New Dual-Arm Assistive Robot for Self-Feeding

Won-Kyung Song[1], Jongbae Kim[1], Kwang-Ok An[1], In-Ho Lee[1], Won-Jin Song[1], Bum-Suk Lee[2]

[1] Research Institute [2] National Rehabilitation Hospital
National Rehabilitation Center, 520, Suyu5-dong, Gangbuk-gu, Seoul, 142-884, Korea

wksong@nrc.go.kr, jbkim@nrc.go.kr, anko04@korea.kr, lio3596@korea.kr, swjli@korea.kr, iambs@nrc.go.kr

Abstract—**We propose a novel self-feeding robotic system that is suitable to handle Korean food including sticky rice. A self-feeding robotic system allows people with disabilities of upper limbs to eat the chosen food when they want it. The proposed robotic system consists of two arms: one is a grab-arm, and the other is a spoon-arm. The grab-arm chooses desired food from a food container, and the spoon-arm provides suitable feeding intervals for users. The merits of a proposed system are (a) easy to handle sticky rice, (b) compatibility of existing food containers, such as bowls, and (c) modularly applications for the economical point of view. We concentrate on Korean people with the upper limbs' disability and Korean food. We describe design concepts and an overall system structure with above mentioned merits.**

I. Introduction

Assistive robots with which users can directly interact have attracted worldwide attention. Assistive robots can assist people with disabilities and older persons in the activities of daily living. For improving quality of life and provisioning for demographic shifts, assistive robots could be one of solutions. The customizing users and their culture is one of crucial issues. In addition, the cost-effectiveness is important issue as well. Several kind of assistive robots have been proposed: self-feeding robots, workstation-based robots, powered wheelchair-based robots, mobile robots, exoskeletons, entertainments and monitoring robots and so on [1].

Officially registered people with disabilities in Korea are already over 2 million due to illnesses, injuries, and natural aging processes [2]. More than one third of the disabled persons are older persons. Moreover, older persons are over 10% in Korea due to lengthening the span of their life and decline in birthrate. Effective care-giving within restricted resources is one of compulsory problems.

In order to support care-giving tasks for the people with disabilities and older persons, caregivers should physically interact with the people. For example, caregivers support the persons to have a meal, change their clothes, reposition their posture, transfer their locations, and take a bath. Other tasks in the care of the disabled and the elderly could include activities of daily living. Among these activities, having a meal is one of essential activities for their living and caregivers should interact with the people frequently, i.e., kind of food, and the feeding interval. Having a meal could be replaced with existing robotic technologies. Assistive robots are solutions to deal with supporting the activities of daily livings.

Several assistive robots that support feeding have been developed since late 1980s. Handy1 [3] is an assistive robot for the daily activities like eating, drinking, washing, shaving, teeth cleaning and applying make-up. Handy1 consists of a five-DOF (degrees of freedom) manipulator, a gripper and a tray unit. Eat supporting is the major function of Handy1. Handy 1 allows a user to select food from any part of the tray. A cup is attached in order to drink water with their meal. The food tray that has partitions makes an important role to scoop the food on the tray.

Winsford feeder [4, 5] is a mechanical system that has one plate. Winsford feeder uses a mechanical pusher to fill a spoon with food and a pivoting arm to raise the spoon to a user's mouth, i.e., a preset position.

Neater Eater [6] has two types: a manual operation type and an automatic operation type. Neater Eater consists of the two degrees of freedom arm and one plate. More than two kinds of food could be mixed on the plate.

My Spoon [7] is suitable to deal with Japanese food. My Spoon consists of 5 DOF arm and a gripper with a meal tray. The meal tray has four rectangular cells. The end-effector of the robotic arm has one spoon and one fork that make the grasping motion. While the robot grasps the food, the gap between a spoon and a fork changes and thus a spoon and a fork grasp the food. Then, the robot moves to the preset position, and the fork moves backward to eat food on a spoon.

Meal Buddy [4] uses three DOF robotic arm and three bowls which can be mounted on the steel plate by the magnet. After this system scoops the food, the spoon can be contact the rod on the bowl in order to removing the food under the spoon.

Mealtime Partner Dining System [8] locates in front of a user's mouth. Three bowls can rotate around the user's mouth. The spoon picks up the food, and then moves the preset location with short travelling distance. This system reduces slipping wet food because the spoon's bottom wipes out after scooping. The user does not need to lean toward the feeder because the system locates in front of a user's mouth.

In some system, the beverage straw is located beside of a spoon [9]. Other system is designed for multiple users [10].

The existing self-feeding robotic systems are difficult to scooping sticky boiled rice that is the staple corp in Korea. Most of feeding systems are scooping the food with a spoon, and those systems are not suitable to treat boiled rice. In addition, some systems have single dish, and thus couples of food could be mixed during the scooping. My Spoon is using the grasping function to pick food up but this system is hard to serve rice due to fixed grasping strength. The food has a bite size in common feeding systems. However, scooping sticky boiled rice or other food is hard to perform a robotic arm.

The feeding robot allows a user to enjoy dishes independently during mealtime. At first, the feeding robot needs to prepare the dishes through a caregiver. After preparing the dishes, a user can directly solve two problems during the mealtime via a feeding robot:

(a) What does a user want to eat?

(b) When does a user want to eat?

The user can independently choose dishes and select a serving time of dishes via a feeding system.

In this paper, we propose a feeding robot for Korean food including sticky rice. We adopt a general food container to reduce the effort to set up the food for the proposed system. In view of the cost-effectiveness, application examples of the proposed system are shown. In Section 2, we will mention the requirement of a feeding robot for Korean food. The specific design results will be presented in Section 3. Section 4 and Section 5 show workspace of a dual-arm robot and application scenarios, respectively. Finally, we will make the conclusion in Section 6.

II. Requirements of a Feeding Robot

A. *Comments form User Candidates and Experts*

The major users of a feeding robot are people with upper limbs' disabilities such as people with C4 (cervical 4) spinal cord injury, people with cerebral palsy, and the muscle disease who cannot make their shoulder motions. Even though the number of target users is not large, we include the number of the senior citizens who have difficulties in the motor function of upper limbs, the overall target users will be growing in the near future.

We survey the requirements of a feeding robot through consumers' focus group meetings and clinical experts' advisory meetings. The focus group consists of a person with spinal cord injury and a person with cerebral palsy. The clinical experts include medical doctors of physical medicine and rehabilitation and occupational therapists. We discuss the requirements of feeding robots in the meetings and interviews. Their opinions are as follows:

First of all, a user can control the feeding interval for desired food. Specifically, one of common problems is hard to control the feeding interval. In case of people with spinal cord injury can talk quickly when the feeding interval is too short. However, people with cerebral palsy are difficult to talk quickly because of the speaking trouble. If the people with severe disabilities use a feeding assistive robot, they can eat the desired food when they want to eat.

Second, the existing feeding systems are suitable to handle western food and those systems do not have the abilities to deal with Korean food in the opinions of specialists and user candidates. Korean food chiefly consists of boiled rice, soup, and side dishes like Kimchi. The procedure of having a meal is as follows: first the user eats the side dishes, and then eats boiled rice. Those steps perform repetitively during dining. In comparison with foreign boiled rice, the Korean boiled rice hold together very well after cooking. One of problems is handling the sticky boiled rice. In addition, the Korean soup includes meat, noodles, and various vegetables, and thus existing feeding robots are hard to handle Korean foods as shown in Fig. 1.

Fig. 1. Korean food on a general food container (From lower left-hand side, rice, soup, and side dishes in counterclockwise direction).

Third, a feeding robot could be applied to both private homes and facilities, e.g., hospitals and nursing homes. In view of an economical point, a feeding robot is effective in facilities that have many people with upper limbs' disabilities. Those facilities do not have enough caregivers for feeding. Thus the people who stay in facilities should wait some time until neighbors eat their meal. Thus a robot reduces the burden of care-giving, i.e., feeding. In contrast, a feeding robot could be applied in the ordinary home in order to improve the quality of life. Members of a family including a person with disabilities can face each other and freely enjoy talking. The other members of the family can go out without the burden of feeding during couples of hours.

Next, the location of bowls or a tray is one of important factors. In Korean culture, the location of bowls or a tray is strongly related in the dignity of a person. Some senior user candidates dislike the bowls in front of a mouth and they prefer to eat the food like the ordinary persons. Thus we mainly focus on using a tabletop tray. However, if the bowls are located in front of a user's mouth, we can make simple feeding system.

Other comments of user candidates are as follows: simple machines that can serve simple dishes with water are required. When the caregiver goes out for a while, a user needs to eat the cereal with milk through a machine. The water supporting machine should be located in side a user's body. The cover's meal tray is required in order to prevent the dust. The price should be reasonable. For example, the price should be between US$1800~2700. The feeding robot should deal with the noodle. The feeding robot could consider the posture of a user. A feeding robot should be lightweight.

On the basis of requirements, the system that supports the activities of daily living depends on a user's culture and environments. Especially Korean food consists of several dishes: rice dishes, meat & poultry dishes, stew & soup-based dishes, and seafood dishes. The Korean food is based on the rice. How to handle the boiled rice is important problem. In general, the rice is sticky, and thus the user is difficult to pick up the rice. Sometime, the user is difficult to release the scooped boiled rice. Feeding robots have strongly related to the user's culture and environment.

We need to consider a handling method of rice. First, the rice is loaded in bowl in general manner. Second, the rice is processed into several lumps of rice. The size of a lump is a bite in a mouth. By the focus group interview, we decide to use rice in a bowl. The user candidates said that the complex preparing process makes the caregiver avoids using the assistive feeding system. Thus we put boiled rice in a bowl generally.

We concentrate on the rice handling. We disregarded the soup into the bowl at first. Soup could be stored in a cup. We will handle the Korean soup in a next version's design. Instead of handling a Korean soup, we will provide the cup with a straw for intake water or soup.

B. Concepts of Feeding Robots

We consider four kinds of concepts of feeding robotic systems in order to grip and release boiled rice effectively as shown in Fig. 2. First, couples of bowls are located in front of a user's mouth, and the food is presented by the spoon with short travelling. In this case, if the number of bowls is four, one bowl has rice and three bowls have side dishes. However, three side dishes are not enough to enjoy the food in comparison with the general Korean. In general, Korean persons eat three or four side dishes with boiled rice at a time. So we need the four or five bowls.

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

Fig. 2. Design concepts of a feeding robot.

Second, the bowls are located in upper front of the user's mouth, and then food drop from the bottom of bowls. The food is located in the spoon by dropping, and then the spoon approaches a user's mouth. This method needs to drop the food on the spoon accurately. The food shaped and squeezed the lump is suitable in this concept, e.g., rice cakes.

Third, the food tray is located on the table, and then the robotic arm picks up the rice, and then the robotic arm moves the food to the user's mouth. The operations are divided into two operations: one is picking up/release food and the other is moving the food on a spoon to a user's mouth. A user candidate talks about the easy installation of the assistive feeding robots. This kind of system could be simpler than others because other concepts need to install a feeding system in front of a user's mouth.

Finally, one bowl is located in front of a user's mouth. In that bowl, the mixed food with rice and other side dishes is loaded. Some user does not like the mixed food even though the user wants to use a simple feeding system.

On the basis of the opinions of specialists and user candidates, we choose third concept that is a table top model as shown in Fig. 2(c).

III. Design of Feeding Robot

We design a simple robotic system that has a dual-arm manipulator in order to handle Korean food like boiled rice in an ordinary food container. According to segmentation principle of the TRIZ (Theory of Inventive Problem Solving)'s 40 inventive principles, we divide a self-feeding task into two sub-tasks: picking up/releasing food and transferring food to a user's mouth [11]. The first robotic arm (Arm #1, **a spoon-arm**) is transferring the food by a spoon from a container on a table to a user's mouth. The second robotic arm (Arm #2, **a grab-arm**) is picking food up on a container and then put the food on the spoon of a spoon-arm. If two arms have different roles, the end-effectors of two arms could be effectively designed. The end-effector of a spoon-arm has a spoon to serve food to a user's mouth. The end-effector of a grab-arm could be suitably designed to pick up or release food including rice. For picking up the food, we can use an odd shaped gripper as shown in Fig. 3 because that gripper does not need to approach nearby a user's mouth.

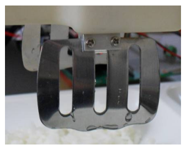


Fig. 3. One example of the gripper tip in a grab-arm.

(a) (b) (c)

Fig. 4. (a) A spoon for scooping food. (b) Chopsticks for picking up food. (c) A person uses a spoon with chopsticks.

Proposed two arms that have different end-effectors mimic Korean eating behavior. Specifically, Korean uses a spoon and steel chopsticks during mealtime as shown in Fig. 4(a) and (b). Some persons use a spoon and chopsticks simultaneously (Fig. 4 (c)). In the designed system, the gripper of a grab-arm and the spoon of a spoon-arm make roles of chopsticks and a spoon, respectively. Some Korean caregivers usually pick up food with chopsticks, and then put food on a spoon in order to serve food to users such as children and patients. In that sense, the proposed system that has two arms stems from Korean eating irons.

A spoon-arm should have one or two degrees of freedom in order to transfer food on the spoon without changing an orientation of the spoon as shown in Fig. 5. If a revolute joint R1 connects to a revolute joint R2 through a belt, R1 and R2 have one degree of freedom. However, the prototype of a spoon-arm, we use two motors, R1 and R2 because of scalability. If a spoon-arm does not use the belt between Axis #1 and Axis #2, we can change of the length between Axis #1 and Axis #2 manually.

A person with cerebral palsy is difficult to eat food on a spoon in front of his/her mouth. The feeding robot could add the additional prismatic joint that can make a linear motion toward a user's mouth.

A grab-arm should pick up food on a container, and at least two revolute joints and one prismatic joint are required for the effective motion on the food container. The revolute joint R5 could be added in order to control the gripper's rotation during picking up food in Fig. 5.

The overall number of DOF of two robotic arms could be 4~7 DOF and a gripper. Between a spoon-arm and a grab-arm, we need to connect electrical signals and fix the posture with respect to each other, and thus a connection bar is applied.

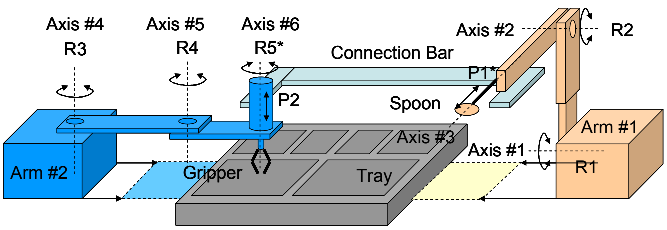


Fig. 5. The proposed design of a novel feeding robot for Korean foods. P1 (Prismatic Joint #1) and R5 (Revolute Joint #5) are optionally applied.

In preliminary experiments on treating boiled rice, we observe that releasing rice is important like picking up rice. According to the temperature of boiled rice, the stickiness of rice is changing. The slightly cool rice is difficult to release rice from the gripper. In order to solve this limitation, the feeding robot optionally put the gripper of a grab-arm in the water before the grasping food. In that case, we can release sticky rice on a spoon as well because the stickiness of rice decreases between rice and the surface of a gripper.

The feeding robot could use two kinds of containers. First of all, we could use a tray in the ordinary cafeteria. The tray could be located between a spoon-arm and a grab-arm. The other is bowls that are usually used in a hospital of Korea. The bowls are hard to fix on the table during picking up food, and thus we will use an adaptor to fix bowls like a tray. The tray adapt reduce the pose change of bowls.

The feeding robot uses a microcontroller unit to control a spoon-arm and a grab-arm as shown in Fig. 6. We add a small sized PC with a touch screen in order to enjoy entertainment environments and to test various kinds of user interfaces. During the mealtime, a user wants to enjoy the multimedia such as movies or music. In addition, the small sized PC has a Windows operation system, and we can effectively add assistive devices for human computer interaction, i.e., switches, a joystick, and bio-signal interface devices.

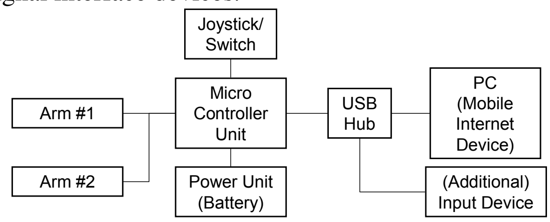


Fig. 6. Block diagram of feeding robot.

The microcontroller unit allows a user or a caregiver to set the following items: an operation mode (automatic/manual), the shape and size of a container, a mouth's location, a robot's speed, time to stay in front of a mouth, and so on. According to the kinds of food, a user also selects the divided grasping region in each container and the grab strength of a gripper of a grab-arm. Our system will be open to select the above parameters. A user can save the parameters of various kinds of food. We hope that a user's community could exchange their own parameters for each food.

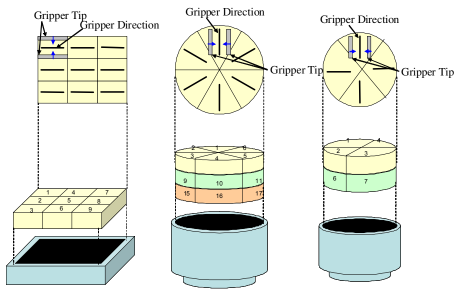


Fig. 7. The definition of grasping volume in containers.

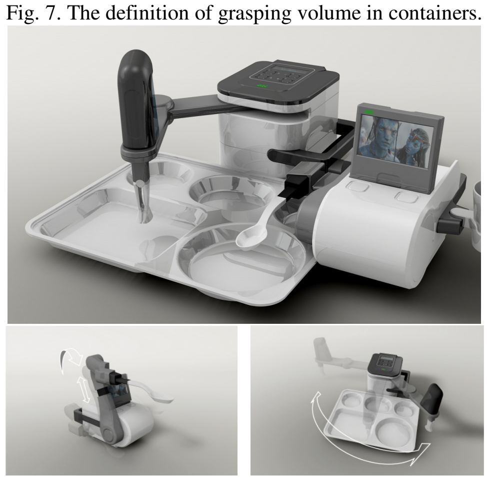


Fig. 8. The design of novel feeding robot for Korean food. A spoon-arm (lower left-hand side figure) for transferring food and a grab-arm (lower right-hand side figure) for picking up and releasing food.

Grasping regions of boiled rice in a bowl could be defines in 3D space because the bowl should have over 50 mm in height. The grasping volume of dishes could be defined as shown in Fig. 7. Our team is making the prototype of the proposed feeding robot. Fig. 8 shows the estimated appearance of the proposed self-feeding system.

IV. WORKSPACE OF DUAL-ARM ROBOT

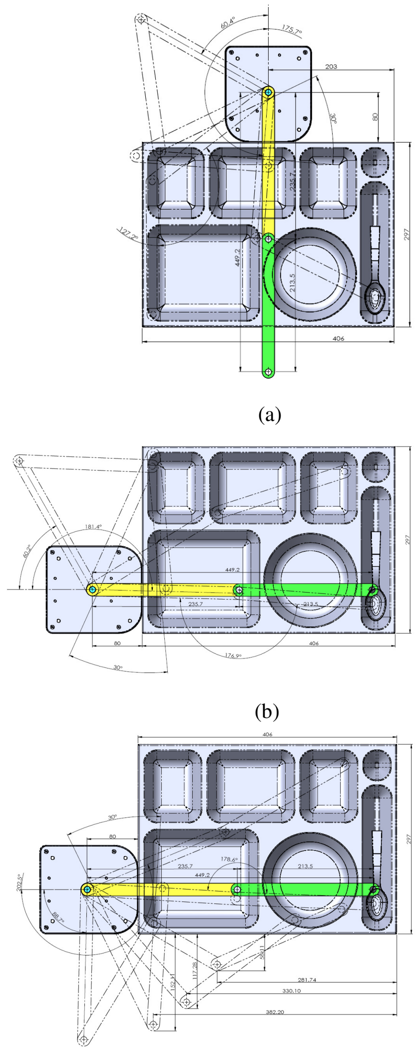
In order to use a conventional food container, we decide the length of links of a grab-arm that covers the whole area of a food container. A grab-arm is located behind a container or in left-hand side of a container. A grab-arm can be located behind a food container on a general table (case #1) as shown in Fig. 9(a). However, the board of a bed does not have an enough space behind a food container; a grab-arm should be located in the left-hand of a food container. The arm could be folded into the backward direction (case #2) or the forward direction (case #3) with respect to a user as shown in Fig. 9(b) and (c). The lengths of first and second links of a grab-arm are 235.7 mm and 213.5 mm, respectively. Table I shows the detailed data of a grab-arm, i.e., link length and range of motion (ROM). The ROM of case #1 is similar with the ROM of case #3, and thus the ROM of a first axis should be around 143 degrees when we consider the union of ROM of case #1 and #3.

The spoon-arm has two additional variables such as the motorized prismatic motion toward a user's mouth, and the manual change of the link length between the first axis and the second axis of a grab-arm. Fig. 10 shows the overall workspace of the spoon of a grab-arm. In accordance with the position of a user's mouth, the presentation location in front of a user's mouth is adjusted when the system is installed.

The height of a spoon of a grab-arm is 250~381 mm with respect to the surface of a table. The height of a grab-arm depends on the table height. We assume that the height of a table is 730 ~ 750 mm. The spoon could be located in 980~1131mm with respect to the ground. According to the statistics of the Korean disabled, the height of a user's mouth could be 1018 mm (female) and 1087 mm (male). Thus, the height of a spoon corresponds with the height of a user's mouth.

TABLE I
DIMENSION OF A GRAB-ARM

Item	Case #1 Behind a food container	Case #2 Left hand side of a food container with backward folding	Case #3 Left hand side of a food container with forward folding	Case #1 + Case #3
Link1(mm)	235.7	235.7	235.7	235.7
Link2(mm)	213.5	213.5	213.5	213.5
Angle1(deg) (ROM)	184.3~299.6 (115.3)	60.2~181.4 (121.2)	157.5~271.3 (113.8)	157.5~299.6 (142.1)
Angle2(deg) (ROM)	30~127.2 (97.2)	183.1~330 (146.9)	30~178.6 (148.6)	30~178.6 (148.6)



(a) (b) (c)

Fig. 9. The configuration of a grab-arm.

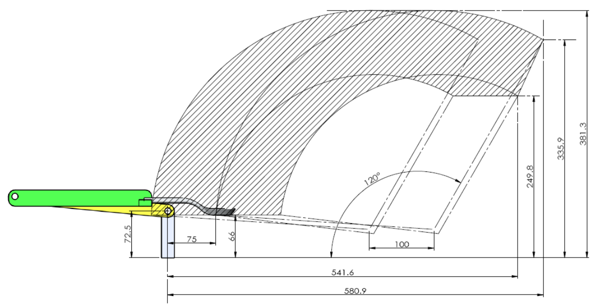


Fig. 10. The workspace of a spoon-arm.

TABLE II
Statistics of wheelchair users

Item	Sitting height on a wheelchair	The distance from a crown to a mouth	Mouse height on a wheelchair
Male	1261	174	1087
Female	1187	169	1018

V. APPLICATION SCENARIOS

If a caregiver's task is replaced with a feeding robot, the caregiver's labor-cost could be reduced. In case of Korea, the cost of caregivers is around US$7. We assume that applying the feeding robot reduces the usage time of ADL assistance by 0.5~1 hour a day. When the feeding robot is US$2000 and 0.5 hour benefit of ADL, the return of investment is 1.6 year. If the user candidate is 0.05% of the population (1 handicapped among 2,000 persons), Korea could save US$32 million annually. We assume that the required ratio is based on 100 times of the case of the wheelchair-based robotic arm [12].

TABLE III
COST OF FEEDING CAREGIVING TASKS

Case		0.5 hour usage	1 hour usage
ADL-assistance	Usage time (hour)	0.5	1
	Labor-cost of ADL caregiver (per hour)	US$7	US$7
	Cost (per year)	US$1,278	US$2,555
Cost of Feeding Robot		US$2,000	US$2,000
Return of Investment (year)		1.6	0.8
Market	Total Population in Korea	50,000,000	50,000,000
	Ratio of ADL assist	0.05%	0.05%
	Consumer	25,000	25,000
Overall saving cost		US$31,937,500	US$63,875,000

We consider two application cases of the proposed system. First, a dual-arm robotic system is applied in accordance with a designed concept. If a caregiver prepares food, users can eat the food on the basis of their intentions. A grab-arm picks up the desired food on a food container, and the arm release the food on the spoon of a spoon-arm. The spoon-arm moves the spoon to a user's mouth. Then a user can eat the food on the spoon.

The proposed system can put two kinds of food on a spoon because the proposed system has two arms. For example, some people in Korea occasionally put rice and a side dish on a spoon at the same time, and the proposed system can mimic that task.

Second, a spoon-arm could be independently applied without a grab-arm. The caregiver manually supports to pick up the food on a food container, and the caregiver put the food on the spoon of a spoon-arm. Next step is similar with the dual-arm robotic arm. In view of a caregiver, the caregiver can reduce the consuming time in order to check or wait the chewing time of a consumer. That is, the caregiver provides a consumer with the food when the spoon is available. In view of consumers, they can eat the food when they want to eat although they are hard to choose food in an automatic manner. In addition, they can chew the food sufficiently without considering the next spoon serving of a caregiver.

In the economical point of view, applying a spoon-arm has advantages in facilities such as hospitals or nursing homes. One caregiver supports more than one consumer. One caregiver can put the food on spoons of consumers' spoon-arms by turns.

For the sticky rice, we perform preliminary tests for picking up and release rice. As shown in Fig. 11, that task performed well specially for warm rice. We found that the stickiness and hardness of rice depend on the temperature of rice and we will study the change of rice on the basis of temperature of rice.

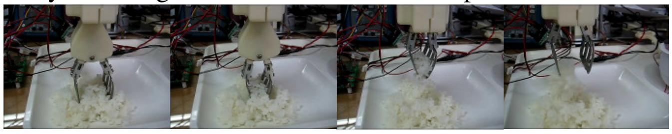


Fig. 11. Picking up and releasing sticky rice.

VI. CONCLUDING REMARKS

The novel dual-arm feeding robot is proposed in order to handle Korean food with sticky rice effectively. According to the preliminary test, the proposed structure is effective to handle sticky rice. The designed feeding robot is suitable to grip/release sticky rice and to use a set of tableware like a general tray or a hospital's tableware with a tray adaptor. In addition, one module, a spoon-arm, of a proposed system could be applied to move the food from a table to a user's mouth level and thus users can eat food on a spoon if they want to eat when a caregiver put food on a spoon. After constructing the prototype of a proposed system, we will progress the usability test of a proposed system. The input device of a proposed system could be a joystick with a couple of buttons. We will improve the overall system and input devices for comfortable use in accordance with usability tests.

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