Paper:

Development of an Automated System for the Selective Harvesting of Radicchio

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In recent years, robotics and automation technology have spread significantly throughout the agricultural harvesting sector. The increased productivity and the high cost of labour are some of the main reasons for this phenomenon. However, the harvesting of some crops is still carried out manually. One such crop is radicchio, which ripens at various times, thus requiring selective harvesting. This paper presents the development of an innovative modular system which aims at automating the harvesting of radicchio. Each module adopts a mechanical sensor to recognize the ripening status of the plant, on the basis of the hardness/compliance of its core. The module contains a cutting system, made of pneumatically actuated blades, and a harvesting system, made of two electrically powered tape conveyors. The module is intended to be used for a single row of radicchio cultivations using a tractor to move it. In laboratory tests the module prototype was manually moved. For this reason, the prototype is equipped with a control panel for monitoring and commanding. The conceived design, technical specifications and the prototype of the module are presented in detail. In addition, performances and functional tests are discussed. Finally, the functionality of the whole system is validated.

Keywords: radicchio harvesting, ripening sensor, agricultural robots, pneumatics

1. Introduction

Modern agriculture shows two opposite trends: on the one hand, an increase in productivity [1, 2], the demand for higher food quality [3], for greater crop yield, size of fields [4] and cost reduction [3]; on the other hand, the increase of the average age of agricultural workers and the difficulty of finding younger trained workers [5, 6]. These dynamics have led to widespread mechanization and automation in many agricultural operations such as soil tillage and fertilizing, seeding, planting, cleaning, handling and transportation of agricultural products [3]. At the same time, high-value crops (so called because of their high labour intensity [7] which accounts for 30% to 60% of the total cost [3, 8]) of fruits and vegetables provide a significant opportunity for robotic systems to automate harvesting [9]. Automation helps to overcome the uncertain availability of labour and reduces costs in terms of time, money and energy saving [10]. Agricultural robots require the development of: sensors allowing for detection and localization of products based on colour, shape, and texture features [10–13]; sensors and algorithms to detect ripening [14–18]; devices for picking, grasping, cutting, weeding [5–8, 19–27], spraying and fertilisation [28]; strategies and algorithms for path planning, as well as robot guidance and navigation systems [4, 29, 30]. Moreover, some wearable/portable robotic devices have already been developed to assist farm workers [31, 32]. However, the harvesting of various high-value crops is still done manually. This is due to the complexity and uncertainty of the field conditions in which operations are to be performed and the lack of suitable technology.

This is the case of Chioggia's red radicchio, hereinafter called radicchio, which calls for time consuming, demanding and laborious harvesting. Moreover, it is a selective process and must be performed several times during the production period. Italy is one of the exclusive producers of radicchio [33], which significantly contributes to total agricultural income on local levels. In fact, in the north eastern region it accounts for 84% of national production with the central region accounting for the remaining national production.

An agricultural robot for the harvesting of radicchio has been developed [34]. It is based on a double four-bar linkage architecture and a specialized gripper. A vision-based module provides for plant detection and localization. However, it is not equipped with devices for the recognition of the ripening status of radicchio plants.

This paper describes an innovative automated modular system for selective harvesting of radicchio. Each module of the system, conceived for central Italy's radicchio cultivation, autonomously recognizes the ripening status of a radicchio plant through an appropriate mechanical sensor.

Moreover, the module performs the cutting and the harvesting of the ripe plants and also provides for their collection. The mechanical design, individual components and the whole prototype of the module will be described. The experimental activity and results will be presented.

The paper is divided as follows: Section 2 presents general features of radicchio; in Section 3, the system's working principle, mechanical design and prototype are described; in Section 4, experimental activities and results are reported and discussed.

2. Radicchio: Morphology, Harvesting and Cultivation Aspects

Radicchio is a leafy vegetable with green coloured non-edible outer leaves and red coloured edible inner leaves [33]. The latter are round in shape with a white midrib. They form the core of the radicchio plant. The root is made of a main inverted cone shaped branch from which small filiform roots branch out.

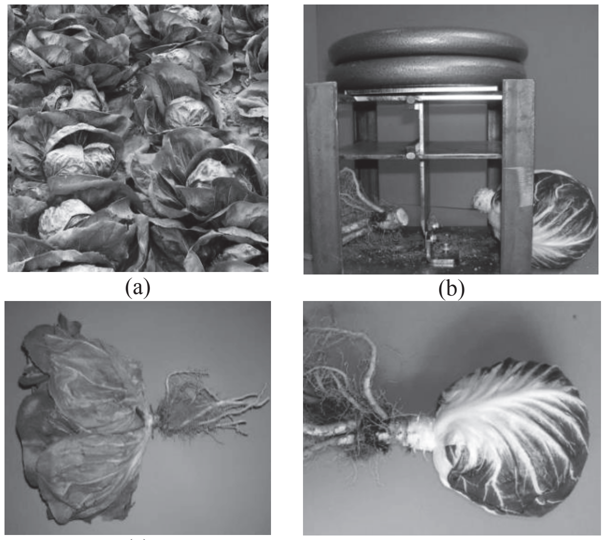
Since this study focused on the harvesting of radicchio in the central region of Italy, quantitative data were not available from literature. Hence, preliminary experimental measurements were carried out on 10 plants to assess typical values of plant dimensions (external diameter, root length, root diameter below the base leaves), of the weight and of the minimal cutting force of the main root. The cutting force measurement required the design and the prototyping of a testbed made of a frame and two commercial blades, used by mowers. One of the blades was fixed and rigidly connected to the frame; the other one moved and sustained an external weight which was applied as a cutting force. Tests were carried out in static conditions: the moving blade was placed on the main root and gradually loaded until the cutting of the main root. The weight of the moving blade was equal to 10 N; each load step was increased by 10 N. **Table 1** reports the range of the measurements results.

Table 1. Range of values in radicchio plants.

External diameter [mm]	Root length [mm]	Root diameter [mm]	Weight [grams]	Cutting force [N]
$150 \div 230$	$150 \div 300$	$20 \div 25$	$180 \div 450$	$90 \div 100$

In the same experimental session, measurements on the placement of the plants in the field were carried out.

To optimize the cultivation field layout, radicchio plants are sown in rows spaced of about 400–500 mm. Along each row, plants are spaced of about 250–350 mm. To avoid standing water, dangerous for the seed, the rows are placed higher than the ground. The suitable placement of the plants is assured by the adoption of precision seeders. **Fig. 1** shows the cultivation field (a), the testbed for the cutting force measurement (b), a whole plant (c) and the core of radicchio (d).



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

Fig. 1. The radicchio plant: (a) typical cultivation field; (b) testbed for the measurement of the cutting force; (c) the whole plant; (d) the core.

Two kinds of plants of radicchio exist: "precoce," sown in August and harvested between September and December, and "tardivo," sown in July and harvested between October and February [33]. In both cases, the time scaled ripening leads to a selective harvesting, manually performed by harvester teams in 2 or 3 shifts. Only in the last shift an automatic commercial mower can be used.

The ripening state of a plant depends on the hardness of its core, as perceived by the touch of the harvester: a compliant (soft) core indicates an unripe plant. On the contrary, a stiff (hard) core means a ripe plant, ready to be harvested. In the latter, the main branch of the root is cut at about 20–30 mm below the soil. The plant is harvested and the outer leaves are removed. Finally, the root is completely cut off.

3. Mechanical Design

3.1. Design Idea

The selective harvesting takes into account two principal aspects: during the first collection of radicchio cultivation not all the plants are ripe; it could be possible that adjacent plants, belonging to different rows, or consecutive plants, belonging to the same row, are not ready to be harvested at the same time. These aspects suggest: the adoption of a device to recognize the ripening status of each plant; an independent processing of each row; the harvesting of a plant has to be performed in order not to interfere with the neighbouring plants. For these reasons, an automated system for the harvesting of radicchio was conceived. It is made of a series of independent moduli, one for each row. Each module performs the operations later described as technical specifications. The architecture of the system is shown in **Fig. 2**.

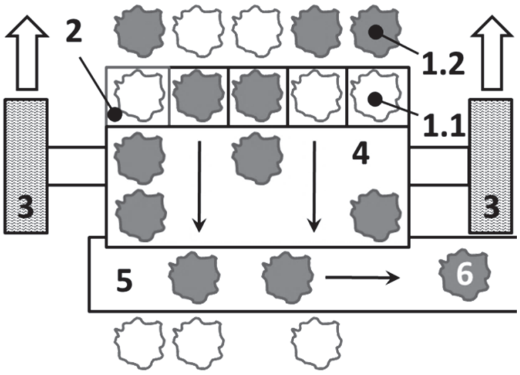


Fig. 2. The architecture of the proposed automated system: (1.1) not ripe plant; (1.2) ripe plant; (2) single module; (3) moving wheels; (4) and (5) conveyors; (6) harvested plants.

The conceived idea allowed the study and the development of a single module, to be replicated for each row.

3.2. Technical Specifications of the Module

Each module must:

- continuously move on the ground;
- recognize the ripening status of the plant without damaging it;
- perform the cutting of the main root;
- move the harvested plant to a fixed height where a common conveying device is placed. The removal of the outer leaves is not required;
- pass over an unripe plant without damaging it;
- recover the rest position between two plants;
- process only one plant at a time, with no interference with other plants;
- be equipped with adjustable devices to be adapted to different operating conditions of the external environment;
- be adjustable along the vertical axis to detect each radicchio plant and, if ripe, to cut and pick it.

Since the average distance between two consecutive plants is about 300 mm and the feed rate is equal to 250 m/h, all the mentioned operations have to be performed in about 4 s. In addition, the cutting force must be at least equal to 100 N and applied under the base leaves.

3.3. The Module

The module is equipped with the *ripening sensor*, the *cutting system* and the *harvesting system*, mounted on the *frame*.

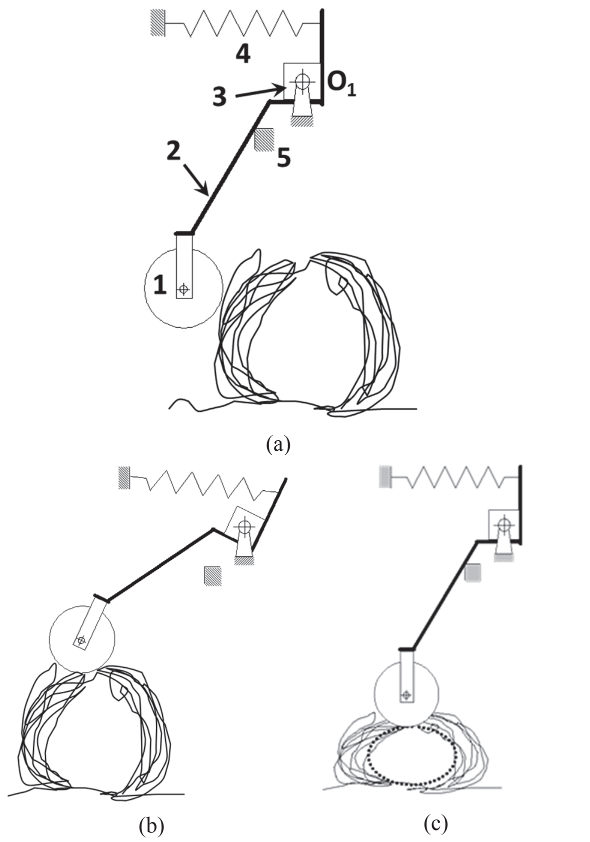


Fig. 3. Schematic of the ripening sensor: (a) components; behaviour with (b) a ripe plant; (c) a not ripe plant.

3.3.1. The Ripening Sensor

The ripening sensor is a mechanical device that recognizes the hardness/compliance of the radicchio plant. The mechanical solution was adopted with the aim to: reproduce the manual operation for the recognition of the ripening status of the plant; provide for a sensor not affected by disturbances from the external environment as water, dirt, soil, temperature and light conditions; avoid the use of an electronic control system and electric wirings.

With reference to **Fig. 3(a)**, the sensor consists in a wheel (1) linked to one end of the shaped bar (2). This bar is rigidly assembled with a cam and the square shaped bar (3), in order to create the hinge O_1 with the aluminium frame of the sensor.

On the other end of the shaped bar, the spring (4) pushes the bar against the mechanical end-stroke (5), belonging to the frame of the sensor. The sensing element is the wheel, the only component in contact with plants. The kinematic of the sensor depends on the stiffness of the plant. The sensor detects only ripe plants. With reference to **Fig. 3(b)**, if the plant is ripe, the wheel-plant contact is stiff: the wheel rolls along the plant, following the profile, and provides for the rotation of the bar around the hinge; the contact wheel-plant is always assured by the pull force of the spring. The rotation of the bar is detected by an end-stroke sensor, activated by the cam, whose output signal provides for the start of the subsequent opera-

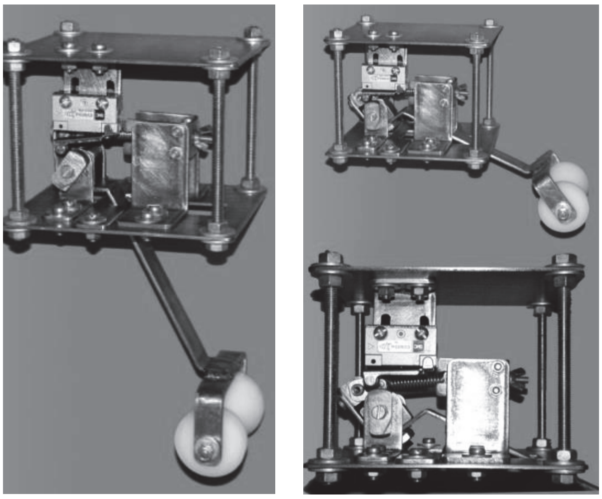


Fig. 4. The prototype of the ripening sensor.

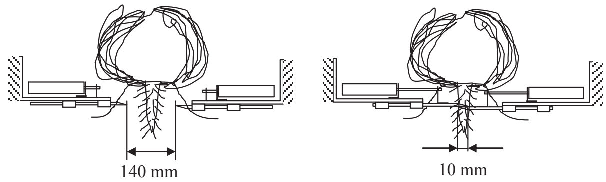


Fig. 5. Schematic of the first cutting system at rest and after cutting.

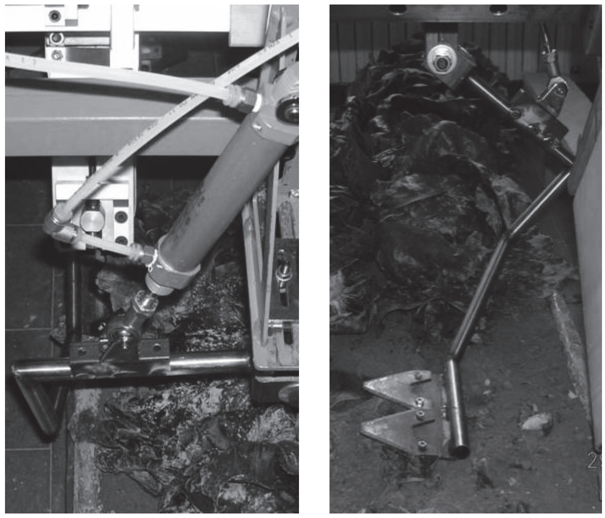


Fig. 6. The second cutting system at rest and after cutting.

tions. If the plant is not ripe, as shown in **Fig. 3(c)**, the wheel-plant contact is compliant: the wheel pushes down the plant, with no rotation of the bar. To facilitate the displacement of the leaves, a central channel was created in the wheel, made of two opposing idler conical frustums mounted as an hourglass. The height of the wheel, the rest angle of the cam and the pre-load of the spring are adjustable to reduce the crushing of the plant, the contact time and to optimize the ripening threshold. The former can be adjusted by changing the placement of the sensor on the module frame; the latter can be changed by rotating the cam; the last one can be changed by moving the extremity of the spring not connected to the bar through a nut-screw system.

The choice of the proposed sensing strategy was a result of the following considerations: 1.) the optimal detection of a plant should be performed from the top side, as also proposed in [34]; 2.) vertical development of the sensor must prevent interference with the other plants; 3.) absence of interference with rocks or soil agglomerations, not present on the top of a plant. The prototyped device is shown in **Fig. 4**.

3.3.2. The Cutting System

Several cutting solutions were considered. This section describes two systems that were considered to be most effective. The first system is made of two opposing blades parallel to the ground. They are placed below the base leaves, to the sides of the root, to reduce cutting time and to avoid interference between the blades and the leaves of each plant. The adherence and blade sliding on the soil could occur. Each blade is guided along a prismatic joint and is powered by a double-effect pneumatic cylinder (stroke, 80 mm; bore, 20 mm), for the approach to and from the root. At rest, the distance between the blades is equal to 140 mm. At the opposite end-stroke, an overlapping of about 10 mm occurs as shown in **Fig. 5**. The blade, the cylinder and the guides of the prismatic joint are supported by a steel frame with adjustable height. The second system consists in a shaped rod: one end is coupled to a fixed hinge, placed on the frame of the module. A couple of commercially available triangular blades were placed on the other end as shown in **Fig. 6**. A pneumatic cylinder (stroke, 100 mm; bore, 25 mm) powers the rod around the hinge: the set of blades dynamically approaches the main root and cuts it. The system should avoid adherence to the soil, perform a clean cut and not interfere with other plants during the movement of the module along the row. Moreover, it is equipped with an adjustable frame for the adaptability requirement previously cited.

3.3.3. The Harvesting System

The harvesting system is made of a couple of parallel tape conveyors whose axes are placed on the vertical plane. The angle of the conveyors, relative to the field, is the same. Each conveyor is independently powered by an electric motor and is made of an aluminium frame. Two opposed double-effect pneumatic cylinders (stroke, 100 mm; bore, 25 mm) allow for the frame to move towards and from the plant to be harvested. The plant is forced between the tapes and moved towards the discharge height H, as shown in **Fig. 7**. The distance L is equal to 240 mm, to allow the passage of each plant. The slope α is adjustable to avoid the crushing of the unripe plant foregoing the one to be harvested. The height H depends on the value of α. The tape is made of Polyvinyl chloride (PVC). To avoid the tape extraction, its inner side

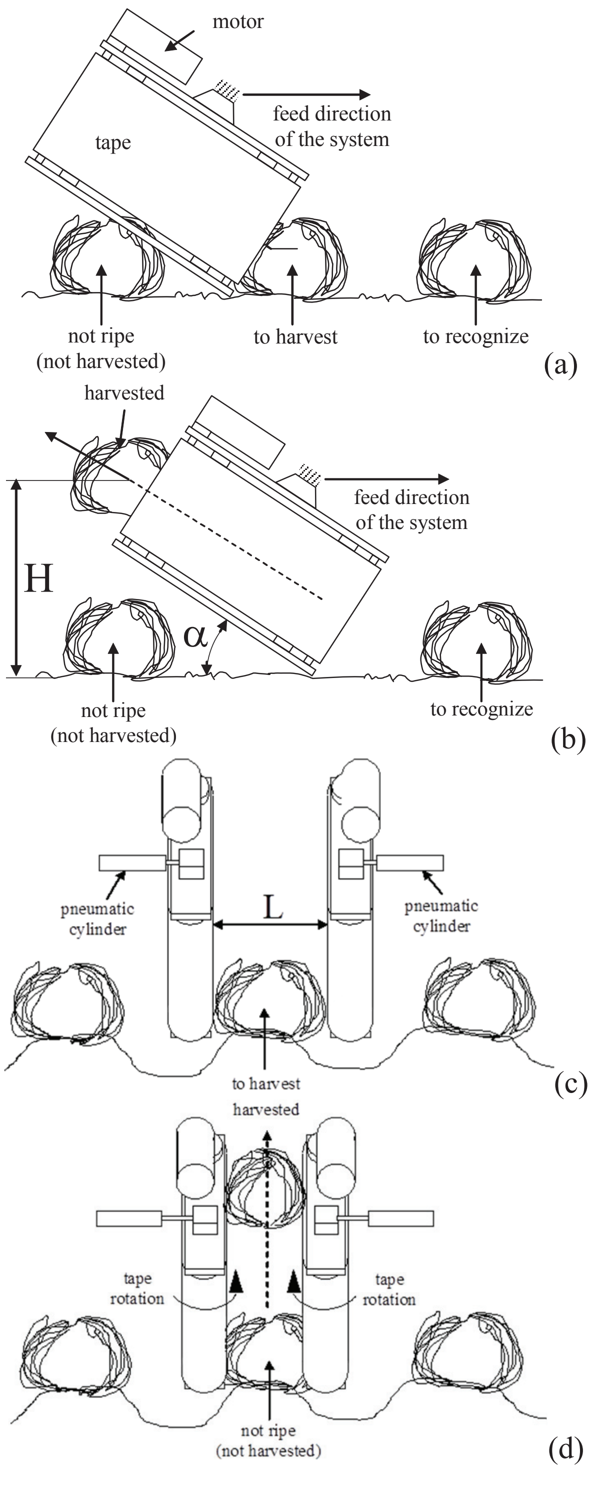


Fig. 7. Schematic of the working principle of the harvesting system. Lateral views: (a) the plant is recognized as ripe; (b) the plant is harvested. Frontal views: (c) tapes at rest; (d) tapes closed to the plant and moved by motors.

has a trapezoidal projecting profile to be interfaced with a groove realized on each pulley.

The outer side is covered by a high friction rubber to optimize plant gripping. The tape conveyor dimensions are 1600×250 mm (length $\times$ height). The pulley diameter is equal to 80 mm. A 45 W power gear motor provides for the movement of each tape, in order to satisfy a linear speed equal to 0.3 m/s. Each frame slides along a ball recirculation guide, directly mounted on the frame of the module.

3.3.4. The Module Frame

The module frame aims to support the previously described components of the module. The frame is made of two steel portals linked by four lateral steel bars to create a lower part allowing for obstacle-free passage of the plant. All components are mounted on the frame with joints. These are able to adjust the position of the components in relation to the plants and the ground.

The height of the module is adjustable since each portal is equipped with two wheels having adjustable heights.

The ripening sensor, placed on the front portal relative to the feed direction, and the cutting system are mounted by means of brackets with slots. The harvesting system is mounted on two moving bars with adjustable slope. For tape conveyors, a 24 V dc power supplier is mounted on the module frame.

The design idea envisions a tractor moving the module. Nevertheless, in the present study manual movement was considered. For this reason, two handles were mounted on the rear portal. In addition, a control, monitoring and command panel was placed between them.

The control entities are:

- cutting rate, controlled by two flow regulators placed between the double-stable valves and the pneumatic cylinders of the cutting system;
- pressure value, fixed by a pressure regulator;
- approach and leaving rate of the tapes.

The monitoring entities are:

- operating pressure: values are read by a manometer;
- ripening status: a pneumatic lamp is on when the ripening sensor detects the plant as ripe.

The command entities are:

- on/off electrical power for dc gearmotors;
- on/off pneumatic power;
- cutting;
- start/stop tape conveyors.

Figure 8 shows the module frame and the panel, as manufactured in the prototype.

4. Experimental Activity

The experimental activity was carried out in two steps: the first, to characterize the performances of the principal components of the module and the second to validate the functionality of the whole system.

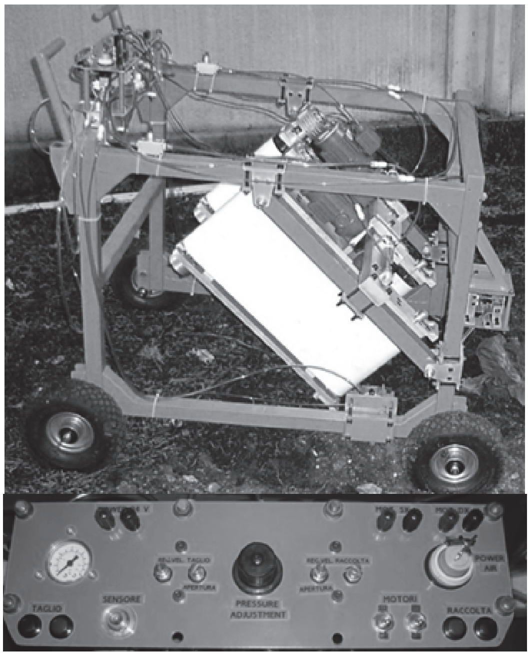


Fig. 8. The module frame: an overall view and the panel.

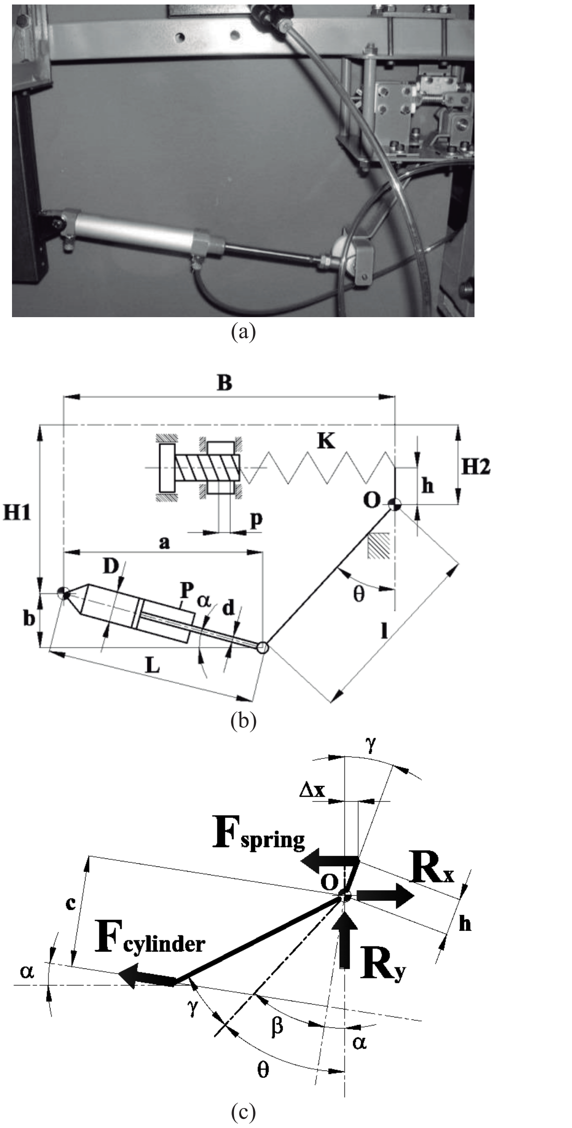


Fig. 9. Characterization of the ripening sensor: (a) the testbed; (b) the kinematic model; (c) the free body diagram.

4.1. Performance Tests

4.1.1. Characterization of the Ripening Sensor

The aim of the test was the assessment of the relationship between the required torque for the activation of the sensor and the rotation angle of the shaped bar according to several pre-load conditions of the spring. The testbed is shown in **Fig. 9(a)**.

The sensor was mounted on the module frame; its activation was provided by a pneumatic cylinder. The sensor, the cylinder and the support frames form the kinematic chain shown in **Fig. 9(b)** ($B = 163$ mm; $H_1 = 187$ mm; $H_2 = 75$ mm; $h = 25$ mm; $l = 207$ mm; $D = 25$ mm; $d = 10$ mm; $p = 0.8$ mm). The L dimension can change from 275 to 360 mm when the sensor is totally activated and at rest, respectively. Within this range of L, the values of θ and of α range from 31.7° to 66.2° and from −5.9° to 10.3°, respectively.

Tests were carried out as follows: for an imposed pre-load of the spring, the inlet air pressure value P of the cylinder was adjusted by a pressure regulator to rotate the shaped bar; hence, L value was measured.

The pre-load was imposed by setting the initial length of the spring by the nut-screw system. Starting from the length at rest, each pre-load condition expected a length increase equal to n times the pitch p of the screw, where n changed from 1 to 10. A manometer was adopted for monitoring the pressure. Six pressure values were settled: 0.05, 0.10, 0.15, 0.20, 0.30 and 0.40 MPa. Some difficulties in measuring the arm of the force of the cylinder around the hinge O were encountered; for the computation of the required torque, the kinematic model and the free body diagram, shown in **Figs. 9(b)** and **(c)**, were taken into account. The mass of the rod (about 0.2 kg) can be neglected if compared to the other forces.

The experimental relationship of L and θ and the analytical relationship computed by the following expressions were compared.

Due to their optimal fit, the same expressions were adopted to predict the behaviour of the sensor in a wide range of conditions, over and above the experimented ones.

With reference to **Figs. 9(b)** and **(c)** and considering the value of θ in its validity range, the following expressions can be written:

$$a = B - l \cdot \sin\theta, \quad (1)$$

$$b = l \cdot \cos\theta + H_2 - H_1, \quad (2)$$

$$L = \sqrt{a^2 + b^2}, \quad (3)$$

$$L \cdot \sin\alpha = b, \quad (4)$$

$$\alpha = \arcsin\left(\frac{l \cdot \cos\theta + H_2 - H_1}{L}\right), \quad (5)$$

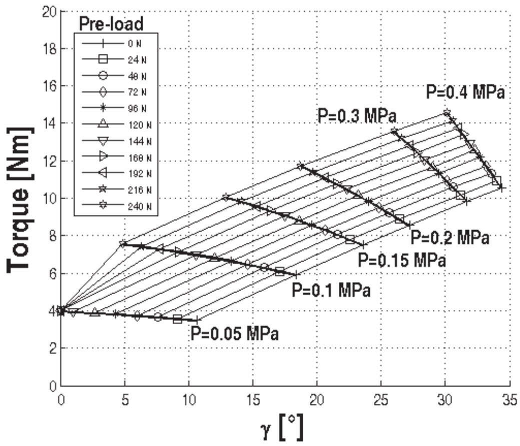


Fig. 10. Characteristic curve of the ripening sensor.

$$c = l \cdot \cos\beta, \qquad (6)$$

$$\beta = \theta - \alpha, \qquad (7)$$

where c is the arm of the force of the cylinder around the O of the sensor. The required torque T is equal to:

$$T = F_{cylinder} \cdot c, \qquad (8)$$

where

$$F_{cylinder} = P\pi\left(\frac{D^2 - d^2}{4}\right). \qquad (9)$$

According to the rotation equilibrium around the hinge O, the equilibrium equation can be written as:

$$F_{cylinder} \cdot c = F_{spring} \cdot h \cdot \cos\gamma, \qquad (10)$$

where

$$F_{spring} = K\left(\Delta x + \delta_{pre\text{-}load}\right), \qquad (11)$$

$$\Delta x = h \cdot \tan\gamma. \qquad (12)$$

For the spring constant K equal to 25 N/mm, the achieved sensor characteristic is shown in **Fig. 10**.

4.1.2. Characterization of the Cutting System

The aim of the test was the assessment of the performance of the cutting systems in order to select the best one.

For the first system, tests were carried out with a plant of radicchio, previously planted in a vase, placed between the two blades. The blades were manually approached to the main root of the plant. From this position, the air pressure value was increased until cutting of the main root occurred. Ten tests were performed. In some of them, the required cutting force was equal to 220 N, twice than the previously estimated, at a 0.65 MPa pressure value.

This result depends on two main factors. Firstly, not all the base leaves of the plants were at the same height from the soil: a greater cutting force was required to take into account contact and friction forces between the soil and the blades. Hence, on the guides of the prismatic joint an amount of soil was deposited and increased the effect of the friction. As consequence, the application of a static force is not sufficient to obtain the execution of the cut at each time.

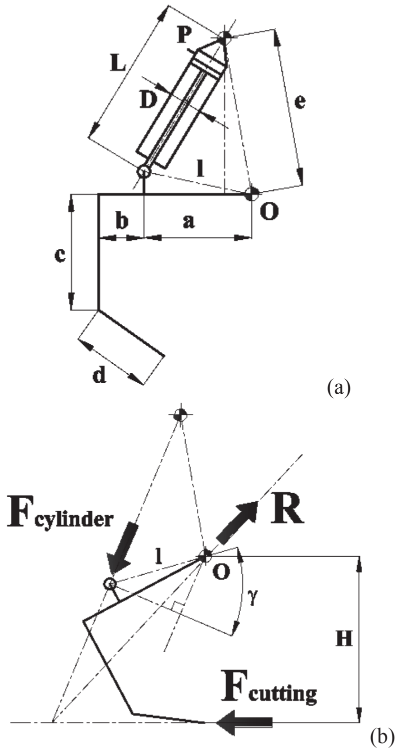


Fig. 11. Characterization of the second cutting system: (a) the kinematic model; (b) the free body diagram.

For the second system, the force-pressure characteristic was achieved considering the kinematic chain shown in **Fig. 11(a)** ($a = 190$ mm; $b = 80$ mm; $c = 205$ mm; $d = 115$ mm; $e = 280$ mm; $l = 200$ mm; $D = 25$ mm; L can change in the range 275–360 mm) and the free body diagram shown in **Fig. 11(b)** ($H = 290$ mm; $\gamma = 49°$). In the latter, the inertial effects were neglected due to the low values of the moving mass. The equilibrium equation around the hinge O can be written as:

$$F_{cylinder} \cdot l \cdot \cos\gamma = F_{cutting} \cdot H, \qquad (13)$$

where $F_{cylinder}$ is the same as defined in Eq. (9). The resulting $F_{cutting}$ is proportional to the inlet air pressure value of the pneumatic cylinder, $F_{cylinder}$. The cutting force equal to 100 N is reached for a pressure value equal to 0.40 MPa. At this value, all the cuts were successfully performed. Due to these results, the second cutting system was adopted and installed on the module frame.

4.1.3. Characterization of the Harvesting System

The aim of the characterization test was the assessment of the relationship between the pressure inside the cylinders for the approach of the tapes to the plant and the maximum closure force of the tapes.

The latter was measured by a load cell (TA4 AEP Transducers, 2000 N f.s.) placed between the tapes in correspondence of the pulleys. Two types of tests were carried out, depending on the placement of the load cell: one in the lower part of the tapes, near the soil; the other in the upper opposite part. Tapes were manually moved to the load cell. Then, starting from a pressure value equal to 0.1 MPa, the pressure was increased to 0.7 MPa, with a step of 0.1 MPa.

Regardless of the placement of the sensor, similar results were obtained.

The resulting curve is linear:

$$F_{closure} = k \cdot P - c, \quad \ldots \ldots \ldots \ldots \quad (14)$$

where $k = 500$ and $c = 33.7$.

4.2. Functional Tests

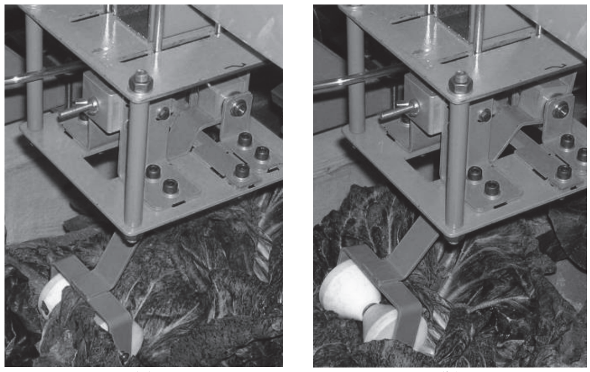
The aim of the functional test session was the assessment of the functionality of the whole module. The real field was simulated in the lab: a testbed was conceived in order to simulate a typical row of the radicchio cultivation. The testbed is a prismatic container (length, 2000 mm; width, 400 mm; depth, 200 mm) in which 8 plants, including four ripe ones, were placed at a distance of 250 mm. In order to move the prototype module, two guides were built and placed on the side of the container. Their height was set to maintain the wheel-ground contact area at the same level of the soil. During the manual movement of the module, the ripening detection, the cut and the harvesting of the plants were checked. Functional parameters of the ripening sensor, of the cutting and of the harvesting systems were settled.

Several attempts were carried out to assess the ripening threshold. The ripening sensor was moved continuously on all the plants at a low speed rate: the pre-load of the spring, the height of the sensor and the rest position of the cam were manually adjusted until the detection of the only ripe plants occurred. The ripening threshold corresponded to a contact force equal to 32 N, for a 160 N pre-load of the spring and for an angle γ equal to 6°. The assessed threshold value was coherent with the average value measured in preliminary tests: ripe plants were placed on a balance and pushed by fingers, as the current manual operation. The behaviour of the ripening sensor is shown in **Fig. 12**. As expected, the not ripe plant was pushed down by the wheel without the rotation of the shaped bar; on the contrary, the wheel followed the ripe plant profile causing the rotation of the shaped bar. The pneumatic lamp was always on in the case of a ripe plant.

At a pressure value between 0.40–0.45 MPa, the adopted cutting system performed a clean cut of all the roots of the ripe plants. Only the main root was involved by the cut; no leaf was damaged, as shown in **Fig. 13**.

At a pressure value of 0.15 MPa all the cut plants were harvested by the tapes. No leaf was damaged and the final core maintained its consistency after the conveying. **Fig. 14** show the harvesting of the plant. The optimal value of α was equal to 80°. During a plant processing, no interferences with the previous and the next plants were recorded.

Due to the manual movement, the sequence of actions was performed in a time little bit higher than 4 s. Qualitative tests were carried out by approaching the ripening sensor to the plants at different feed rates. All tests revealed the recognition of the only ripe plants. On the basis



(a) (b)

Fig. 12. The ripening sensor behaviour during the functional tests: (a) the plant is not ripe; (b) the plant is ripe.

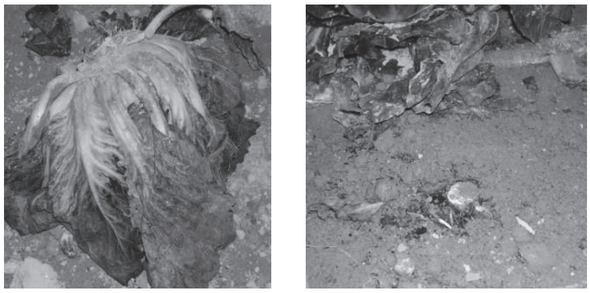
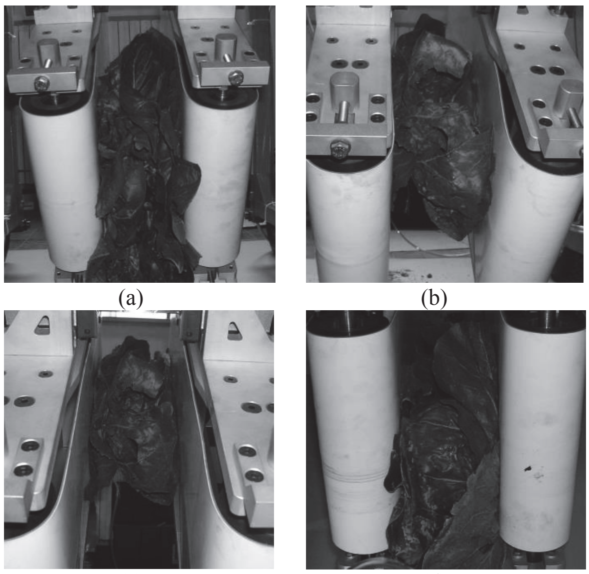


Fig. 13. The result of the cutting performed by the cutting system.



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

Fig. 14. Four steps of the harvesting process: (a) the plant is closed by the tapes; (b) plants starts to be moved by the tapes; (c) plant reaches the middle part of the tapes; (d) plant at the end of the tapes, ready to be moved towards the collecting system.

of the experimental results, system satisfied the technical specifications.

Compared to the existing robot [34], the proposed module shows the following advantages: the use of the ripening sensor, absent in the robot, detects only the plants to be really harvested; the possibility to treat 300 mm spaced plants along the row despite of 700 mm ones; due to the absence of a vision based control system, no false detections or poor localizations can occur if the plants are completely obscured by the leaves or if the plants are too small and uncentred, respectively; absence of an electronic control system and electronic devices; no sensors calibration with the exception of the pre-load of the spring; compact size and modularity for a simple interfacing to a tractor.

5. Conclusions

The harvesting of radicchio is still manually performed because the ripening status of such plant is time scaled. This means a selective harvesting to be performed three or more times during the harvesting period. In this paper, a concept of an automated system for the radicchio harvesting was presented. The system was conceived to be made of independent moduli, one for each cultivation row of radicchio, moved by a tractor. Each module is equipped with three principal components: 1.) a ripening sensor that autonomously recognizes the ripening status of radicchio on the basis of the hardness of the plant; 2.) a cutting system, consisting in a shaped bar with two triangular blades that dynamically provide for the cut of the main root of a ripe plant, under the base leaves; 3.) a harvesting system consisting in two parallel tape conveyors which move the cut plant towards a collecting system.

Characteristic curves of the above mentioned components were reported. The module, moreover, is equipped with pneumatic and electric actuation. Experimental tests, carried out in laboratory with a testbed simulating the real field condition, validated the functionality of the module and revealed a good performance. Each ripe plant was correctly recognized; a clean cut was performed under the base leaves without damaging the processed plant and the adjacent ones; all the cut plants were harvested with no damage. The module overpassed unripe plants without damaging them. In addition, all the components can be adjusted on the basis of the field conditions.

In the near future, a larger prototype based on this concept will be used for field tests, for further assessment.

References:

[1] S. Y. Nof, "Handbook of automation 1st ed.," Springer, 2009.

[2] Q. Zhang, "Opportunity of robotics in specialty crop production," IFAC Proc. Volumes, Vol.46, No.9, pp. 38-39, 2013.

[3] M. Ruiz-Altisent, J. Ortiz-Cañavate, and C. Valero, "Fruit and vegetables harvesting systems," Production Practices and Quality Assesment of Food Crops, Vol.1, Springer Netherlands, pp. 261-285, 2004.

[4] Y. Nagasaka, N. Umeda, Y. Kanetai, K. Taniwaki, and Y. Sasaki, "Autonomous guidance for rice transplanting using global positioning and gyroscopes," Computers and Electronics in Agriculture, Vol.43, No.3, pp. 223-234, 2004.

[5] M. Iida, M. Suguri, R. Uchida, M. Ishibashi, H. Kurita, C. Won-Jae, R. Masuda, and K. Ohdoi, "Advanced Harvesting System by using a Combine Robot," IFAC Proc. Volumes, Vol.46, No.4, pp. 40-44, 2013.

[6] Z. Zhang, N. Noguchi, K. Ishii, L. Yang, and C. Zhang, "Development of a robot combine harvester for wheat and paddy harvesting," IFAC Proc. Volumes, Vol.46, No.4, pp. 45-48, 2013.

[7] C. W. Bac, E. J. van Henten, J. Hemming, and Y. Edan, "Harvesting Robots for High-value Crops: State-of-the-art Review and Challenges Ahead," J. of Field Robotics, Vol.31, No.6, pp. 888-911, 2014.

[8] A. Bechar and C. Vigneault, "Agricultural robots for field operations: Concepts and components," Biosystems Engineering, Vol.149, pp. 94-111, 2016.

[9] S. Bachche, "Deliberation on Design Strategies of Automatic Harvesting Systems: A Survey," Robotics, Vol.4, pp. 194-222, 2015.

[10] A. Gongal, S. Amatya, M. Karkee, Q. Zhang, and K. Lewis, "Sensors and systems for fruit detection and localization: A review," Computers and Electronics in Agriculture, Vol.116, pp. 8-19, 2015.

[11] E. J. Pekkeriet, E. J. Van Hente, and J. B. Campen, "Contribution of innovative technologies to new developments in horticulture," Acta Hortic., Vol.1099, pp. 45-54, 2015.

[12] M. Monta and K. Namba, "Mobile Quality Evaluation Robot for Making Agricultural Products Traceable," Int. J. of Automation Technology, Vol.8, No.2, pp. 238-242, 2014.

[13] M. Yuasa and I. Mizuuchi, "A control Method for a Swarm of Plant Pot Robots that Uses Artificial Potential Fields for Effective Utilization of Sunlight," J. of Robotics and Mechatronics, Vol.26, No.4, pp. 505-512, 2014.

[14] N. Sivakumar, P. Kulkarni, and M. D. Nandesh, "Automatic Recognition and Harvesting of Ripe Tomatoes under Greenhouse Conditions – A Survey," Int. J. of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering, Vol.3, No.12, pp. 40-42, 2015.

[15] H. Mohamadi, M. Omid, and R. Alimardani, "Detection of red ripe tomatoes on stem using Image Processing Techniques," J. of American Science, Vol.7, No.7, pp. 376-379, 2011.

[16] N. B. Ghozlen, Z. G. Cerovic, C. Germain, S. Toutain, and G. Latouche, "Non-Destructive Optical Monitoring of Grape Maturation by Proximal Sensing," Sensor, Vol.10, No.11, pp. 10040-10068, 2010.

[17] Y. Sarig, "Potential Applications of Artificial Olfactory Sensing for Quality Evaluation of Fresh Produce," J. AGric. Engng. Res., Vol.77, No.3, pp. 239-258, 2000.

[18] M. Li, D. C. Slaughter, and J. F. Thompson, "Optical chlorophyll sensing system for banana ripening," Postharvest Biology and Technology, Vol.12, pp. 273-283, 1997.

[19] T. Raparelli, P. Beomonte Zobel, and F. Durante, "Development of a picking device of an orange harvesting machine," ICFP Proc. of the 6th Int. Conf. on Fluid Power Transmission and Control, pp. 335-339, 2005.

[20] N. Irie, N. Taguchi, T. Horie, and T. Ishimatss, "Development of Asparagus Harvester Coordinated with 3-D Vision Sensor," J. of Robotics and Mechatronics, Vol.21, No.5, pp. 583-589, 2009.

[21] N. Kondo and M. Monta, "Fruit Harvesting Robotics," J. of Robotics and Mechatronics, Vol.11, No.4, pp. 321-325, 1999.

[22] T. Mitsui, T. Kobayashi, T. Kagiya, A. Inaba, and S. Ooba, "Verification of a Weeding Robot "AIGAMO-ROBOT" for Paddy Fields," J. of Robotics and Mechatronics, Vol.20, No.2, pp. 228-233, 2008.

[23] J. Liu, P. Li, and Z. Li, "A Multi-Sensory End-Effector for Spherical Fruit Harvesting Robot," Proc. of the IEEE Int. Conf. on Automation and Logistics, pp. 258-262, Aug. 2007.

[24] M. G. Antonelli, L. Auriti, P. Beomonte Zobel, and T. Raparelli, "Development of a New Harvesting Module for Saffron Flower Detachment," Romanian Review of Precisione Mechanics, Optics and Mechatronics, Vol.39, pp. 163-168, 2011.

[25] T. Raparelli, P. Beomonte Zobel, M. G. Antonelli, and F. Durante, "An experience on the Automation of Plant Cutting Technique for Propagating Plants," Proc. of the 7th JFPS Symposium on Fluid Power, pp. 809-814, Sep. 2008.

[26] B. Jia, A. Zhu, S. X. Yang, and G. S. Mittal, "Integrated Gripper and Cutter in a Mobile Robotic System for Harvesting Greenhouse Products," Proc. of the 2009 IEEE Int. Conf. on Robotics and Biomimetics, pp. 1778-1783, Dec. 2009.

[27] A. P. Chatzimichali, I. P. Georgilas, and V. D. Tourassis, "Design of an advanced prototype robot for white asparagus harvesting," Proc. of 2009 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, pp. 887-892, Jul. 2009.

[28] G. Belforte, R. Deboli, P. Gay, P. Piccarolo, and D. Ricauda Aimonino, "Robot Design and Testing for Greenhouse Applications," Biosystems Engineering, Vol.95, No.3, pp. 309-321, 2006.

[29] D. D. Bochtis, C. G. C. Sorensen, and P. Busato, "Advances in agricultural machinery management: A review," Biosystems Engineering, Vol.126, pp. 69-81, 2014.

[30] I. A. Hameed, A. la Cour-Harbo, and O. L. Osen, "Side-to-Side 3D coverage pathe planning approach for agricultural robots to minimize skip/overlap areas between swaths," Robotics and Autonomous Systems, Vol.76, pp. 36-45, 2016.

[31] H. Kobayashi, T. Aida, and T. Hashimoto, "Muscle Suit Development and Factory Application," Int. J. of Automation Technology, Vol.3, No.6, pp. 709-715, 2009.

[32] E. Yagi, D. Harada, and M. Kobayashi, "Upper-limb Power-Assit Control for Agriculture Load Lifting," Int. J. of Automation Technology, Vol.3, No.6, pp. 716-722, 2009.

[33] M. Lucchin, S. Varotto, G. Barcaccia, and P. Parrini, "Chicory and endive," I. Vegetables, J. Prohen and F. Nuez (Eds.), New York, Springer, pp. 3-48, 2008.

[34] M. M. Foglia and G. Reina, "Agricultural Robot for Radicchio Harvesting," J. of Field Robotic, Vl.23, No.6/7, pp. 363-377, 2006.

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• "Control architecture of a 10 DOF lower limbs exoskeleton for gait rehabilitation," Int. J. of Advanced Robotic Systems, Vol.10, art. No.68, 2013.
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