12*, 241. [CrossRef]
17. Mbakop, S.; Tagne, G.; Frouin, M.H.; Achille, M.; Merzouki, R. Inverse Dynamics Model-Based Shape Control of Soft Continuum Finger Robot Using Parametric Curve. *IEEE Robot. Autom. Lett.* **2021**, *6*, 8053–8060. [CrossRef]
18. Porichis, A.; Vasios, K.; Iglezou, M.; Mohan, V.; Chatzakos, P. Visual Imitation Learning for Robotic Fresh Mushroom Harvesting. In Proceedings of the 2023 31st Mediterranean Conference on Control and Automation, MED 2023, Limassol, Cyprus, 26–29 June 2023; pp. 535–540.
19. Tao, K.; Wang, Z.; Yuan, J.; Liu, X. Design of a Novel End-Effector for Robotic Bud Thinning of Agaricus Bisporus Mushrooms. *Comput. Electron. Agric.* **2023**, *210*, 107880. [CrossRef]
20. Gaweł, A.; Kuciel, S.; Liber-Kneć, A.; Mierzwiński, D. Examination of Low-Cyclic Fatigue Tests and Poisson's Ratio Depending on the Different Infill Density of Polylactide (PLA) Produced by the Fused Deposition Modeling Method. *Polymers* **2023**, *15*, 1651. [CrossRef] [PubMed]
21. MatWeb Overview of Materials for Polylactic Acid (PLA) Biopolymer. Available online: https://www.matweb.com/search/DataSheet.aspx?MatGUID=ab96a4c0655c4018a8785ac4031b9278 (accessed on 9 July 2024).
22. MatWeb Overview of Materials for Silicone Rubber. Available online: https://www.matweb.com/search/DataSheet.aspx?MatGUID=cbe7a469897a47eda563816c86a73520&ckck=1 (accessed on 9 July 2024).
23. Amazon Miuzei MG90S 9G Micro Servo Motor Metal Geared Motor Kit for RC Car Robot Helicopter, Mini Servos for Arduino Project. Available online: https://www.amazon.com/Miuzei-Geared-Helicopter-Arduino-Project/dp/B0CP98TZJ2?th=1 (accessed on 12 June 2024).
24. Amazon Smooth-On Ecoflex 00-50 Platinum Silicone 2 Lb Kit. Available online: https://www.amazon.com/Smooth-Ecoflex-00-50-Platinum-Silicone/dp/B00GJ80HIC (accessed on 12 June 2024).
25. Amazon Thin Film Pressure Sensor 20 g–2 Kg DF9-16 High Precise Force Sensitive Resistor Force Sensor Pressure Sensor Resistance Type Thin Film Pressure Sensor Force Sensing Resistor. Available online: https://www.amazon.com/Pressure-Precise-Force-Sensitive-Resistor-Resistance-type/dp/B07T1CHY58 (accessed on 12 June 2024).

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