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Article

Design, Development and Testing of Feeding Grippers for Vegetable Plug Transplanters

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Abstract: Vegetable transplanting is an important and advantageous practice in vegetables production systems. In recent years, the development of vegetable transplanting tools has increased, as well as the interest for automatic and robotic transplanters. However, at present, the feeding of transplanting machines is often still performed by hand. This paper presents the design, development and testing of a needle gripper and a two-finger gripper for vegetable transplanting. Both grippers were self-designed and tested for picking, lifting and transplanting plug seedlings. Tests have been conducted on fennel (*Foeniculum vulgare* L.), leek (*Allium ampeloprasum* L.) chicory (*Cichorium intybus* L.) and lettuce (*Lactuca sativa* L.) seedlings to determine the impact that gripper typology might have on the further growth of plants after transplanting. The average success rate of the two-finger gripper in the transplanting experiment was 95% and of the needle gripper 81.75%, respectively. Although neither gripper typology affected the growth of the seedlings after transplanting, several design implications were identified in order to improve the performance of both grippers. Furthermore, the two-finger gripper is more reliable for lettuce and chicory, while the needle gripper requires root plugs with higher firmness and cohesion to prevent shattering.

Keywords: seedling transplanting; friction gripper; needle gripper; intrusive grasping; green cover analysis; plug-picking devices

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1. Introduction

Transplanting vegetables provides several benefits and improves the final yield. Manual transplanting requires a significant amount of labor and is not reliable since it is subject to human error [1]. Indeed, when transplanting is fulfilled manually, it usually leads to non-uniform spacing between seedlings [2]. Consequently, these field conditions make it difficult to implement other mechanical operations. Mechanized vegetable transplanting is a widely adopted solution and is fulfilled by vegetable transplanters. Vegetable transplanters are machines that efficiently and precisely transplant seedlings in various soil conditions [3,4], thus reducing the production cost [5,6]. Three categories of vegetable transplanters are reported: semi-automatic, automatic, and robotic [7]. Nowadays, semi-automatic vegetable transplanters are the most common solutions, and they require more than one person to control the whole transplanting process. With these machines, people are needed to move the transplanter and to feed seedlings into the mechanism [8]. Automatic transplanters refer to tailored or integrated machines that further reduce labor requirement by means of a seedling transfer unit consisting of a picking device [8–11]. These devices allow one to automatize the feeding process of the transplanter, thus providing for higher precision, accuracy and effectiveness [12]. Robotic vegetable transplanters refer to fully automized machines that do not need an operator to move through the field [13]. In both cases (automatic and robotic vegetable transplanters), work performance depends on the success rate of the picking device [7]. The design of picking devices depends on which mechanized transplantation technique a device must fulfil. Lastly, developed picking devices provide for a simultaneous seedling transfer on horizontal and vertical directions [13]. The main methods for transplanting seedlings developed in the last years include transplanting seedlings from plastic plug trays [11] and transplanting seedlings in biodegradable paper pots [14,15]. Therefore, two main categories of automatic transplanters were developed by researchers: plug seedling transplanters [13,16,17] and paper pot transplanters [18–21]. Focusing on plug seedling transplanters, picking devices consist of grippers approaching the tray cell and targeting the centre of the seedlings, then cautiously separating the whole plug from the tray [22]. Besides grippers for mechanical parts in technological and production applications, comprehensive research has also been conducted on grasping objects that have individual shapes, textures and types of softness [23–26] using different principles such as intrusion, Coanda, Bernoulli and thermal flow. Handled objects included but were not limited to textiles, leather, meat and fish, and fruits and vegetables. Grippers have further been applied in a wide variety of different agricultural settings. Most of these settings involve crop harvesting [27], with tentative work done also in plant phenotyping [28] and seedling grasping. However, few studies have been carried out to assess the best gripper design for automatic plug transplantation. To date, finger grippers [29,30] and sliding needle grippers [31–33] have been demonstrated to be the most successful.

Among the various plug seedling characteristics, root plug firmness and cohesion are considered the most important factors affecting transplantation success [34]. Retaining root soil during the transplantation process is crucial to avoid transplantation stress and to ensure further growth [14]. In addition, a good balance between the extrusion and adhesive forces acting on the root plugs results in an ease of extraction of plugs from the trays, which is crucial in the transplanters' feeding process [35]. The extrusion force refers to the force that the gripper uses to lift the root plug, while the adhesive force refers to the force exploited between the root plug and the plug cell inwall [35]. Jiang et al. [35] established a relationship between transplantation success rate and the two forces acting on the seedling plugs. Indeed, in order to have an optimal success rate, they found that the extrusion force should be in a range between six and eight times of the adhesive force. However, still little is known about the performance of these gripper typologies. Difficulties in seedling picking, holding and releasing processes as well as eventual seedling damage have been reported for both gripper typologies. Jiang et al. [35] state that finger grippers are not reliable when it comes to seedling picking and seedling holding during the transplanter feeding process. Instead, finger grippers showed high accuracy related to seedlings releasing. Choi et al. [36] developed a plug-picking device consisting of a pick-up pin and tested it under various operational conditions. The device functioning consisted of two-pins with a synchronous movement similar to the two-finger gripper developed for this trial. Choi et al. [36] found that the device was able to pick up 30 seedlings per minute, with a success rate of 97%. Needle grippers, instead, showed better performances when picking and holding seedlings and plugs compared to the finger grippers. However, these grippers have shown difficulties when it comes to release seedlings since plugs may stick to the needles [7]. Sun et al. [37] tested the performance of an end-effector with mechanical sliding needles, obtaining a transplanter success rate of 95.76% and a seedling damaging rate of 3.06%.

Thus, the situation among grippers design is still evolving, and a dominant design is far from being consolidated. This paper aims to evaluate performances of a sliding needle gripper and a finger gripper for automatic transplantation of vegetables and analyze the forces involved in the transplantation process. A prototype of each gripper typology was designed, developed and tested on four different species of vegetables. Forces involved in the detaching and lifting of seedlings, the transplantation success rate and eventual damage to the seedlings were assessed.

2. Materials and Methods

Three different trials were carried out. Trial 1 consisted of a punching experiment to detach the seedlings from the tray. Trial 2 consisted of a plug-lifting experiment. Trial 3 consisted of a plug-transplanting experiment. The three trials were performed on four different vegetable species: fennel (*Foeniculum vulgare* L. cv "Montebianco"), leek (*Allium ampeloprasum* L. cv "Belton"), chicory (*Cichorium intybus* L. cv. "Catalogna") and lettuce (*Lactuca sativa* L. cv "Dallas"). All the four species mentioned above are generally transplanted as usual practice in Italy both in small and large cultivation systems [38]. Seedlings were seeded in 160 cells polystyrene plug trays of 27.7 cm^3 volume per plug (inverted truncated cone: height 50 mm, top diameter 29 mm and bottom diameter 24 mm), and the trials were conducted with seedlings between three and five leaves growth stage. Cells were filled with a potting mix consisting of peat and perlite with a 70:30 ratio. Two different grippers were used in this study. Both grippers were entirely self-designed and built. Figure 1 illustrates the working principles of the two grippers.

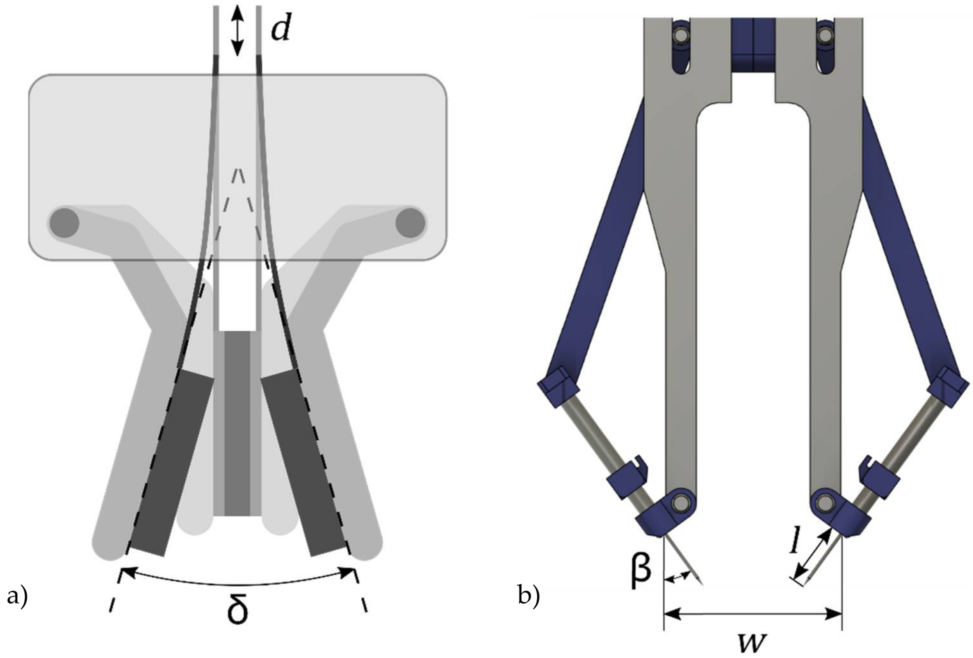

Figure 1. Gripper concepts: (**a**) two-finger; (**b**) needles.

The first gripper is a simple two finger gripper with synchronous finger movement (Figure 1, left). The closing angle (δ) of the gripper can be regulated through the lateral actuation (d). For a soft touch, the fingertips of this gripper are covered in polyurethane foam, which deforms when in contact with an object. The grasping force of the gripper increases with the deformation of the foam. The second gripper is a needle gripper (Figure 1, right). The needle gripper is an ingressive gripper that grasps objects through intrusion. The authors designed this special gripper with two fingers that each possess a row of needles on their fingertip. They can regulate the finger distance (w), the needle angle (β) and the intrusion dept (l). The needle movement is synchronized. Figure 2 shows the final grippers after assembly.

The grippers were built with the help of an innovative design process (the fast development cycle) [39], which served ideally for the required development tasks. The fast development cycle provides a schematized methodology for the rapid development of new grasping devices. Its key aspect is to break down an idea to its most fundamental principle and convert it into a gripper pretotype, which can be tested as soon as possible [39]. Guided by this methodology, the authors utilized Lego® Bricks, cable ties, Dyneema® cables, and packaging foam for the two-finger gripper. The structural components of the needle gripper were milled from a steel metal sheet. They were assembled with metal pins and FDM 3D printed parts. Needles were mounted on two 3D printed units. Each unit wass guided via two pins, on which it could slide. The needle units were simultaneously pulled downwards through tendons to extend the needles into the grasped object. To release the object, the needles were retracted through rubber bands. The needle units could easily be changed against units with different needle arrangements (shapes, number of needles, needle thickness and distance of needles). In Figure 2, the basic row configuration is shown. The description of the exact configuration used during the experiments, including the values of all relevant parameters, is given in the following section. Both grippers are actuated through a linear movement and can be blocked in the desired position. The actuation was done manually during the experiments.

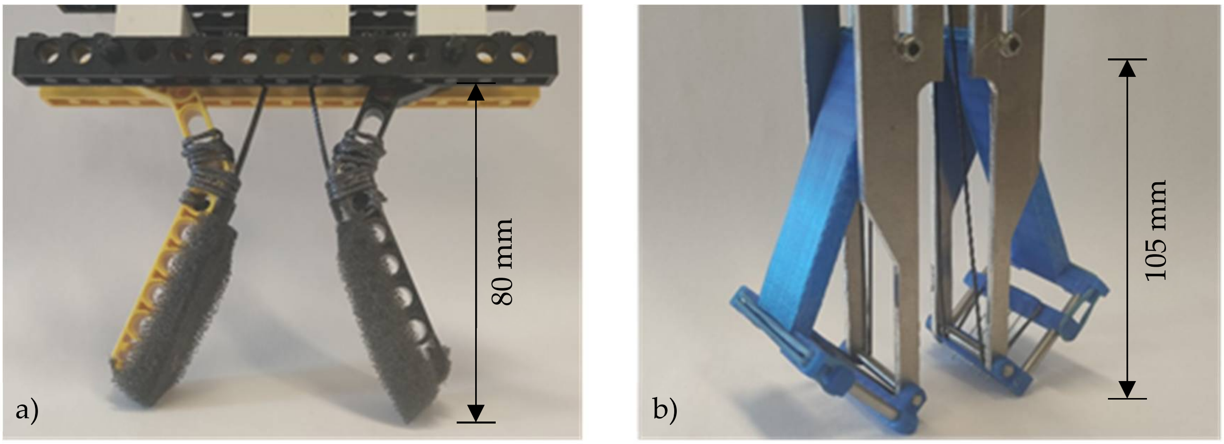

Figure 2. The two grippers employed in the experiments: (**a**) two-finger gripper; (**b**) needle gripper.

Design of Experiment

Generally, to plant vegetable seedlings using autonomous transplanters, plants with good growth and heavy soil block around their roots are needed [40]. Commonly, plug soil is moist before the transplantation [35]. This condition was not fulfilled by the received seedlings. Consequently, to recreate the optimal plug conditions, the whole trays were watered manually one hour prior to the experiment [36], allowing plug soil to soak in the water. Then, all the trays were left to drain in order to achieve the required homogenous level of moisture (soil available water capacity) throughout the entire plugs. Trial 1 consisted of a punching experiment to detach the seedlings from the tray. The purpose of the first trial was to collect the forces required to detach the different seedlings from the trays. A puncher that fits in the holes under the seedlings on the bottom side of the trays was designed and 3D-printed with a Flashforge Creator Pro FDM printer (Zhejiang Flashforge 3D Technology Co., Ltd., Jinhua, China). The puncher has a diameter of 10 mm and a height of 35 mm (see Figure 3, left). It was mounted on an ATI Mini45 (ATI Industrial Automation, Inc., Apex, NC, USA), six axis load cells were attached to a Micos Precision Linear Stage PLS-85 (Physik Instrumente (PI) GmbH and Co. KG, Karlsruhe, Germany) with a 35 mm stroke. The setup is shown in Figure 3, right.

The tray was placed on a table, and the puncher was automatically moved vertically upwards from underneath by the linear actuator. During the experiment, the trays were fixed on the table. This was necessary as the required force for detaching the seedlings exceeded the gravitational force of the trays for some species. The experiment was conducted with five repetitions for each species.

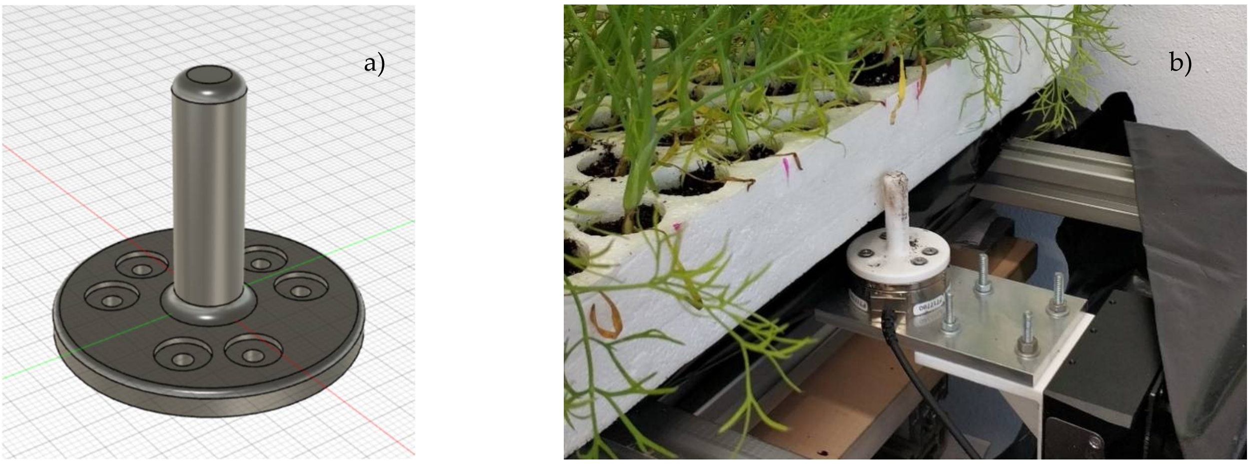

Figure 3. Punching experiment: (**a**) 3D model of puncher; (**b**) experimental setup with fennel seedlings.

Trial 2 consisted of a plug-lifting experiment. The second experiment was designed to determine the performance of the two grippers when lifting the plugs out of the tray and to collect the lifting force. Therefore, the two grippers were successively mounted on a setup consisting of the previously mentioned load cell and linear actuator. The two-finger gripper was oriented horizontally to grasp the seedlings by their stem or leaves about 5 mm above the soil (see Figure 4, left). The gripper was consistently closed until the two fingers were parallel and then blocked in this position. The finger height in the area of contact is 15 mm. Instead of grasping the plants by their stems or leaves, the needle gripper grasps the seedlings by their soil. The gripper approaches the soil of the seedling from above. It then extends its needles, which intrude into the soil of the seedling at a 45° angle. The gripper was used with five needles on one side. The needles had a diameter of 0.5 mm, a distance of 5 mm from each other, and a maximum extension length of 18mm (see Figure 4, right). After grasping the seedlings, the grippers were moved upwards through the linear actuator for a vertical distance of 35 mm with a speed of 5 mm/s. The experiment was designed with a total of 40 repetitions for each gripper. These include ten repetitions for each species, five with the pre-treatment of the previous experiment (trial 1) and five without. The following cases were considered as failures: (1) when the grippers could not extract the plugs from the cell trays; (2) when the grippers shattered more than 1/4 of the plugs soil [36].

Lastly, trial 3 consisted of a plug-transplanting experiment. The aim of the third trial was to observe how well both grippers worked when transplanting plugs and determine if there would be an eventual damage. All seedlings were transplanted in boxes. Therefore, boxes were completely filled with soil. The soil was watered through and perforated with wholes via a cylindrical object slightly bigger than the seedling plugs. Eventually, twelve seedlings of each species were transplanted with three different methods: four by hand, four with the two-finger gripper and four with the needle gripper. Furthermore, this experiment allowed the authors to investigate the performance of each gripper during the releasing of the seedlings after positioning them in the perforated wholes. With the first gripper, the releasing was realized through opening the two fingers. To release the seedling from the grasp of the needle gripper, the needles were simply retracted. The following cases were considered as failures: (1) when the grippers could not extract the plugs from the cell trays, (2) when the grippers shattered more than 1/4 of the plugs soil, (3) when the grippers lost the plugs before transplanting and (4) when the gripper failed to release the plugs on the ground. Eventual damages caused by the grippers on the vegetable species influencing their further growth were assessed by measuring the green cover percentage of each plant [41]. The green cover percentage was calculated from digital images using the app Canopeo (Mathworks, Inc., Natick, MA, USA). Pictures were taken for each plant and treatment right after the treatment, 12 days after the treatment and 35 days after the treatments, for a total of 144 pictures. The distance between plants and the camera was constant (0.30 m). Data were analyzed using the statistical software R [42]. The Shapiro–Wilk test was used to settle data normality, and the Levene's test was used for homoscedasticity (package "car"). ANOVA was performed to test the significance ($p < 0.05$) of different gripper treatments and picture dates on green cover percentage. The ANOVA analysis was followed by post hock LSD test at the 0.05 probability level provided by the package ("agricolae").

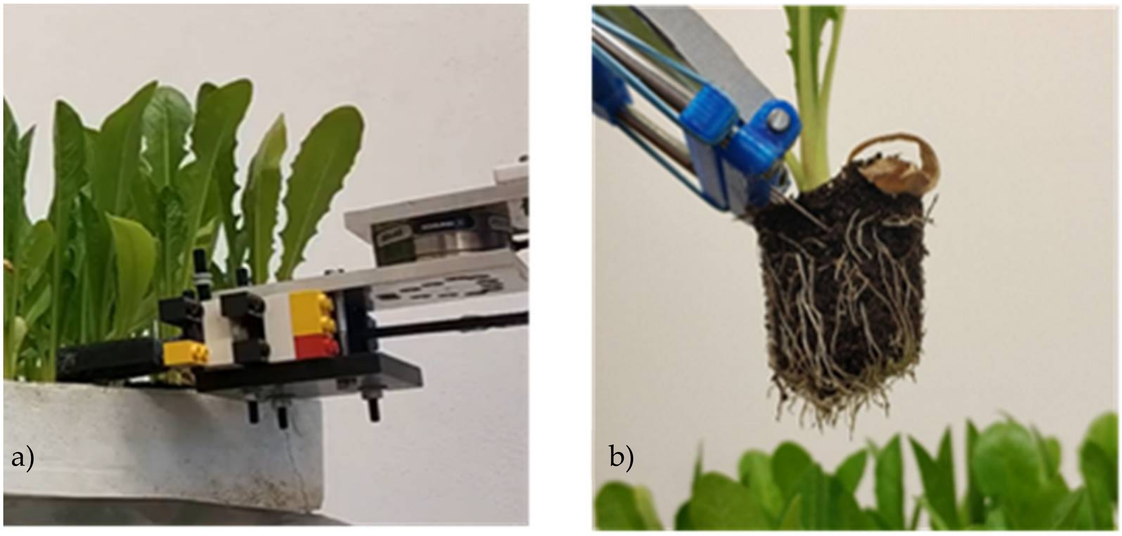

Figure 4. The two gripper typologies grasping chicory seedlings. (**a**) two-finger gripper; (**b**) needle gripper.

3. Results and Discussion

In the three trials, the aim was to better understand the effects of two gripper designs when used to transplant four different vegetable seedlings.

In trial 1 (the punching experiment to detach the seedlings from the tray), forces to detach every single seedling of the four species have been measured. The maximum punching force was determined for each repetition of the experiment. The five maxima are represented within a boxplot for each species in Figure 5. From left to right, the median forces are 36.0 N (leek), 23.8 N (fennel), 3.2 N (lettuce), and 3.5 N (chicory), with the interquartile ranges of 29.2 N, 16.2 N, 7.4 N, and 2.7 N, respectively.

It is noticeable that the forces applied on leek and fennel seedlings are about one order of magnitude greater than the forces on lettuce and chicory (Figure 5). This effect is related to the root systems of leek and fennel, which form a strong bond with the tray.

In trial 2 (the plug-lifting experiment), the two grippers have been tested on four different vegetable seedling species for their capacity to lift seedling plugs from a tray. With both grippers, lifting was successful on almost all seedlings that had been detached from the tray beforehand without compromising the plugs' soil structures. Only one exception was observed: when lifting leek seedlings by grasping the soil of the plugs with the needle gripper, the soil frequently got detached from the roots and was solely lifted without the plant or even shattered. However, the needle gripper was not able to lift seedlings out of their trays if they havd not been detached prior since the adhesive force exceeded the lifting force. Likewise, using the two-finger gripper leek and fennel seedlings that had not been detached prior caused problems. The fingertips slid along the stems upwards without detaching the plugs from the tray. Yet, the lifting of chicory and lettuce seedlings through the two-finger gripper without prior detachment was mostly successful. The lifting force progressions of the latter are shown in Figure 6. The lifting starts at 2 s, when the actuator moves upwards with the constant velocity of 5 mm/s until it reaches its final position at 9 s.

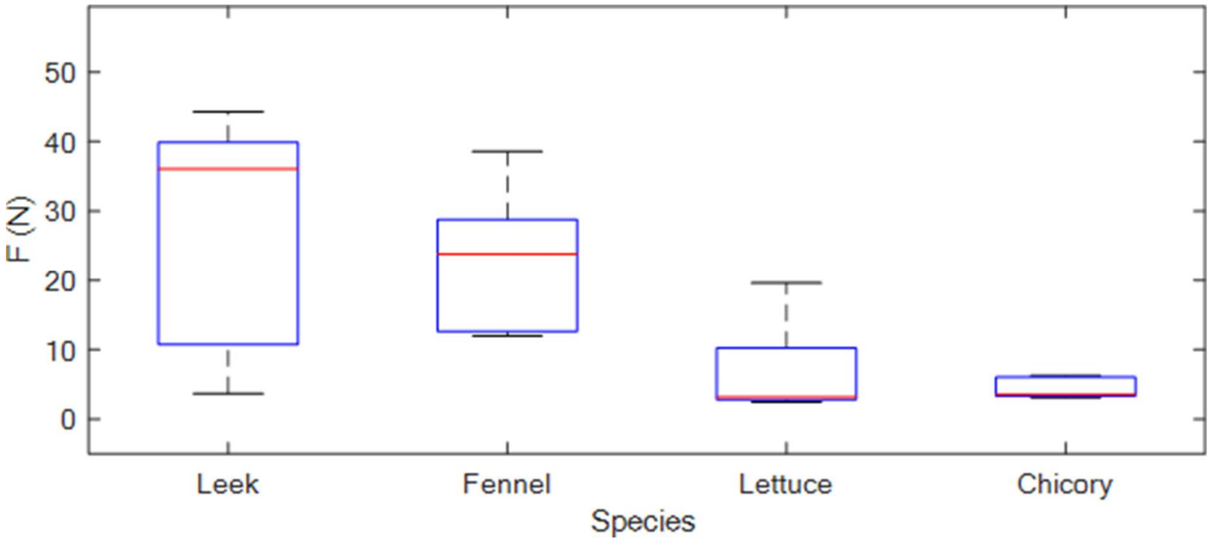

Figure 5. Boxplot of the force needed to detach the seedlings from their trays.

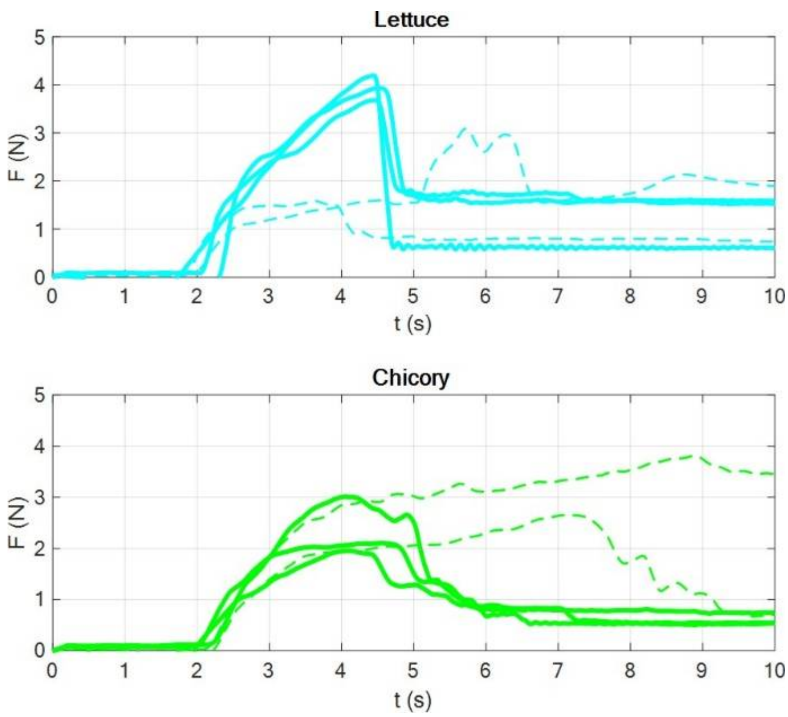

Figure 6. Results of lifting experiment: lettuce (**above**) and chicory (**below**).

While lifting lettuce seedlings, the force increased until about 4 N at 4.5 sec and then dropped steeply. A sudden detachment of the plugs from the tray was characteristic for the lettuce seedlings. Two outliers to this behaviour could be observed: in one case, the plug got detached at less than 2 N (Figure 6, above, dashed lines). In the other case, a sliding phase between the fingertips and the leaves was observed until the force increased again and the plug eventually got detached. The detaching of chicory seedlings started at maximum values between 2 and 3 N. The observed detachment of the plugs from the tray was more gradual than with lettuce. This is reflected in the force progressions via a smaller inclination of the decrease after the maximum. Two outliers could also be observed (Figure 6, below, dashed lines). A sliding took place with one seedling, which finally got detached at 7 s. Another seedling could not be lifted at all, and the force increased to 3.8 N at the end of the linear motion when the seedling was still attached to the tray.

Furthermore, the overlapping leaves of different seedlings represent a hindrance to each other on the tray. This made reaching the seedlings and separating them generally more difficult when the grasping operation was fulfilled by a two-finger gripper. On the other hand, the needle gripper did not show problems when reaching plugs with overlapping leaves. In addition, the seedlings belonging to the four species presents two distinct forms of growth: the rosettae-like form for lettuce and chicory and the single stem form for leek and fennel. The findings of these trials suggest that the two-finger gripper is more suitable for grasping seedlings with a rosettae-like form of growth (i.e., lettuce and chicory) instead of a single stem seedlings (i.e., leek and fennel). Rosettae-like plants are characterized by having multiple leaves at the bottom, which increase the frictional force for the gripper and allowed one to lift those seedlings even when no detaching occurred. Conversely, leek and fennel seedlings were lifted only when plugs were previously detached. Thus, it is reasonable to say that form of growth may represent an important factor involved in gripper development. However, no studies are present in the current literature.

In trial 3 (the transplanting experiment), transplanting repetitions have been conducted for each combination of species and transplanting method until four seedlings have been successfully transplanted. The transplanting success rates are shown in Table 1.

Table 1. Transplanting success rates by percent.

	Hand	Two-Finger	Needle
leek	100	80	80
fennel	100	100	100
lettuce	100	100	67
chicory	100	100	80

All repetitions performed by hand were successful. Using the two-finger gripper, only one failure occurred over all species. A leek seedling fell down during the transplanting experiment. It was entangled with the neighbouring seedlings on the tray and got pulled out of the grasp of the two-finger gripper. Another leek seeding fell down when using the needle gripper because the soil of its plug shattered. No failures occurred with fennel at all. However, some failures were registered with lettuce and chicory using the needle gripper. One failure with lettuce occurred due to soil shattering. For both lettuce and chicory, one seedling could not be grasped because the tray cells were not properly filled with soil and the needles could not intrude the plugs sufficiently. This resulted in the average success rates of 95% for the two-finger gripper and 81.75% for the needle gripper. Success rates of 95% and higher are desired and achievable [35–37]. Insights about design implications, especially for the needle gripper, described later in this section, were gained through the trials and will help to further improve the performance. However, the low number of repetitions is not sufficient to calculate a representative success rate. Both aspects will be subject to future studies.

In this trial, green cover percentage was measured on the different species in order to estimate eventual plant injuries caused by different grippers and consequent issues on seedling growth; results are shown in Table 2.

Table 2. Results of analysis of variance testing the effects of the independent variables treatment, date and their interaction on green cover percentage of the four species.

Source	Leek	Fennel	Lettuce	Chicory
	p-Value			
Treatment	ns	ns	ns	ns
Date	***	***	***	***
Treatment × Date	ns	ns	ns	ns

*** Significant at 0.001 probability level. Ns: not significant at 0.05 probability level.

The analysis of variance revealed that seedlings' green cover percentage was affected by picture date (p-value < 0.001) for all the four different species. Treatment and the interaction between treatment and date did not affect the green cover percentage in a significant way. Green cover percentage was measured on the different species in order to estimate eventual plant injuries caused by different treatments and consequent issues on seedling growth. Results shown in Table 3 suggests that plants were not injured by the different grippers compared to the hand treatment; instead, plants' green cover percentage kept increasing over time (Table 3).

Table 3. Mean values of the green cover percentages of the four different species at different times after transplantation (0 DAT: after transplantation; 12 DAT: 12 days after transplantation; and 35 DAT: 35 days after transplantation).

Species	Green Cover Percentage (%)			LSD
	0 DAT	12 DAT	35 DAT	
leek	10.2 b	14.79 b	23.97 a	5.97
fennel	20.99 b	38.08 a	45.28 a	7.31
lettuce	14.12 b	18.22 b	30.01 a	4.54
chicory	16.06 b	19.63 b	35.9 a	4.86

Different letters on the same line indicate significant differences at $p < 0.05$ (LSD test).

Plugs automatic transplanting requires an adequate firmness and cohesion of the root plugs to avoid soil shattering when removed from tray cells [35]. Furthermore, plug soil should not break into small pieces when handled in the mechanical components of the transplanting machines in order to reduce transplantation stress [14,43]. Leek plug soil fell off completely when lifting a seedling out of the tray. This also happened when the experiment was performed by hand. The characteristic high force needed to lift leek plugs together with the loss of plug soil makes it particularly difficult to be grasped with a needle gripper. Although the success score with the needle gripper in the experiment was the same as with the two-finger gripper, needle gripper is not recommended when grasping leek plugs. Dihingia et al. [43] found that initially compacting plug soil is a good compromise between seedling growth and force needed to lift up the plugs. In this trial, plug soil consisted of a potting mix of peat and perlite with a 70:30 ratio and did not completely filled up the tray cells. Instead, there was a gap in height of 5 to 10 mm. This height difference hindered the grasping with the needle gripper in the current design. These results highlight that needle grippers need to be improved in order to preserve plug structure and soil. Indeed, there is a potential for grasping improvement through longer needles and/or another arrangement.

The two-finger gripper instead worked well for all the four species when they were previously detached. The simple prototype served as a proof of concept and to collect data. However, also this design has further potential for improvement. In the next step, different fingertip shapes and materials could be investigated. Furthermore, a base that does not use Lego would result in a stiffer structure. Lastly, the kinematics could be optimized for a parallel finger movement.

4. Conclusions

In this study, the authors designed, built and tested two grippers for the feeding of vegetable transplanters: a two-finger gripper that picks seedlings from their leaves or stems, and a needle gripper that picks seedlings from the soil of their plugs. Three separate experiments on seedlings of four different species (fennel, chicory, leek and lettuce) were conducted. The experiments included the detaching of the seedlings from their trays and a lifting and a transplanting experiment. In general, the two-finger gripper was successful in all experiments with seedling plugs detached from tray cell walls. In addition, the two-finger gripper was able to lift lettuce and chicory without a previous detachment. The results achieved with the needle gripper were also satisfactory; however, plug soil shattering occurred when prior detachment was not performed. From this observation, the authors derived the policy to always conduct a plug detachment from the tray cells before using grippers for transplanting due to the significantly lower forces involved. Furthermore, the plug soil should be moist and with an adequate firmness and cohesion. The transplanting success rate was satisfactory for each gripper, and no negative effects or damages affecting the further growth of the seedlings were found. The designs of the grippers can still be improved, especially for the needle gripper. Eventually, all the undertaken experiments allowed the authors to collect practical design implications, such as longer needles and modified kinematics, to further improve the devices and increase their success rates in the future.

Within this work, several future research directions became perceptible. A study with seedlings of species with different forms and stages of growth could reveal if increased root plug cohesion leads to a higher grasping success rate and eventually improves the transplantation performance. Furthermore, a feeding unit consisting of a gripper on a moving robotic arm must be tested in a relevant environment such as on a semi-automated transplanter in an actual field test.

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