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Verification of Self-Healing Ability by Plant Root Growth Achieving Plant-Symbiotic Robot Skin*

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Abstract—**For a robot, its skin is an important element that determines its performance and rigidity. Although a wide variety of robots have been actively developed, the performance of their skins is best when they are new. Research has been conducted on self-healing robots, however, their repair capabilities are limited and their performance after repair is no better than their original performance. In contrast, organisms can self-heal and can improve their individual capabilities through growth. Therefore, we aim to incorporate plants into the robot skin to give it different capabilities from conventional robots. In this study, we focused on the rapid growth of plant sprouts and grew pea sprouts and measured their root strength in a tensile test. Furthermore, we connected the two separated sponges by growing pea sprout roots, and confirmed their strength through tensile experimentation. This result indicated the possibility of using plant growth for self-healing capabilities.**

I. INTRODUCTION

In general, robot skins are composed of metal or other rigid materials. Although such robots are robust, they are difficult to repair if damaged. And, its rigidity could also cause harm to the outside environment. Therefore, the skin of the robot is one of the important factors that must be considered not only for the robot itself but also for its impact on the real environment. As an example, artificial skins have been developed, and devices with sensors and other functions have been proposed [1-3].

In recent years, there are also robots with soft skin, such as those called soft robots [4, 5]. In addition, many soft robots, such as the worm-type robot and the starfish-type robots, are implemented together with biomimicry [6,7]. Thus, soft robots are a field of active research, but there is concern about the possibility of damage due to their softness.

Because of the above and other factors, research is also being conducted on robots that can repair themselves when damaged. For example, research exists on pneumatic soft actuators that are self-healing by controlling temperature [8-10]. In addition, the leg-type robot that repairs itself using low-melting-point alloys for legs damaged under load, and the small-scale robot that repairs its function and structure for swimming using magnetic materials have been reported [11,12]. Most of these studies are realized by using magnetic objects and phase transitions of constituent materials due to temperature and so on. However, the repair capabilities of robots using the above methods are limited and often do not exceed their original performance. In contrast, even if a real organism is damaged, it can recover and regain its original shape and function, or it can grow and become even stronger.

Recently, bio-hybrid actuators using living organisms themselves have been developed, such as pneumatic grippers using spiders [13]. In addition, finger-shaped robots with skins cultured from cells of living organisms have also been reported [14,15]. On the other hand, research has also been conducted using plants, and a gripper that uses electrically controlled flycatcher has been reported [16]. Other examples include the paper-type soft actuator using pollen, the pine cone robot and the awn seed robot, they are controlled by moisture [17-19]. These studies can use the properties of animals and plants themselves because they do not mimic their abilities, but on the other hand, they mostly use dead organisms, parts of them, and plant seeds because of their ease of handling.

In the architectural field, the development of structural materials using photosynthetic cyanobacteria, called Living Building Materials (LBM) [20]. In addition, there exists research on the use of microorganisms in concrete restoration technology [21]. These are attempts to utilize living microorganisms and are made possible by their metabolism. However, since this is an architectural application, the scene of use is assumed to be a static environment, and it is assumed that the necessary materials can be supplied from outside sources. This makes it difficult to use in dynamic environments such as robots.

Therefore, we propose a framework of the plant-symbiotic robot skin that can be used in dynamic environments such as robots. Plants need water and light for growth, especially in the early stages, and we considered that these are relatively easier to access in the natural environment than artificial materials. Here we are going to use living plants, the growth of the plants is expected to improve the performance of the robotic skin. In this study, we focused on sprouts, which can be grown hydroponically, have low growing costs, and grow quickly. Then, among the sprouts, we decided to use pea sprouts experimentally. In this study, we first investigated the strength of the roots of the pea sprouts themselves by tensile tests. In addition, we grew pea sprouts on a foam material that was assumed to be a soft robot skin and verified the ability of the roots of the pea sprouts to connect the two sponges.

II. SUPPOSED SCENARIO

This research is a validation experiment conducted for the development of a plant-symbiotic robot skin. Our goal is for the robot skin that contains the plant to have the performance

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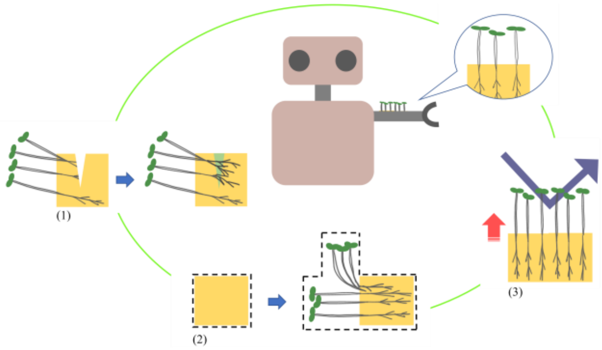

Figure 1. Schematic diagram showing the effectiveness of applying plant growth to robot skins. By using appropriate plants, the plant-symbiotic robot skin has the ability to (1) self-healing, (2) shape deformation, and (3) strengthen rigidity.

shown in the schematic diagram in Fig. 1. We believe that the plant-symbiotic robot skin can (1) self-healing, (2) shape deformation, and (3) strengthen rigidity of the skin, by containing plants. The numbers above correspond to the numbers in Fig. 1. And of the above developments, we have already examined the strengthening of rigidity by plant growth [22]. In that experiment, we first focused on sprouts because they are easy to grow and fast-growing. Therefore, we actually grew white radish sprouts, broccoli sprouts, and pea sprouts on foam material. And after their growth we measured their compressive stress using their medium. The experiment indicated that the pea sprouts showed 2 to 4 times the maximum compressive stress of the others. Based on these results, in this study, we decided to examine the self-healing ability by using pea sprouts, which were highly evaluated in the strengthening of rigidity. As a preliminary step in the implementation of the robot, we used the growth of pea sprouts to suture two separated soft materials by their roots.

III. TENSILE TEST OF ROOT OF PEA SPROUT

A. *Experimental Preparation*

To verify the self-healing ability of plant roots, we first measured the tensile strength of the pea sprouts themselves. First, since the roots of a single pea sprout were used as the sample, we needed to grow the pea sprouts in such a way that their roots did not tangle with each other. We fabricated containers using a 3d printer to enclose the roots of each pea sprout individually, and cultivated hydroponically by separating each of them (Fig. 2). The pea seeds were placed one by one at the top of this container, which was then further placed in a plastic container. And we filled these plastic containers with water up to the surface where the seeds were and started growing them. After sowing, the peas were stretched in the dark for about one week and then moved under LED for photosynthesis. In these processes, the reduced water was added as needed.

After growing pea sprouts as described above, a tensile test was conducted. MCT-2150 (A&D Co., Ltd.) was used for the test. The movement speed of the load cell was set at 10 mm/min.

When peas germinate, they develop parts that are roughly buds and roots. In this study, we aimed at self-healing by the roots of pea sprouts; therefore, it was necessary to measure the tensile strength of their roots. Therefore, in the actual tensile test, the part of the pea sprouts above the stem was cut off because it interfered with the test. In addition, plant roots tend to branch repeatedly and become thinner as they grow. This suggests that there may be differences in tensile strength depending on the location of the roots of the pea sprouts. In the test machine used in this study, tensile tests could only be performed from a minimum width of 2 cm due to interference between the jigs for the tensile test. Based on the above, we conducted tensile tests in the range of 0 cm to 2 cm of the root and in the range of 2 cm to 4 cm of the root. Here, the root range indicated corresponds to the distance from the area near the seed of the pea sprout. Four pea sprouts were used for each test.

Figure 2. Photograph of a container fabricated to prevent the roots of pea sprouts from entangling with each other during hydroponic cultivation. This is compartmentalized for each pea sprout. Part of the top is closed just enough to allow the roots to pass through to hold the seed in place.

B. *Experimental Result*

First, we grew the pea sprouts for about 35 days using the procedure as described above. Fig. 3(a) shows a photograph of grown pea sprouts taken out of the container and laid out. Some of the pea sprouts shown in Fig. 3(a) had become entangled only with their own roots. Since the purpose of this experiment was to measure root tension of pea sprouts, a certain amount of root length and a shape that could be easily clamped in the jig were required. Therefore, we selected pea sprouts with as few clumped roots as possible. Also, as shown in Fig. 3(a) we cut off the part of the stem that interfered with the test in the middle of the stem.

From the above, we performed tensile tests on the roots of pea sprouts. Fig. 3(b) shows an example of a pea sprout for the tensile test. As shown in Fig. 3(c), we conducted the experiment by directly clamping the top and bottom of the roots of the sample pea sprouts tight with a tensile test jig.

The results of the tensile test are shown in Fig. 3(d). In this graph, the horizontal axis represents the distance traveled by the load cell and the vertical axis represents the load applied to it. Based on the above test results, Table I summarizes the maximum tension applied to the roots of the pea sprouts before breakage. In addition, the average value of the maximum

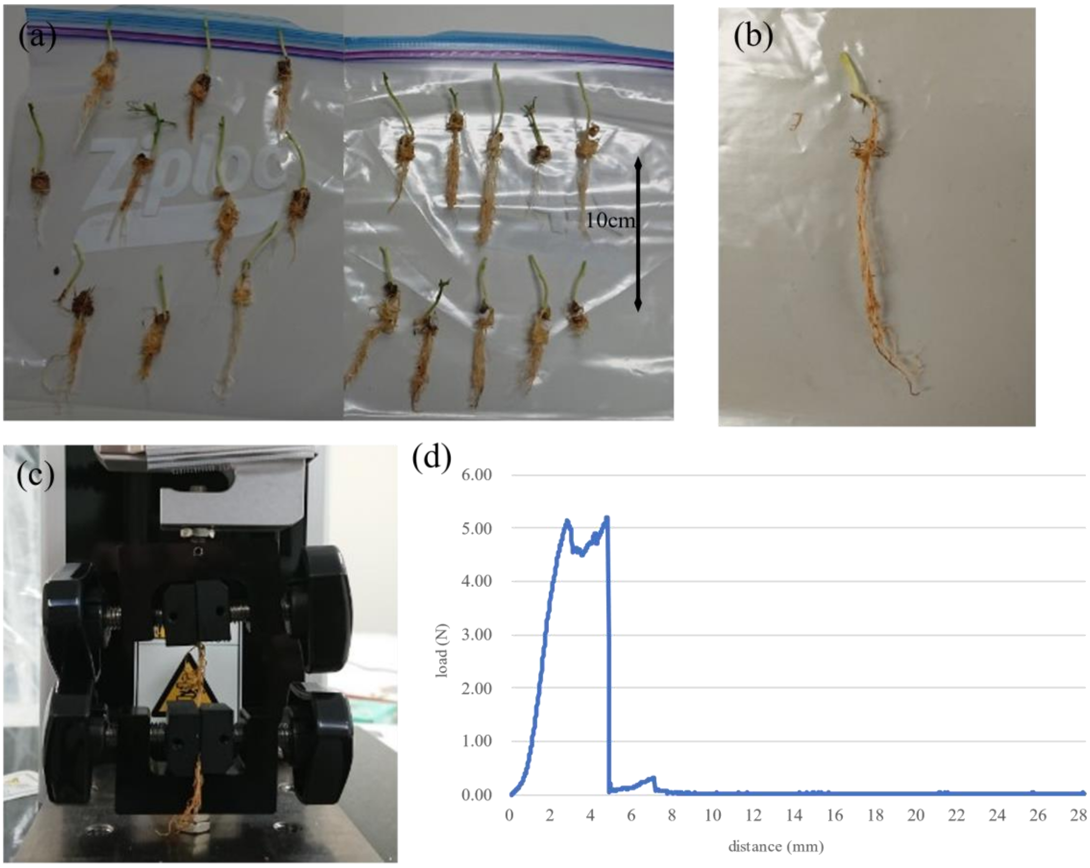

Figure 3. Pea sprouts as samples and their tensile tests. (a) Photograph of pea sprouts resulting from hydroponic cultivation, taken out of their containers and arranged side by side. From these, the samples were selected for tensile experiments. (b) Photograph of the root of pea sprout used as sample for the test. (c) Photograph showing a tensile test being performed on (b). The sample itself is gripped by the jig of the tensile testing machine. (d) Graph from the tensile test in (c). The horizontal axis represents the distance traveled by the load cell and the vertical axis represents the load applied to the sample. After the start of the test, the load on the sample increased rapidly, followed by intermittent rupture of it, and finally, the sample completely split apart.

TABLE I. MAXIMUM TENSILE LOAD APPLIED TO EACH SAMPLE IN TEST

Test Range (cm)	**Sample No.**	**Maximum Tensile Load (N)**
0 - 2	***1***	5.208
	2	5.943
	3	8.159
	4	2.711
	Average	5.505
2 - 4	***1***	5.452
	2	3.584
	3	6.207
	4	1.906
	Average	4.287

tension was calculated for each tested root section. Comparing the averages indicate that the maximum tension is slightly higher in the 0 cm to 2 cm range of the pea sprout roots than in the 2 cm to 4 cm range.

IV. RESTORATION BY PEA SPROUT ROOT

A. Experimental Preparation

The above experiments provided a measure of the strength of the pea sprout roots themselves. Next, based on this, we conducted an experiment to try to repair the soft material by pea sprout roots. In this study, we used polyurethane foam sponge as the restoration target. For restoration, first prepare a 3 cm × 3 cm × 3 cm cube of sponge. Then, a 3 cm × 3 cm × N cm (N = 1, 2, 3) sponge is placed on top of this sponge so that the 3 cm × 3 cm surface is touching. And then, pea sprout seeds are sown on top of these, and the sponges are allowed to connect with each other by growing pea roots. As described above, in this experiment we will observe how much the sponges are repaired from the completely separated sponges stacked on top of each other in the pre-repair state. The degree of repair is determined by measuring its tensile load using the same tensile testing machine (MCT-2150) as in the previous section. And in this experiment, in order to observe the differences in the bonding due to the depth of the roots, we prepared samples with varying thicknesses of the upper sponge: 1 cm, 2 cm, and 3 cm.

The structure of the sample is shown schematically in Fig. 4. In this experiment, we aim to evaluate the strength of the connection between sponges by the roots of grown pea sprouts by using a tensile test. In addition, the samples must be clamped and held in place by a jig during the tensile test. However, since the samples are made of sponges with pea sprouts, they are greatly deformed when held in the jig. Because of this problem, we fabricated a case with a 3d printer that was designed for tensile testing, and grew pea sprouts in the case. First, as shown in Fig. 4, we placed each sponge in a square cylindrical case, which is divided into upper and lower sections. The lower case has protrusions to be clamped by the jig. And then, the top and bottom cases containing the sponges were stacked so that the sponges were in contact with each other. Here, we envision that repair occurs as the roots of the pea sprouts grow and pass through the spaces between the upper and lower sponges. Therefore, it is necessary to hold the sponges in place in a manner that does not inhibit the growth of the pea sprouts so that they do not fall out of the case during the test. Therefore, we decided to hold the sponge in place by stringing it with polyester threads. As described above, the cases with the sponges inside were stacked and placed upright in a plastic container, and the container was filled with water so that the top layer of the sponges were soaked to the surface. We then sowed nine pea seeds in each sample and cultivated them for 35 days, as in the previous section. We also prepared four samples, one for each thickness of the upper sponge layer.

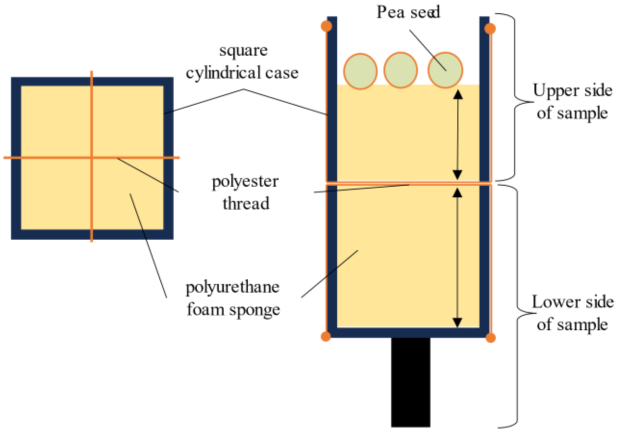

Figure 4. Schematic diagram of the sample for the soft material healing ability experiment by growth of pea sprouts roots. Sponge as a soft material is placed inside a square cylindrical case and held in place with a string. Stack two of these, and connect these by growing pea sprouts roots from the top. The lower part has a protrusion for a jig.

B. Experimental Result

Fig. 5(a) shows the pea sprouts grown for approximately 35 days according to the above procedure. As a result of the growing, each sample was sown with nine pea seeds to begin with, but not all of them actually grew normally. The actual number of pea sprouts grown was as described in Table II. Here, the number in parentheses indicates the number of pea sprouts, when counting the pea sprouts that had germinated but had not fully grown their stems. We then performed tensile tests on these samples. Fig. 5(b) is an example of a photograph of a sample in a tensile test. Thus, we used the grown pea sprouts and the 3d-printed case that supports them as a sample and placed them in a tensile tester. We fastened the lower case itself to the lower jig. However, the upper case parts could not be pre-installed with a structure to be gripped by the jig because of the need to provide space for the pea sprouts to grow.

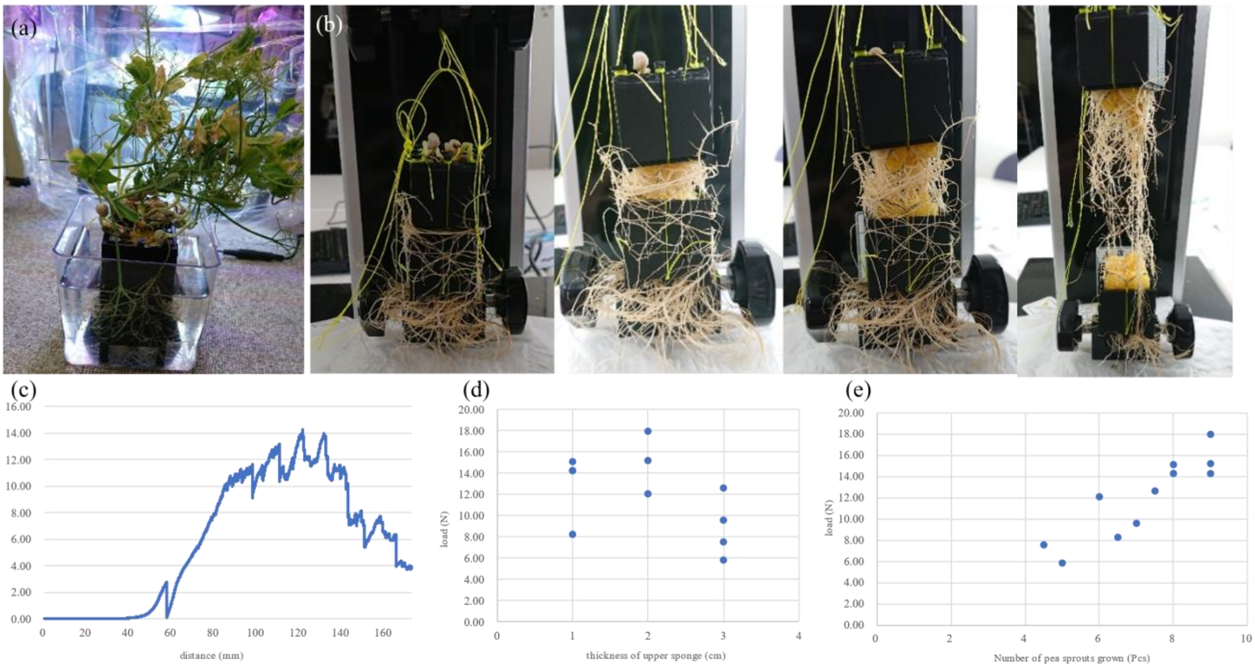

Figure 5. Tensile test to verify the reparation ability of sponge by root growth of pea sprouts. (a) Photographs showing the growth of the sample after the growth period. (b) Photograph of a tensile test being performed on a sample with pea sprouts growing on it. The pea sprouts are cut off at the stem because they interfere with the test. Photographs of the tensile test in progress are arranged in timeline order from left to right. (c) Graph from the tensile test in (b). The horizontal axis represents the distance traveled by the load cell and the vertical axis represents the load applied to the sample. It shows that as the sample is pulled, multiple pea sprouts' roots are continuously ruptured or pulled out of the sponge. (d) Graph showing on the horizontal axis the thickness of the upper sponge of the sample and on the vertical axis the maximum tensile load on the sample. (e) Graph showing on the horizontal axis the number of pea sprouts growing on the sample and on the vertical axis the maximum tensile load on the sample. The number of pea sprouts is positively correlated with the maximum tensile load.

Therefore, we decided to tie new polyester threads to the upper growing case, which was then gripped by the upper jig. And we also set the load cell travel speed of the tester to 10 mm/min in this test.

As a result of the above, a graph like Fig. 5(c) was obtained as an example. This graph shows the distance traveled by the load cell on the horizontal axis and the load on the vertical axis. And we summarize in Table II the maximum tension applied to the samples obtained as a result of the tests on each sample. Here, experimental data for the third sample when the thickness of the upper sponge was 2 cm was only obtained halfway through the experiment. Therefore, the maximum tension of the sample in question is the value in the data up to the halfway point. And from the above results we compiled our data into a graph. In this process, the data for sample 2cm-3 was omitted because it was clearly not obtained correctly. First, the graph in Fig. 5(d) shows the relationship between the maximum tensile load applied to the sample and the thickness of the upper sponge. This indicates that the effect of upper sponge thickness on tensile strength is almost minimal at this thickness scale. Furthermore, in Fig. 5(e), the relationship between the actual number of pea sprouts grown and the maximum tensile load is shown in the graph. This indicates that the maximum tensile load clearly increases with the number of pea sprouts growing.

TABLE II. NUMBER OF PEA SPROUTS AND MAXIMUM TENSILE LOAD OF SAMPLES IN EXPERIMENTS ON SOFT MATERIAL REPAIR BY ROOT GROWTH OF PEA SPROUTS

Thickness of Upper Sponge (cm)	**Sample No.**	**Number of Grown Pea Sprouts**	**Maximum Tensile Load (N)**
1	***1***	8	14.277
	2	6 (7)	8.262
	3	9	14.254
	4	8	15.110
2	***1***	9	17.962
	2	9	15.205
	3	9	4.154
	4	6	12.076
3	***1***	7	9.581
	2	4 (5)	7.549
	3	5	5.831
	4	7 (8)	12.624

V. DEGREE OF PLANT RESTORATIVE CAPACITY

Finally, we performed a tensile test on the sponge to verify the effectiveness of the plant's ability to repair the sponge. First, we cut out urethane sponges for tensile test samples. The shape of the sample was with a length of 5 cm and a square cross section. We used four types of sample cross-sections with single side lengths of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm. And we prepared eight samples of each cross-sectional size for tensile testing. The samples were directly fixed to the jig, and the movement speed of the load cell was 10 mm/min.

Fig. 6(a) shows the results of tensile tests on samples of each cross-sectional area. As shown in Fig. 6(a), the maximum tensile load increased with increasing cross-sectional area, and the elongation percentage until rupture occurred also increased.

Based on the results of the above tensile tests on sponges, we compared those with the results of the tensile tests on plant roots in Section 3. Fig. 6(b) shows the tensile load curves for plant roots and for sponges with cross sections of 0.5 cm and 1.0 cm on one side. As shown in Fig. 6(b), the maximum tensile load on the plant roots is about the same as that of a sponge with a cross section of 1.0 cm per side. In addition, with regard to the breaking elongation, it can be seen that the sponge is pulled 20 to 30 mm to rupture, in contrast to the plant, which is elongated only a few millimeters to rupture. Here, the cross-section from stem to root of the pea sprouts that were subjected to tensile testing was about 3 mm in diameter. This means that plant roots can obtain higher tensile stresses when compared to sponges of the same apparent cross-sectional area.

Next, we evaluated the ability of the sponge to be repaired by plant root growth which we did in Section 4. Fig. 6(c) shows the tensile load curves for a sponge with a cross section of 1.5 cm per side and for a sponge with connections by plant roots. As shown in Fig. 6(c), although the maximum tensile load is almost the same, the connection by the plant roots can be maintained over a longer distance compared to the sponge. This result is opposite to the relationship between the bean seedling roots themselves and the sponge shown in Fig. 6(b). This suggests that in the samples restored by plant roots, not only breaking of the pea sprouts themselves, but also pulling of the roots from the sponge and shape deformation of the sponge microstructure occurred. In addition, we approximate the

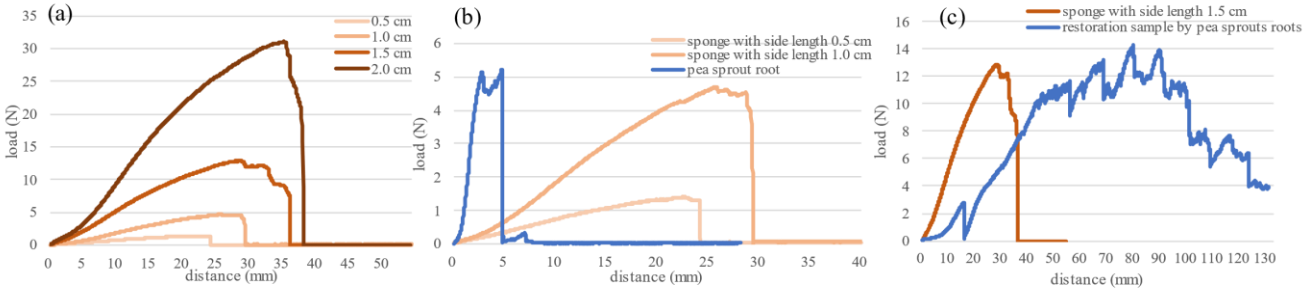

Figure 6. Tensile testing on sponges and the ability of plant roots to repair sponges. (a) Tensile load curves on sponge samples. The cross section of the sponge sample is square, and the side lengths are 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm, respectively. (b) Comparison of tensile load curves for the pea sprout root itself and for sponges with cross-sections of 0.5 cm and 1.0 cm in length per side. (c) Comparison of the tensile load curves for the sponge that was restored and connected by the growth of the pea sprouts' roots and for the sponge with a cross section of 1.5 cm in length per side.

cross-section of a pea sprout root to a circle about 3 mm in diameter, and assume that the sponge was joined by 9 pea sprouts in the restored sample. In this case, compared to the cross-sectional area (1.5 cm × 1.5 cm) of a sponge with approximately the same maximum tensile load, the connection by plant roots can be made with a smaller cross-sectional area. As a result, we can say that the restoration of the sponge (cross-sectional area 3 cm × 3 cm) by the pea sprout roots performed in Section 4 could be performed with the same intensity as if a quarter of its cross-sectional area were connected, in terms of the tensile stress of the sponge.

VI. CONCLUSION

In this study, we grew pea sprouts hydroponically and used a tensile tester to verify their ability to self-heal through their root growth. In these experiments we found that the soft material, sponge, could be held together by the roots of the pea sprouts. There was little effect on the maximum tensile load by changing the thickness of the sponge. This indicates that a soft skin with a thickness of about 3 cm can be repaired by the growth of pea sprout roots with a force of up to 12 N on average. In addition, we compared the results of restoration by plant roots to the maximum tensile load of the sponge itself. This suggests that about a quarter of the cross-sectional area of the sponge was repaired by plant roots. In the future, we suspect that the restoration intensity could be increased by allowing plant roots to grow at higher densities.

In the tensile test of the pea sprouts themselves, we used a method in which the samples were grasped directly with a jig. This may have affected the material of the sample in a way that it was pinched even before it was pulled.

Furthermore, the results of a tensile test on the pea sprouts themselves showed that they break when pulled with a force of about 2 to 8 N. However, the maximum connecting force of the sponges by the roots of multiple pea sprouts was about 18 N. We considered that the resulting values using multiple pea sprouts were relatively small compared to the tensile load of a single pea sprout. This result may be caused by the fact that the roots of the pea sprouts were pulled out of the sponges during the test. And, in this experiment, the sponges were pulled while held in place by the tensile test case and polyester threads. Therefore, the sponge could avoid serious deformation by the jig. But instead, they were pulled in a precarious condition of being supported by strings. This distorted the sponges, which we thought might have created a situation in which the roots of the pea sprouts could easily fall out. Thus, we considered that the roots of the pea sprouts showed a smaller maximum tension than expected because they were released from the tension before they reached the point of breakage.

In the future, we would like to explore the usefulness of plants-symbiotic robot skin, such as by examining the ability for shape deformation using pea sprouts. And we would also like to select plants that are more effective as robot skins.

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