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RESEARCH ARTICLE

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# Development of a doorframe-typed swinging seedling pick-up device for automatic field transplantation

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## Abstract

A doorframe-typed swing seedling pick-up device for automatic field transplanters was developed and evaluated in a laboratory. The device, consisting of a path manipulator and two grippers, can move the pins slowly to extract seedlings from the tray cells and return quickly to the pick-up point for the next extraction. The path manipulator was constructed with the creative design of type-II mechanism combination in series. It consists of an oscillating guide linkage mechanism and a grooved globoidal cam mechanism. The gripper is a pincette-type mechanism using the pick-up pins to penetrate into the root mass for seedling extraction. The dynamic analysis of the designed seedling pick-up device was simulated with ADAMS software. Being the first prototype, various performance tests under local production conditions were conducted to find out the optimal machine operation parameters and transplant production conditions. As the gripper with multiple fine pins was moved by the swing pick-up device, it can effectively complete the transplanting work cycle of extracting, transferring, and discharging a seedling. The laboratory evaluation showed that the pick-up device equipped with two grippers can extract 80 seedlings/min with a 90% success and a 3% failure in discharging seedlings, using 42-day-old tomato plantlets. The quality of extracting seedlings was satisfactory.

**Additional key words:** agricultural engineering; plug seedling; transplanter; gripper; kinematics simulation.

**Abbreviations used:** FR (failure ratio in discharging seedlings); MC (moisture content of the root lumps); SG (seedling grippers); SR (success ratio in picking up seedlings); TR (transplanting rate)

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## Introduction

China is the largest producer and consumer of vegetables in the world, with a production of 20 million hectares and a yield of 700 million metric tons in 2012. Vegetable industry has been greatly developed and become the second largest crop industry next only to food crops in planting in 2010. The mechanization of vegetable production has become one key research field in agricultural mechanization (MAPRC, 2011). At present, main vegetables, such as cucumber (*Cucumis sativus* L.), eggplant (*Solanum melongena* L.), tomato (*Solanum lycopersicon* L.), pepper (*Capsicum annuum* L.), and cabbage (*Brassica oleracea* var. *capitata* L.), have been widely planted with transplanting production in China. In 2010, output of commercial plug seedlings exceeded 80 billion of plants (MAPRC, 2011). It is regretful that seedling transplantation with the increasing of production and income is still at the manual level despite of semi-automatic transplanters in marketing promotion (Zhang *et al*., 2013). The semi-automatic transplanter can plant seedlings into the ground, but it needs hand-fed seedlings, which still consumes some labors. Long-term continuous operation is also unfeasible because of operators' work fatigue. Overall, seedling transplantation is still labor-intensive, inefficient, and not implemented in time. It often leads to non-uniform plant distribution (Kumar *et al*., 2011). Thereby, it is difficult to obtain comprehensive benefits from transplant production. To speed up the seedling transplanting mechanization can be the priority for mechanization of vegetable production. Besides, the shortage of skilled labors and the increase of labor cost have strongly demanded China and other countries to develop fully automatic transplanters that allow for high-speed operation and labor saving (Kumar *et al.*, 2008; Mao *et al.*, 2014).

One key point of automatic seedling transplantation is to develop seedling pick-up devices on basis of cultural practice for vegetable production (Choi *et al.*, 2002). The articles authored by Brewer (1994) were reviewed to develop a conceptual framework of a seedling pick-up device that will satisfy such transplanting requirements. The FUTURA transplanter is such an automatic machine that has been studied for transplantation of vegetables in modules or in trays (FMC, 2014). This machine extracts the seedlings automatically by means of a system based on cylindrical-shaped plungers, whose diameters may vary depending on the holes on the lower part of the tray used. The plants will be caught up by moving grippers that will place them into a carousel. Its working capacity is up to 8,000 plants/hour/row. However, the FUTURA complex structure and high price have restricted its use in China and other developing countries. Tsuga (2000) reported that three models of riding-type, fully automatic vegetable transplanters were jointly developed by a research institution and some agricultural equipment companies. These prototypes are suitable for cell mold seedlings and pulp mold cell pot seedlings (mainly for leafy vegetables such as cabbage, Chinese cabbage, and lettuce). The pick-up pins are designed to penetrate and hold the root soil of seedlings, and then release them in the planting unit. In the Yanmar vegetable transplanter, a slider and a fixed slot-type mechanism are used to extract the root portion of seedlings from the tray cells and discharge them into the moving conical-type planting unit. The Kubota-type transplanter generates an appropriate path of approach and regress when picking up seedlings by using a more sophisticated mechanism composed of a slider, a cam, and links. The prototypes enable continuous transplanting work on two rows simultaneously, at a planting speed of 60 cells/row/min, with vegetable seedlings fed automatically. Although these transplanters perform well, they are not widely practiced except for product exhibition in China. The reasons are that these transplanters require higher levels of site preparation, and in particular, the flexible standard trays. These requirements are divorced from cultural practice for vegetable production according to the Agricultural Professional Standard of China (MAPRC, 2012). In addition, these transplanters are also economically unfeasible for local production of vegetable seedlings because of their high manufacturing costs. The seedling pick-up device for vegetable transplanters developed by Choi *et al.* (2002) is a five-bar mechanism comprised of a fixed slot, a driving link, a driven link, a connecting link, and a slider for generation of seedling extraction motion. The pick-up device can extract thirty 23-day-old lettuce seedlings per minute at a success rate of 80.0-94.4%. However, more than 1/4 of the root soil broken in seedling extraction is up to 10% functional failures. Therefore, its performance needs further improvement by mechanism optimization for a higher-speed operation.

As the demand for vegetable production mechanization in China has been intensified, many attempts have been made to develop seedling pick-up devices for automatic field transplanters. The relevant researches focus on mechanism design and structure parameter optimization. Yu *et al.* (2011) designed a rotary transplanting mechanism with planetary elliptic gears. Based on Visual Basic 6.0 and a parameter-guided optimization method, Yu *et al.* (2013) developed the software of aided analysis and parameter optimization for a rotary transplanting mechanism. A set of parameters were computed and optimized, which met the work trajectory requirements of pick-up mechanisms. Cui *et al.* (2013) reported a geared five-bar linkage seedling pick-up device, and determined the ideal pick-up trajectory through simulation and optimization of structural parameters. On basis of theoretical studies, a seedling pick-up bench was designed. Experimental results proved the feasibility and rationality of this geared five-bar linkage seedling pick-up device. The studies above have made great contributions to the development of automatic vegetable seedling transplanters. Despite all these activities and others not mentioned, seedling automated transplanting is not widely practiced in China. The reported success ratios in picking up seedling are 84% (Yu *et al.*, 2013) and 80% (Ye *et al.*, 2013), respectively, none of which is completely satisfactory.

To sum up, automatic seedling transplantation is still one major concern in the field of agricultural mechanization, and needs long-term scientific explorations. The factors that affect the transplanting work efficacy fall into mechanical factors and horticultural factors, such as angle of gripper needles, plug extraction acceleration, forces for grasping root mass, plant species, seedling age, root connections, adhesion between roots and cell walls, root zone moisture, and number of seedlings in one cell (Yang *et al.*, 1991; Mao *et al.*, 2014). Therefore, synergistic innovation, both from horticultural and engineering perspectives, must be further strengthened in terms of transplanting efficacy, success in picking up seedlings, and much adaptability to different tray sizes and configurations.

This study is one of many attempts to develop a seedling pick-up device. Its objectives are to make a reasonable transplanting plan on basis of cultural practice of vegetable production in China, and then design a structurally simple seedling pick-up device with the analytical principle of mechanical laws. Finally, a prototype of the device was constructed, and its performance was investigated under local production conditions.

## Material and methods

### Design plan

The functions of seedling pick-up devices are to auto-extract seedlings from growing trays, transfer them, and release them into the planting unit where they are to be transplanted into the ground (Brewer, 1994). Although the working speed was about the speed of hand placement, it was intended at the beginning of the study to concentrate many efforts on making the extracting function of the seedling pick-up device more accurate. Thereby, this transplanting operation requires that the pick-up device can reliably pick up the plugs without any damage to leaves, the stem and the root mass (Fig. 1a). As showed in Fig. 1b, a reasonable transplanting plan must be made as follows:

– The plug tray is moved flat at an angle θ to the transplanting space. The tray translation can be decomposed into the cell-to-cell horizontal shift and the row-to-row longitudinal feed. The feeding angle θ should be almost close to 90°, which narrow the feeding translation space, and thus is more beneficial for the structure layout.

– Point F (black spot), as the extraction point of the pick-up pins, is against the tray cell center. It should be at least higher than one cell height H, which makes the root plug smoothly away from the cell. The pick-up pins extract seedlings from the cells at an angle of 90° between line FE and the longitudinal feeding direction. For a high-quality seedling extraction, the pick-up pins should penetrate into the root soil of a cell along line FE, and then lift the root plug along the same way. It can avoid cut damage to the root plug as much as possible.

– When the pick-up pins penetrate into the root lump for seedling extraction, the penetration depth should be smaller than the cell depth H. Besides, the penetration opening of the pins should be smaller than the top width of a cell (W1). As the pins move toward a seedling plug in a cell, they should close gradually within the cell edges. Finally, the pick-up pins, always smaller than the bottom width of a cell (W2), squeeze and hold the root lump firmly at the maximum penetration depth.

– The pins should transfer the seedlings along a curve FG so as to adjust the attitude from their tilt to an upright position. Thereby, the seedlings can be dropped upright into the planter at the minimum inertia.

### Mechanical development

The seedling pick-up device may be divided into two major components: a path manipulator which looks like a robot arm and a gripper equated with a robot

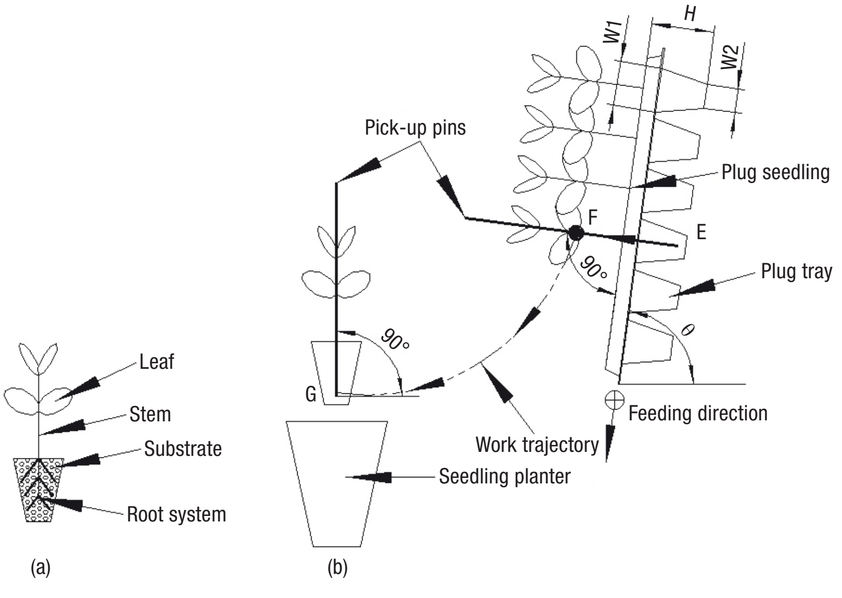
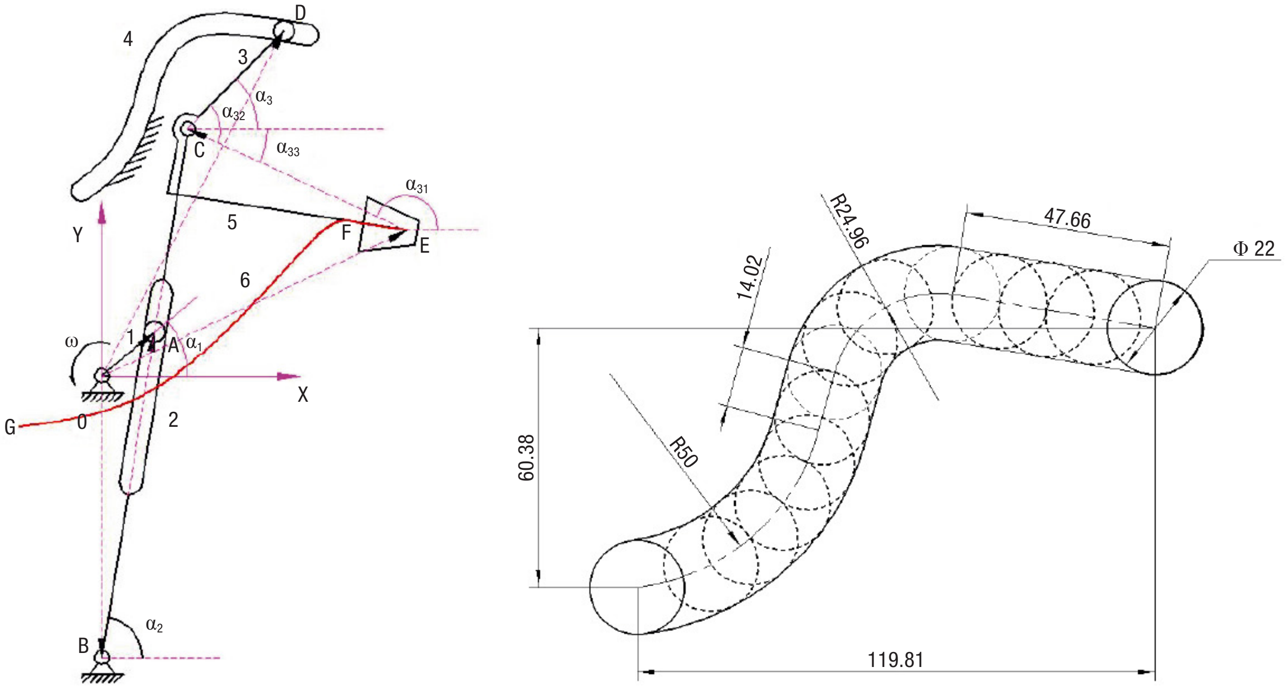


**Figure 1.** Design planning of the seedling pick-up device: (a) plug seedling, (b) transplanting planning.



(a) (b)

**Figure 2.** Schematic diagram of the seedling pick-up path manipulator: (a) path manipulator, (b) copying groove. 1, driving link; 2, swinging link; 3, connecting link; 4, fixed groove; 5, gripper; 6, work trajectory.

hand. The function of the path manipulator is to generate an appropriate work trajectory of seedling extraction for the pick-up pins. The mechanical functions of the gripper are to grasp seedlings within the tray cell, hold them and release them into the planter where they are to be transplanted into the ground.

## Path manipulator

An innovative path manipulator for seedling extraction was constructed with a creative design of type-II mechanism combination in series (Fig. 2a). Its mechanical work principle is the mechanism combination in series consisting of an oscillating guide linkage mechanism (links 1 & 2) and a grooved globoidal cam mechanism (link 3 & groove 4). Specifically, the grooved link 2, driven by the revolved link 1, can swing with an angle range. The swinging link 2 is connected to the sliding link 3. The sliding of link 3 is constrained on the fixed globoidal groove 4. Thereby, the sliding link 3 which is moved by the swinging link 2 copies the required work trajectory jointly under the constraint of the globoidal of the fixed groove 4.

The key point in designing the path manipulator is to form the globoidal of the fixed groove 4, which is used to create the planned seedling pick-up trajectory (E→F→G) from the growing tray to the top of the planter. Fig. 2a shows a mechanical schematic diagram of the path manipulator. According to the theory of mechanisms, the closed-loop vector equation is expressed as follows:

$$\begin{cases} \overrightarrow{OA} = \overrightarrow{OB} + \overrightarrow{BA} \\ \overrightarrow{OD} = \overrightarrow{OE} + \overrightarrow{EC} + \overrightarrow{CD} \end{cases} \qquad [1]$$

After the coordinate projection transformation, the rectangular functions of Eq. [1] are described as follows:

$$\text{Point A:} \begin{cases} x_A = L_1 \cos\alpha_1 = x_B + L_{BA}\cos\alpha_2 \\ y_A = L_1 \sin\alpha_1 = y_B + L_{BA}\sin\alpha_2 \end{cases} \qquad [2]$$

$$\text{Point C:} \begin{cases} x_C = x_B + L_2 \cos\alpha_2 \\ y_C = y_B + L_2 \sin\alpha_2 \end{cases} \qquad [3]$$

$$\text{Point D:} \begin{cases} x_{Di} = x_{Ei} + L_{EC}\cos\alpha_{31} + L_3\cos\alpha_3 \\ y_{Di} = y_{Ei} + L_{EC}\sin\alpha_{31} + L_3\sin\alpha_3 \end{cases} \qquad [4]$$

where ($x_A$, $y_A$), ($x_B$, $y_B$) and ($x_C$, $y_C$) are the coordinate values of point A, B and C, respectively; ($x_{Di}$, $y_{Di}$) is the coordinate of the central point Di in the copying groove 4; ($x_{Ei}$, $y_{Ei}$) is the coordinate of any point Ei on the work trajectory; $L_1$, $L_2$ and $L_3$ are the length of the driving link 1, the swinging link 2 and the connecting link 3, respectively; $L_{BA}$ and $L_{EC}$ is the distances from point B to point A and from point E to point C, respectively; $\alpha_1$, $\alpha_2$ and $\alpha_3$ are the angles of the positive x axis intersected with the driving link 1, the swinging link 2 and the connecting link 3, respectively; $\alpha_{31}$, $\alpha_{32}$ and $\alpha_{33}$ are the angles between the line $\overrightarrow{EC}$ and the positive x axis, between the line $\overrightarrow{CE}$ and the line $\overrightarrow{CD}$, and the line $\overrightarrow{CE}$ and the positive x axis, respectively.

According to the geometric coordinate relations of the basic linkage group, a set of rectangular equations can be easily determined as follows:

$$\begin{cases} L_{BA} = \sqrt{\left(x_B - x_A\right)^2 + \left(y_B - y_A\right)^2} \\ \tan\alpha_2 = \left(y_A - y_B\right) / \left(x_A - x_B\right) \\ \tan\alpha_{31} = \left(y_C - y_{Ei}\right) / \left(x_C - x_{Ei}\right) \\ \alpha_3 = \alpha_{32} - \alpha_{33} = \alpha_{32} - \left(\pi - \alpha_{31}\right) = \alpha_{31} + \alpha_{32} - \pi \end{cases} \quad [5]$$

Based on the structural and spatial layout of the pick-up device, the basic dimensions of the linkage group can be determined, such as $L_1$, $L_2$, $L_3$, $L_{EC}$, $\alpha_{32}$, and $(x_B, y_B)$. As a series of $(x_{Ei}, y_{Ei})$ are planned, they combine into the working trajectory of the pick-up pins for seedling extraction. Given the varying values of $\alpha_1$, the trajectory of point D can be solved with the numerical analytical method using Eqs. [2] to [5]. Thereby, it is found that the trajectory of point D creates the center line of the copying groove′s globoidal. Then after a rolling circle is added to the trajectory of point D, the inner globoidal groove can be copied out with the envelope method (Rothbart, 2004). Finally, the design of the path manipulator for seedling extraction is finished.

As is well-known, transplant production is implemented in China to meet the Agricultural Professional Standard of China (MAPRC, 2012). In particular, two types of the injection-molded polystyrene trays are widely used for vegetable seedling production, which contain 72 cells (6 × 12) and 128 cells (8 × 16), respectively. The dimensions of each tray are 280 mm W × 540 mm L. The dimensions of each cell are 45 mm height × 40 mm top in the 72-cell tray, and 42 mm height × 32 mm top in the 128-cell tray. The shape of each cell is like an inverted truncated pyramid.

The seedling-tray transfer was designed to move along its width direction. As a result, the total distance for longitudinal feed is 280 mm. The initial feeding angle of the growing tray was set at 80° (Fig. 1b: plug tray′s feeding angle θ). This feeding angle may change depending on the actual need. Thereby, the maximum horizontal distance of the longitudinal feed was up to 48.62 mm (280 mm × cos80°). The distance of a seedling lifted from a cell should be approximately equal to the root lump′s height, which guarantees the smoothness of the seedling extraction. Therefore, the length of line FE should be close to 93.62 mm (72-cell tray: 45.00 mm + 48.62 mm). With preliminary consideration, $L_1$, $L_2$ and $L_3$ were set at 35 mm, 230 mm and 50 mm, respectively; the distance from the tip of the pick-up pins to the joint C was 160 mm. Thereby, automatic transplanting of most seedlings can be carried out (see Tian *et al.,* 2014). Considering $\alpha_{32} = 70°$, the gripper fixed on the connecting link 3 can swing at a large range without interfering with other parts. The rotation centers of the driving link 1 and the swing link 2 were both located in the same vertical axis, and their center distance was kept at 130 mm. Through numerical analysis, the trajectory of point D can be calculated using Eqs. [2] to [5] under varying $\alpha_1$ and the initial size conditions mentioned above. In order to avoid friction-induced heat and wear in the globoidal groove, self-aligning ball bearings with diameter at 22 mm were used as a type of slider motion. Finally, the main structure size of the copying groove was determined by the envelope method (Fig. 2b).

## Gripper

After many tests, an innovative U-type gripper driven by a sliding pull rod was developed. Fig. 3a shows a mechanical structure drawing of the gripper. The gripper is a pincette-type mechanism consisting of pick-up pins, a U-type pull rod, a shaft, a stop block, a compression spring and a frame. Each pick-up pin rotating around a shaft is connected to the frame via a hinge joint. The pins are ringed by the U-type pull rod. As the pull rod moves down and up in the frame, the pins may open and close, correspondingly. Meanwhile, the U-type pull rod may also push the seedling out of the pins during its downward movement, which is triggered the compression spring inside the frame assembly.

In a work cycle of seedling extraction, the operation of the pincette-type gripper can be elaborated as follows:

- At the start, the pick-up pins open and the gripper moved by the path manipulator gradually approaches the top of a seedling′s root mass along the normal direction to the cell surface (Fig. 3a);
- As the pin tips start to penetrate into the root soil symmetrically from both sides of a seedling (Fig. 3b), the U-type pull rod is pulled backward. At the same time, the gripper sequentially moves toward the root mass until the pick-up pins penetrate into the soil at

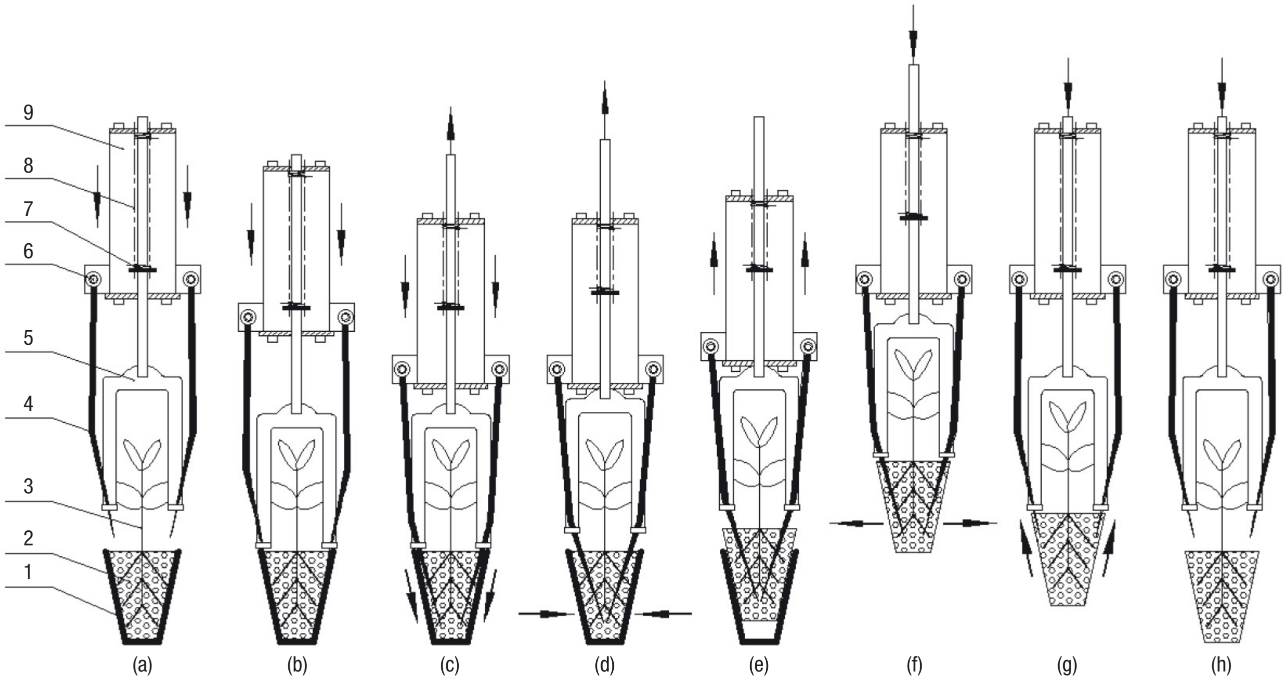


**Figure 3.** Operation of the pick-up pins for a seedling extraction: 1) tray cell; 2) root lump; 3) seedling; 4) pick-up pin; 5) U-type pull rod; 6) shaft; 7) stop block; 8) compression spring; 9) frame. (a-h): operation phases of the seedling extraction.

their maximum depth. Thereby, the pick-up pins close gradually as they penetrate into the root mass within the edge of the cell (Fig. 3c);

– When the pick-up pins hold the root mass at their maximum penetration depth, the U-type pull rod is rapidly pulled backward. Thereby, the pins close instantly and also grasp the maximum amount of root soil firmly (Fig. 3d). As the gripper moves up with the drag from the path manipulator, it lifts the seedling out of the cell (Fig. 3e);

– At the discharge point, the pick-up device keeps the gripper motionless. The U-type pull rod, triggered by the spring inside the frame assembly, moves downward. As a result, the U-type pull rod holds the pick-up pins open (Fig. 3f). Meanwhile, the rod pushes the seedling down, and the pins retract gradually from the root soil (Fig. 3g);

– As the U-type pull rod moves forward further, the seedling is driven out of the pins. Finally, the gripper discharges the seedling into the transplanting hopper steadily (Fig. 3h).

The mechanical dimensions of the gripper were determined by the tray cell sizes and plant characteristics. As the pick-up pins penetrate into the root mass within the tray cell for seedling extraction, it should be ensured that the pins grasp the maximum amount of root mass (Yang *et al*., 1991). The optimal opening of the pins was found to be 2 to 3 mm less than the cell width (Choi *et al*., 2002). Therefore, the opening for the initial penetration was set at 2-3 mm. In order to grasp the maximum amount of root soil, the pick-up pins were designed to penetrate into the roots as deep as possible at 35 mm within the cell depth. The gripper was finally developed on basis of cultural practice of vegetable seedlings in China (Tian *et al*., 2014). The movement of the U-type pull rod was triggered by a cam mechanism, and its profile curve was designed using the mechanical reverse method (Rothbart, 2004). The cycloidal motion method was considered as a push and return program of the cam without any sudden change in acceleration and impact.

## Virtual prototype simulation

A 3D solid model of the seedling pick-up device was designed on Solidworks 2012 (Dassault Systemes S.A ©, Concord, MA, USA). In order to improve work efficiency of seedling extraction, a doorframe-type pick-up system equipped with two grippers was constructed (Fig. 4). The two equal swing links connected by a crossbeam were configured as the swing door-frame for the seedling pick-up device. The two grippers were fixed on the crossbeam with the half-and-half treatment for seedling extraction of the entire tray. In other words, the device can extract two seedlings synchronously in one work cycle. Taking the 72-cell plug seedlings as an example, each gripper on the crossbeam was designed to extract 6 seedlings of the entire row as the

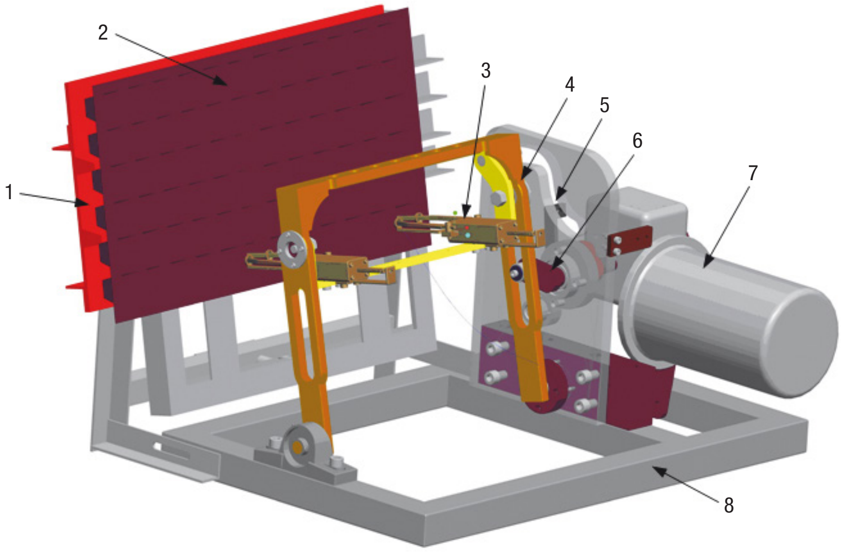


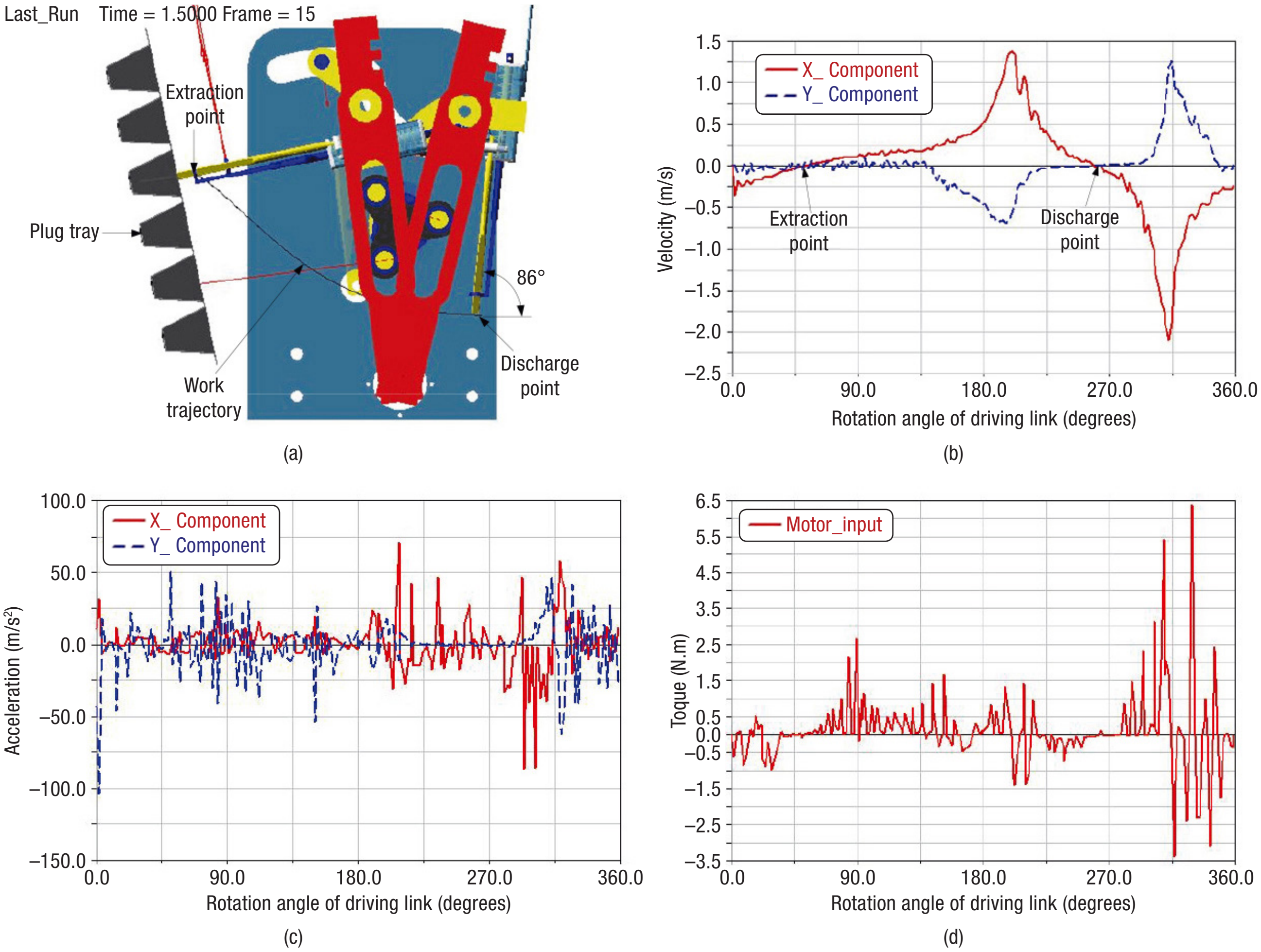
**Figure 4.** 3D model of the seedling pick-up device: 1, cradle; 2, plug tray; 3, gripper; 4, door frame; 5, copying groove; 6, driving link; 7, driving motor; 8, frame.

longitudinal feeding direction was along its width direction. Thereby, the entire row of extraction, with 12 seedlings continuously transplanted one by one, was repeated for 6 times using two grippers. After an entire row of seedlings was transplanted, the tray was moved forward to place the next row into the gripper's working space. This transplanting procedure was repeated until all seedlings in the plug tray were transplanted. In the initial stage, the motor drive was considered as the power supply to the seedling pick-up device. The motor shaft was directly connected by a coupling to the driving link. Thereby, the motor rotation speed was equal to the transplanting capacity. As the motor rotates a cycle, the pick-up device completes a seedling extraction for a transplanting work. A 72-cell tray of seedlings was constructed, and the seedling pick-up device was installed in front of the tray. The distance between a seedling and the pick-up device can be adjusted. Finally, the seedling pick-up device was modeled with the configuration of other fasteners.

As the concepts for a machine are modeled on a computer in the agricultural engineering, sufficient information is presented to allow the judgment of design feasibility (Brewer, 1994). Therefore, the dynamics of the seedling pick-up system were simulated on Adams (Mechanical Dynamics Inc.©, Ann Arbor, MI, USA), which is able to analyze the trajectory, velocity and acceleration of the pick-up pins and the input torque required to drive the device. Firstly, the 3D model of the seedling pick-up device in Solidworks 2012 was saved as a new parasolid type file (*.x_t). Then, the parasolid-type CAD geometry data were imported to Adams. The mass and inertia data necessary for the simulation were created within the Adams program when the device was modeled and its material was specified as steel. Variable kinematic joints were also added to the CAD geometry data for constraint modeling, and force modeling was conducted to apply interaction units among parts. Finally, it was set at a complete revolution of the driving link with a velocity of 40 r/min in the clockwise direction (Fig. 5a). This setting value was determined based on the existing transplanter′s working capacity (Tsuga, 2000; Choi *et al*., 2002). The simulation step was 200 steps/s.

As shown in Fig. 5a, the extracting and discharging work statuses of the seedling pick-up device were recorded in the resulting data, and the work trajectory of the pins seemed like a falcate claw. At the seedling extraction point, the pick-up pins approach a seedling in a cell and penetrate into the root soil along the straight-line path. When the pins hold the seedling firmly, the gripper moves back along the same straight-line path. After an attitude adjustment, the pins release the seedlings at an angle of 86° downward from the horizontal direction. This releasing angle is quite acceptable, since Choi *et al*. (2002) emphasized that the pins should release seedlings at an angle of 75° to account for the inertia of the seedlings. The work trajectory of the pins for the seedling extraction was the same to that of the seedling discharge. The horizontal distance between the extraction point and the discharge is 279 mm, and the vertical distance is 115 mm. Obviously, there is enough space for the tray feeding.

As shown in Figs. 5b and 5c, the peak velocities, from the horizontal and the vertical directions, were estimated to be 2.10 m/s and 1.26 m/s, respectively, and the peak accelerations were 86.93 m/s$^2$ and 103.82 m/s$^2$,



(a) (b) (c) (d)

**Figure 5.** Virtual prototype analysis of the pick-up device in motion: (a) work trajectory, (b) velocity of pick-up pins, (c) acceleration of pick-up pins, (d) driving torque.

respectively. The peak acceleration of this pick-up device was far less than the five-bar mechanism (Choi *et al.*, 2002) despite of a higher driving speed. Both the kinematic velocities at the extraction point and at the discharge point were 0 m/s, which is beneficial for automatic seedling transplantation. As a result, the inertia to keep the pick-up pins acting on the seedlings can be minimized. The rotational angle of the driving link to move the pins from the extraction point to the discharge point was 210° in the clockwise direction, and that one from the discharge point to the extraction point was 150°. Thereby, the time ratio of the working phase to non-working phases was 1.4, which is far superior to the pick-up device at the time ratio of 1.1 (Choi *et al.*, 2002).

The peak torque with a velocity 40 rpm is 6.37 N·m for the clockwise direction (Fig. 5d), and 12.58 N·m for the counter-clockwise direction. Therefore, the driving link was designed to rotate at the clockwise direction (Fig. 5d). As showed in Fig. 5d, the peak torque to drive the device is in the return movement (from the discharge point to the extraction point). Factors associated with this peak torque include the heat and friction in the globoidal transitional region between the slider and the slot, which can be improved by surface smoothing treatment, such as refining the globoidal groove and greasing the machine. The power required to drive the device or the driving power (*P,* kW) was affected by the rotational speed and torque, and can be calculated as follows:

$$P = \frac{Tn}{9.55\times 10^3} \qquad [6]$$

where $T$ is rotational torque, N·m; and $n$ is rotational speed, r/min.

After calculation, the driving power was 0.027 kW and 0.077 kW for the motion simulation driving speed at 40 r/min and 50 r/min, respectively. Taking some engineering factors into account, the actual numerical value may be larger than the theoretical calculation. Nevertheless, this calculation provides evidence about the entire power distribution of the transplanter.

Kinematics simulation of the pick-up device indicated that the device worked correctly. So its performance test could be further conducted through prototype trial-production.

## Performance test

A prototype of the seedling pick-up device was constructed to examine whether its working efficacy was satisfactory or not. With a chain transmission, the tray feeding system was synchronized with the drive system of the seedling pick-up device so that the pick-up pins extracted the seedlings one by one. An NMRV050-20 worm reducer (Devoter Motor Corporation, Suzhou, China) was used to drive the device. Its rated power is 0.25 kW, the rated speed is 70 r/min, and the output torque is 26 N·m. An FR-A540-0.75K-CH A500-type frequency changer (Mitsubishi Electric Corporation, Tokyo, Japan) was configured for motor speed control. Its rated power is 0.75 kW, and the maximum speed ratio is 1: 120.

Firstly, the pick-up device was test-operated to examine the opening and closing flexibility of the gripper, and the movement coordination among different parts. In front of the device, a set of tray bracket was installed for feeding seedlings. The trays can be conveyed automatically along the horizontal direction from cell to cell, and fed manually along the longitudinal direction from row to row. In the initial trials, the velocity of the driving link was set to be 30 r/min. In the blank 72-cell tray, the pick-up pins can be prevented from piercing the cell wall as the penetration opening was less than 35 mm. As a result, the opening was reduced by 5 mm less than the top width of the cell. Besides, the pins may penetrate into the root soil as deep as possible within the cell depth when the distance between the extraction point and the tray surface was estimated to be 30 to 35 mm. Taking 42-day-old tomato seedlings in the 72-cell trays as the testing objectives, when the grippers approached the cells along the normal direction to the tray surface, the seedlings were not completely extracted from the cell. The reason was that their leaves were often tangled with the pins. Meanwhile, when the gripper moved vertically to pick up the root lumps, the seedlings were often bent, and could be easily damage. Many trials were conducted to adjust the installation angle of the feeding tray. When the pick-up pins were moved to approach the seedlings slightly in the downward normal direction to the cell surface from the bottom of the upright stems, it can effectively prevent the gripper from foliage entanglement. Further, as the pins penetrated the root soil to a maximum depth of 33 to 35 mm, the gripper can completely extract the seedlings from the cells with the pins quickly closing by 12 mm. Based on the results of the trials, the prototype was modified and subjected to a satisfactory performance test. Fig. 6a shows the modified prototype of the doorframe swinging seedling pick-up device.

In the performance tests, various factors that affect the efficacy of the gripper need to be strictly investigated. For mechanical factors, the penetration angle and depth of the pick-up pins were investigated for structure optimization according to the tray cell sizes and seedling characteristics. Also, the squeezing capacity of the root lump for extraction was determined by adjusting the

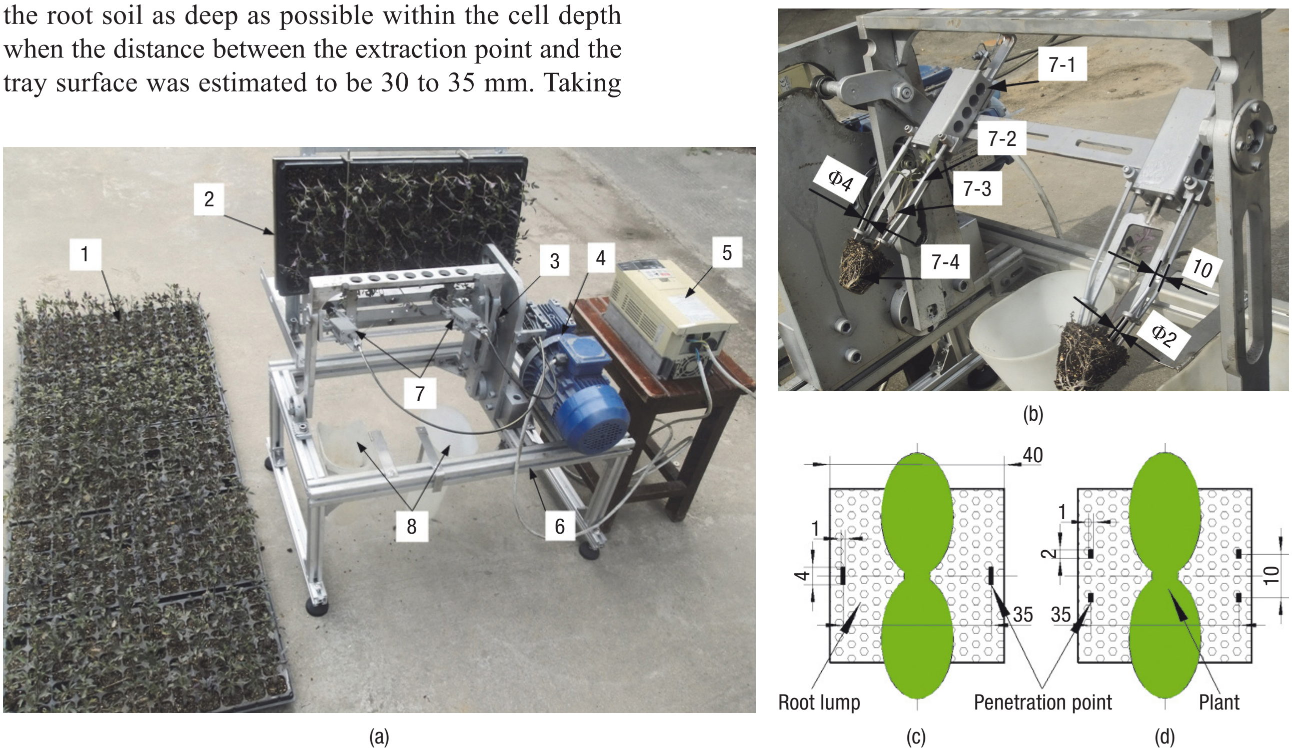


**Figure 6.** Performance tests of the seedling pick-up device. (a) The prototype of the pick-up device; 1, plug seedling; 2, feeding tray; 3, path manipulator; 4, driving motor; 5, variable-frequency drive; 6, frame; 7, pick-up gripper; 8, transplanting hopper. (b) Seedling extraction; 7-1, supporting block; 7-2, pick-up pins; 7-3, foliage; 7-4, root lump. (c) Two pins. (d) Four pins.

opening and closing of pins. All tests were done to ensure that the pins can grasp the maximum amount of root soil. For horticultural factors, an optimum range of root system moisture content should be determined to facilitate the seedling extractions (Ryu *et al*., 2001; Mao *et al*., 2014). Thus, the seedlings moisture conditions were strictly investigated in this study. When transplant production is conducted to meet the seedling agronomic standard (MAPRC, 2012), seedling characteristics are uniform despite of a few individual differences. For automatic transplanting widely practiced, more works are needed to improve the device′s working efficacy that matches with seedling characteristics. In this study, the seedling extraction efficacy was further tested under the conditions of two kinds of grippers and varying transplanting rates. Fig. 6b shows how the grippers extract seedlings from the cells. Seedling extractions using the pincette-type gripper with two pins or four pins are shown in Figs. 6c and 6d. The pins were composed of 304 stainless steel. The diameter of pins was 4 mm in the two-pin gripper (Fig. 6c), and 2 mm in the four-pin gripper (Fig. 6d). For the four-pin gripper, the width of the two fork-type tips was 10 mm, and no damage to the tray cell will occur when the pins penetrate into the root soil at their maximum depth. For the two grippers, there extraction conditions were the same, including the optimal pin opening at 35 mm, the maximum penetration depth of 33 mm, the squeezing capacity of 12 mm, and the equal grasping area. The differences among the two grippers were the number, size and position of grasping action on the root soil. There were two actions and four smaller actions on the root soil for the gripper with two pick-up pins and the one with four pins, respectively. In order to alleviate root soil breakage from penetration, the pin tips were flattened to a thickness of 1 mm for a length of 30 mm.

Finally, performance tests were conducted considering various seedlings and operational parameters, such as moisture content of the root lumps (MC), transplanting rate (TR) and two types of seedling grippers (SG). There were 4 levels of MC (50 ± 2%, 55 ± 2%, 60 ± 2%, 65 ± 2% day basis), 3 levels of TR (30 r/min, 40 r/min, 50 r/min) and 2 types of SG (one two-pin gripper and one four-pin gripper). A success ratio (SR) in picking up seedlings represents how successfully the device performs extracting, transferring, and discharging of seedlings (Choi *et al*., 2002). SR was determined as follows:

$$\mathrm{SR}\ (\%) = \frac{\mathrm{NSF} - \mathrm{NMS} - \mathrm{NFF} - \mathrm{NLD}}{\mathrm{NSF} - \mathrm{NMS}} \times 100\% \quad [7]$$

where NSF is the number of seedlings fed, NMS is the number of missing seedlings, NFF is the number of functional failures (more than 1/4 of the root lump considered as a whole soil breakage), and NLD is the number of seedling damages (the stems torn by the pins).

A failure ratio (FR) in discharging seedlings represents whether a gripper can release seedlings into the transplanting hopper at the upright state (Fig. 6a). Discharging failures were classified as follows: (1) seedlings fall off the pins during the transferring movement (FOP); (2) seedlings were not removed completely from the pins at the discharge point (RCP); (3) seedlings were released outside of the transplanting hopper (ROS). FR was defined as follows:

$$\mathrm{FR}\ (\%) = \frac{\mathrm{FOP} + \mathrm{RCP} + \mathrm{ROS}}{\mathrm{NSF} - \mathrm{NMS} - \mathrm{NFF} - \mathrm{NLD}} \times 100\% \quad [8]$$

where FOP, RCP and ROS are the number of seedlings in the classification mentioned above.

The performance of the seedling pick-up device was tested with Hezuo 908 tomato seedlings grown in 72-cell trays on a farm in Zhenjiang, Jiangsu Province. The plug trays were precision-injection-molded plastic trays (Taizhou Jinnong Mesh Factory, Zhejiang), and the seedling substrate is a mixture of herbaceous peat, perlite, vermiculite and other agricultural materials in some volume proportions (Zhongnuo Agric. Technol. Dev. Co. Ltd, Huai'an, Jiangsu). Seedling production was conducted to meet the Agricultural Professional Standard of China (MAPRC, 2012). In the tests, the basic information of the tomato seedlings was: seedling age, 42 days; plant height, 110-130 mm; stem diameter, 2.5-3 mm; leaf area, 30-40 cm$^2$; and true leaves, 4 or 5. The cell root volume becomes so large that the root lumps cannot be spread out as the plugs were extracted through grasping their stems for lifting. The tests were conducted in full factorial experimental design. There were 24 tests. Each test had one tray seedlings transplanted continuously and the process was repeated 3 times. The results were recorded, and statistical analysis was conducted on SPSS 18.0 (SPSS Inc., Chicago, IL, USA). Duncan's new multiple range method ($\alpha = 0.05$) was used in in multiple comparison.

## Results and discussion

On basis of cultural practice for vegetable production in China, the design conditions for the seedling pick-up device firstly were defined. According to the design planning formulated, a doorframe-type swing seedling pick-up device for automatic transplantation of several field-grown vegetables was developed. The device consists of a path manipulator and two grippers. The path manipulator was constructed with the creative design of type-II mechanism combination in series consisting of an oscillating guide linkage mechanism and a grooved globoidal cam mechanism. Each gripper is a pincette-type mechanism and uses the pick-up pins to penetrate into the root mass for seedling extraction. Kinematics simulation with the seedling pick-up device showed that the work trajectory of the pins looks like a falcate claw suitable for seedling extraction from the tray cells, and the device can release seedlings at an angle of 86 degrees, with consideration into the minimum inertia of the plants. Further, the seedling pick-up device can move the pins quite slowly to extract the seedling from the cell and return quickly to the extraction point for the subsequent transplantation. Such operation is favorable for automatic extraction of the flexible plug seedlings. It was consistent with the findings of Yang *et al*. (1991) who reported that one possible way to achieve a higher extraction rate with a minimum transplanting time is to separate the seedling from the cell at a lower acceleration and then to complete the lifting motion with further acceleration.

As the seedling pick-up device works properly, its prototype is constructed to further investigate the factors that affect the extracting efficacy of the gripper. Those factors were the situations encountered during the testing of transplanting more than 5,000 plugs. Each influencing factor was varied at different levels and tested to investigate its effects on the success of plug transplanting and the failure ratio in discharging seedlings. The results of the tests are shown in Fig. 7, and their statistical analysis is listed in Table 1.

Fig. 7 shows that a higher SR was obtained at MC of 60 ± 2%, TR of 30 r/min, and with the four-pin gripper. The relatively minimum FR occurred at MC of 50 ± 2%, TR of 30 r/min and with the four-pin gripper. On the whole, the maximum SR was 91.57% and the minimum SR 85.79%. The maximum FR was 3.76% and the minimum FR, 2.43%. As can be seen from the obtained analysis of variance (Table 1), SR was affected by the main factors MC, TR and SG. FR was affected by TR and SG and their interaction (TR×SG). Further, MC, TR and SG had highly significant effects on SR ($p < 0.01$), but their interaction had no significant effects ($p > 0.05$). TR, SG and their interaction (TR×SG) had highly significant effects on FR ($p < 0.01$) and those associated with MC had no significant effects ($p > 0.05$).

As shown in Fig. 7a, with the lifting of MC, the SR increased first and then decreased. The SR at MC of 60 ± 2% was significantly higher than those at other levels with 95% confidence interval. The optimum range of root system moisture content that would facilitate the seedling extraction in China was 55 ± 2% to 60 ± 2%. This range is slightly different from the

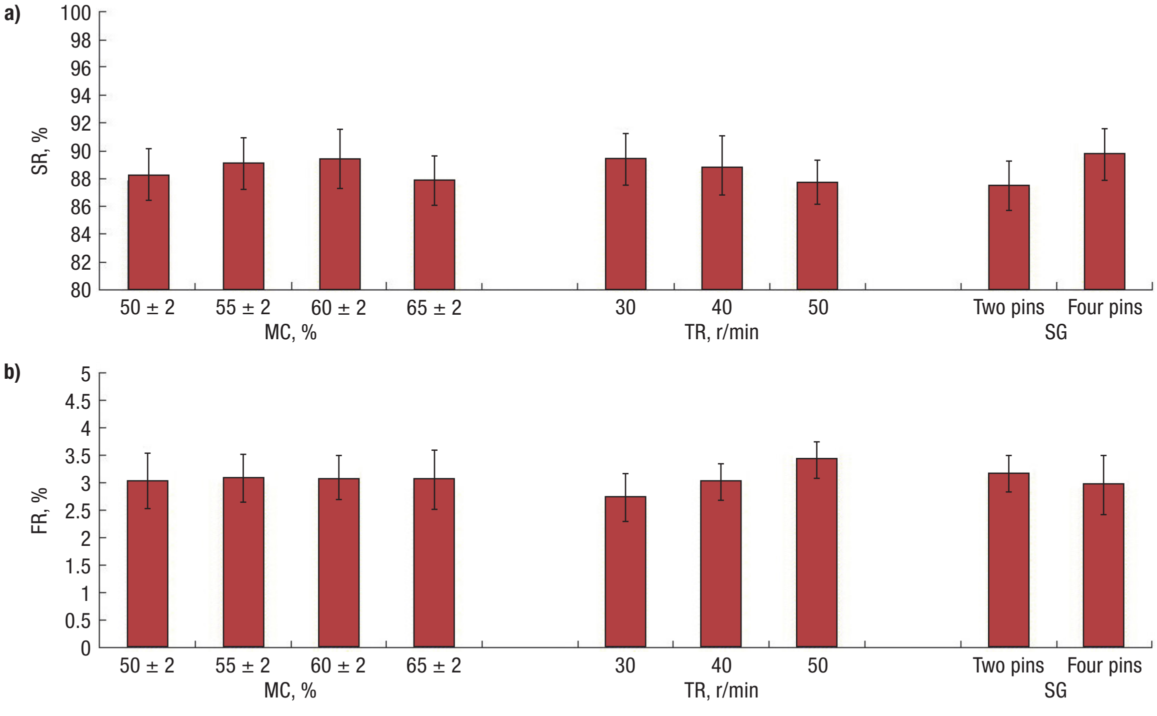


**Figure 7.** Results of seedling pick-up tests: (a) SR, success ratio in picking up seedlings; (b) FR, failure ratio in discharging seedlings. MC, moisture content of the root lumps. TR, transplanting rate. SG, seedling grippers. Data are means ± standard deviation.

**Table 1.** ANOVA for the results of seedling pick-up tests

| Source[1] | Index[2], % | Sum | DOF[3] | Mean square | F-value | *p* value | Significance[4] |
|---|---|---|---|---|---|---|---|
| MC | SR | 29.4735 | 3 | 9.8245 | 4.9952 | 0.0044 | ** |
| | FR | 0.0382 | 3 | 0.0127 | 0.1622 | 0.9213 | NS |
| TR | SR | 33.7276 | 2 | 16.8638 | 8.5743 | 0.0007 | ** |
| | FR | 6.2449 | 2 | 3.1225 | 39.7166 | 0.0001 | ** |
| SG | SR | 95.4041 | 1 | 95.4041 | 48.5074 | 0.0001 | ** |
| | FR | 0.6689 | 1 | 0.6689 | 8.5087 | 0.0054 | ** |
| MC×TR | SR | 4.2827 | 3 | 1.4276 | 0.7258 | 0.5418 | NS |
| | FR | 0.0393 | 3 | 0.013 | 0.1653 | 0.9192 | NS |
| MC×SG | SR | 9.7704 | 6 | 1.6284 | 0.8279 | 0.5544 | NS |
| | FR | 0.1362 | 6 | 0.0227 | 0.2886 | 0.9394 | NS |
| TR×SG | SR | 4.283 | 2 | 2.1415 | 1.0888 | 0.3451 | NS |
| | FR | 2.6882 | 2 | 1.3441 | 17.0965 | 0.0001 | ** |
| MC×TR×SG | SR | 4.1787 | 6 | 0.6964 | 0.3541 | 0.9038 | NS |
| | FR | 0.0618 | 6 | 0.0103 | 0.131 | 0.9917 | NS |

[1] MC, moisture content of the root lumps; TR, transplanting rate; SG, seedling grippers. [2] SR, success ratio in picking up seedlings; FR, failure ratio in discharging seedlings. [3] DOF, degrees of freedom. [4] NS, no significant effect; **, significant level at $p < 0.01$.

optimal level of soil moisture content (44-59%) reported by Ryu *et al*. (2001). The difference may be attributed to the physicochemical properties of the substrates used in the two studies. In China, seedling substrates are a mixture of herbaceous peat rather than moss peat, which is mainly used in Europe and other countries (Mao *et al.,* 2014). Water availability to plant roots may improve the cohesion force of the root lumps, and wetting the roots may also serve to reduce the adhesion between the roots and the cell walls (Yang *et al.,* 1991). However, much water may make the root lumps so soft that it was hard for the pick-up pins to hold the herbaceous root soil firmly (Mao *et al*., 2014). The lowest SR (87.93 ± 1.75%) occurred at the maximum MC (65 ± 2%). The FR with MC of 3.04 ± 0.51%, 3.11 ± 0.43%, 3.09 ± 0.42% and 3.07 ± 0.52% were 50 ± 2%, 55 ± 2%, 60 ± 2% and 65 ± 2%, respectively. Obviously, the testing results were rather equivalent. The developed device equipped with the pincette-type grippers could effectively discharge the seedling into the transplanting hopper regardless of the root system moisture content. The cases for discharging failures occurred mainly when the leaves were tangled with the pins, and thus, the seedlings could not be removed off the pins easily. This fact confirms again that short plants are more suitable for mechanized transplantation (Shaw, 1993).

With the increase of TR, FR decreased and FR rised (Fig. 7b). At TRs of 30 r/min, 40 r/min and 50 r/min, the SRs were 89.42 ± 1.79%, 88.86 ± 2.24% and 87.77 ± 1.54%, respectively, and the FRs were 2.74 ± 0.44%, 3.04 ± 0.32% and 3.46 ± 0.31%, respectively. Obviously, a high performance could be achieved as the seedling pick-up device worked at a low speed of 30 r/min. The reason for the decrease of SR was that seedling damages at the extraction point were significantly intensified as the device ran fast. It was also found that the leaves were often torn by the pins at the high-speed picking operation. When the uniform, short and sturdy seedlings were used for transplanting, the problem of entanglement between leaves and pins could be significantly alleviated (Shaw, 1993). In some cases, the pins released seedlings backward into the hopper wall or out of the hopper, which resulted in much breakage of root soil and inexact seedling discharge. At the discharge point, the pins must be slightly upward relative to the vertical direction, so as to adequately account for the inertia acting on the seedlings (Choi *et al*., 2002). In this case, the seedlings were released freely downward into the transplanting hopper. An effective method was that the seedlings could be released before the discharge point through adjusting the spring inside the gripper trigger action. With the help of a slight inertia, the seedlings were smoothly discharged into the hopper where they were to be transplanted into the ground.

For the pincette-type four-pin gripper, SR = 89.84 ± 1.47% and FR = 2.98 ± 0.55%. For the two-pin gripper, SR = 87.53 ± 1.75% and FR = 3.17 ± 0.34%. Obviously, the effects of seedling extraction using the four-pin gripper were higher versus the two-pin gripper. Although four smaller action points were available for seedling extraction, the gripper with multiple fine pins was very likely to dispersedly grasp the maximum amount of root mass. As a result, the gripper holded the seedlings firmly to conquer the adhesion force between roots and cell walls. When two pieces of pins were used to penetrate into the root mass for seedling extraction, the root system along the grasping line became a major component for intensively bearing force. If the root soils were not well developed, soil crack might occur easily along the grasping line once the gripper tried to hold the root system firmly. Thereby, root crack is gradually expanded along with the lifting, transferring, and discharging of seedlings, and thus the seedlings could not be completely extracted from the tray cell. Cell root volume may be so large that the root soil would not fear any grasping. However, formation of a large root system requires the use of high-level seedling raising techniques, including more fibrous growth media, fine growth environment control, and strict management of water and fertilizer. Such techniques will raise the production costs for seedlings. In fact, seedlings used for mechanized transplanting only need to be uniform, short, and sturdy (Shaw, 1993). It is always hoped that the full potential of seedling production and automatic transplanting is to be realized. According to the testing results in this study, seedling removal with a four-pin gripper should be accomplished as simply as possible to reduce the transplanting cost. Compared with other studies (Yang *et al*., 1991; Ryu *et al*., 2001; Choi *et al*., 2002; Yu *et al*., 2013; Ye *et al*., 2013), it was further proved that acting on the root mass with four fine pick-up pins could facilitate the seedling extraction better.

On the whole, there existed an optimum range of the root system moisture content that would facilitate the extraction and discharge of seedlings. To achieve a high percentage of successful extractions, the pick-up pins should be guaranteed to grasp the maximum amount of root soil within the cell. For this reason, the pick-up pins should open very large to penetrate into the root system as deep as possible within the cell depth, and then hold the root soil firmly for extraction. The testing results showed that the pick-up device can extract 80 seedlings per minute with a SR of 89.17 ± 2.24% and a FR of 3.04 ± 0.32%. The gripper with multiple fine pins moved by the swing pick-up device could effectively complete a work cycle of extracting, transferring, and discharging a seedling. If the root system was well developed, and the blank cells and unhealthy seedlings in the trays could be filled by another robotic transplanter based on machine vision, the pick-up device would perform well. Further, if the pick-up device equipped with more grippers can extract one row of seedlings from the tray at a time, its working speed may greatly exceed that of hand placement. This transplanter with the doorframe-type swinging pick-up device would play an important role in the mechanization of vegetable seedling transplanting production.

As conclusions, a doorframe-type swing seedling pick-up device for automatic transplanting of several field-grown vegetables was successfully developed with design planning, innovation of mechanism combination, and kinematics simulation. Its performance was evaluated in laboratory. Equipped with two grippers, this device can extract two seedlings at a work cycle from the 128/72-cell tray and transfer them to a discharging point where they can be transplanted into the soil. As the first prototype, the performance tests were conducted to find out the optimal operation parameters and transplant production conditions. The testing results showed that the gripper with multiple fine pins moved by the swing pick-up device could effectively extract seedlings from the tray cells. The success ratio in picking up seedlings was up to 90% and the failure ratio in discharging seedlings was 3%. The developed seedling pick-up device was thus evaluated as practically applicable to the locally made vegetable transplanters.

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