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# Development of a Meal Support Device for Functional Recovery Using EMG Signals

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**ABSTRACT** This paper describes a device to support a patient's motion of their upper limbs. The device has three functions in a single system: power assistance, rehabilitation, and meal support. The former two functions have been described in a previous study. In this paper, designs and evaluations of the meal supporting function considering maintaining residual muscular strength are presented. The mechanical design is based on human body statistical data. The controller consists of an electromyogram signal-based interface used for maintaining muscular strength. We evaluate the effectiveness of the meal supporting mode through some experimentation.

**INDEX TERMS** Pneumatic actuators, rehabilitation robotics.

## I. INTRODUCTION

In recent years, a shortage of caregivers has become a severe problem in Japan because of its aging society [1]. Some elderly people have weakened muscular strength due to injury or aging, and need support for living activities. Support for such patients is often provided by caregivers. However, along with the rising rate of aging, the sufficiency rate of caregivers is decreasing [2]. Therefore, for people who cannot independently move their upper limbs, various devices have been developed to allow them to perform actions without caregivers. In light of these issues, many assistive devices have been developed. We have also developed a compact and lightweight upper limb device for assisting rehabilitation and supporting living activities using a pneumatic cylinder with a linkage mechanism [3]–[5]. This device is focused on providing support and rehabilitation for shoulder and elbow movements. Additionally, the device provides a rehabilitation function via loading and moving a patient's upper limbs to facilitate rehabilitation for patients and occupational therapists.

Self-feeding and eating are important activities of daily living (ADL). Therefore, many meal assistance devices exist in the form of robot arms controlled by a

joystick [6], [7], electroencephalogram (EEG) [8], hands-free pointing device [9], voice commands [10], [11], laser pointing [12], or an exoskeleton [13]–[15]. However, these meal assistance devices are fixed on a desk or to the floor, and are difficult to move or transport, due to their weight. Furthermore, most fully support the patients [16], and thereby may cause decreasing residual muscular strength.

For the reasons noted above, we developed a meal supporting function for the upper limb device in this study. This device aims to realize three functions in a single system: power assistance, rehabilitation for functional recovery, and meal support while maintaining residual muscular strength. In this paper, mechanism and controller designs and evaluations are described. Section 2 presents the basic structure of the developed upper limb supporting device. The mechanical design of the meal supporting system is explained in Section 3. The design is based on statistical data of the human body and experimental data. The controller is designed such that the meal supporting function maintains residual muscle strength using electromyogram signals, as shown in Section 4. Finally, evaluations with healthy elderly people are conducted in Section 5.

## II. UPPER LIMB SUPPORTING DEVICE

Figure 1 shows the pneumatically driven upper limb supporting device we developed. This device is composed of two

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TABLE 1. Dimensions of the device.

Symbol	Dimension	Requirements [17][18]
<i>a</i>	0.42 m	> 0.34 m (Hip breadth)
<i>b</i>	0.25 m	0.25 – 0.26 m (Armrest height)
<i>c</i>	0.30 m	> 0.27 m (Acromion-elbow length)
<i>d</i>	0.25 m	0.22 – 0.25 m (Forearm length)
<i>e</i>	0.31 m	< 0.37 m (Buttock-popliteal length)

main components, namely, the seat and the support. As the figure shows, this device is placed on a chair and the users sit on the seat part of the device. The elbow is placed on joint 3 of the supporting part of the device. The supporting part consists of two pneumatic cylinders, four linkages, and five joints. In this device, reducing weight is important for portability because the device is expected to be moved around the home or buildings such as a hospital. Therefore, a pneumatic cylinder that has a high power–weight ratio was selected as the actuator. Additionally, safety is necessary for such a device used in contact with humans. By using a pneumatic cylinder, it is expected that the impact force is absorbed due to the compressibility of the inner air.

In Figure 1, a right-handed coordinate system is defined such that the *y*-axis represents the direction from hip to knee and the *z*-axis represents the direction from hip to shoulder. Joint 1 is a prismatic joint that is moved along the *y*-axis by the force of the user. Joints 2 and 3 are rotational joints that are rotated around the *x*-axis by a pneumatic cylinder or a pneumatic guide cylinder connected to linkages. Joints 4 and 5 are rotational joints that are rotated around the *z*-axis by the torque of users. Thereby, in this device, the movement of the shoulder and elbow joints in the vertical plane is assisted by the pneumatic cylinders, but that in the horizontal plane is caused by the force of users. In this way, this device aims to be a portable device by restricting its functions to only shoulder and elbow support, which is the minimum support required for eating.

Figure 2 presents the outline drawing of the device designed previously [4]. Table 1 shows the dimensions of each part, which were obtained based on human body data [17] and human dynamics data [18]. The dimension of the seat width “*a*” was set as 0.42 m, which is the value determined from the breadth of the human hip. Similarly, that of the seat depth “*e*” was set as 0.31 m from the buttock–popliteal length. The dimension of “*c*” was set as 0.30 m from the acromion–elbow length, and that of “*d*” was set as 0.25 m from the forearm length. Finally, “*b*” was determined as 0.25 m from the elbow height.

In the device we developed previously, the only requirement for the forearm part was to maintain position (living activity supporting function), so the forearm part (joint 3) was a passive gas spring. Since the purpose of this paper is to realize a meal supporting function, a new actuator is required to be mounted on the forearm part for activation. Therefore, the mechanism design of the forearm part is required, and is described in the next section.

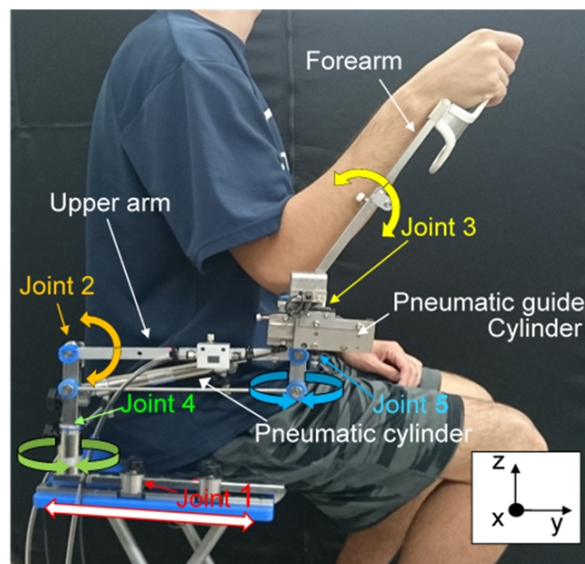


FIGURE 1. A pneumatically driven upper limb supporting device we developed. It consists of two pneumatic cylinders, three linkages, and five joints and supports the upper limb movement in the vertical plane.

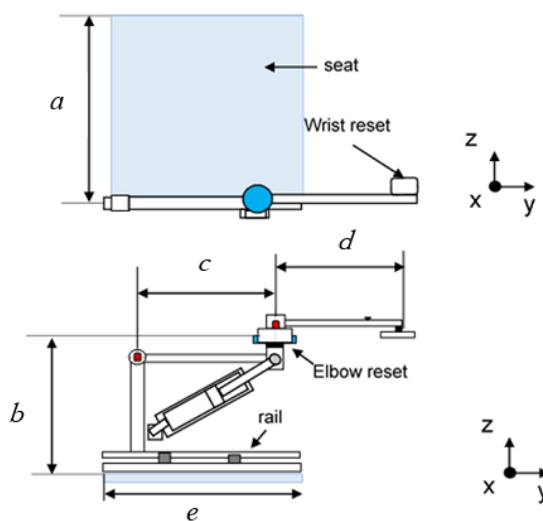


FIGURE 2. Outline drawing of upper limb supporting device.

### III. MECHANICAL DESIGN

#### A. MOVABLE RANGE OF JOINT

First, we determined the requirements of the movable range of each joint for the meal supporting function experimentally. Four cameras (Sunflower GE 60 series; Library Inc.) were used for measuring the range of the meal action. The experimental motion was conducted by scooping the food using a spoon, moving it to the mouth, and restoring the forearm to its original position. In this experiment, the horizontal state of the forearm was defined as the original posture. Camera images of the motion were captured and input into a PC for use in the measurement system (CaptureEX; Library Inc.). Analysis was conducted using motion analysis software (Move-tr/3D; Library Inc.). Measurement points were set as

TABLE 2. Personal information of subjects.

Symbol	Age	Height	Forearm length
Subject A	23	1.66 m	0.23 m
Subject B	25	1.72 m	0.25 m

elbow, wrist, and cheek. In this study, targets for the device were elderly people with weak muscular strength or young people with disabilities of the upper limb. However, subjects examined in this study were two young healthy men, because the relevant dimensions are determined only by geometric relationships with height. The personal information of each subject is presented in Table 2. From statistical data in [17], the average forearm length of men and women is 0.23 m. Even considering the maximum variation of 0.03 m within each gender and age group, the forearm length of these subjects falls within this range. Therefore, the motion trajectory analyzed using these subjects can yield effective data to define the movable range requirements for the meal supporting function.

Figure 3 shows the motion trajectory of the meal action. The top images ((a), (b)) show the motion trajectory on the x-z plane, and the bottom images ((c), (d)) show that on the y-z plane. These motion trajectories show that the meal action is achieved by rotating forearms 70 deg around the x-axis. From the trajectory, the maximum flexion angle of joint 3 is obtained as 70 deg from the original posture. On the other hand, the maximum extension angle can be specified based on the horizontal working area. Figure 4 illustrates the geometric relationship around the human elbow joint. The horizontal length from the shoulder joint to the working position of the hand  $L_B$  was determined as 0.42 m for males and 0.38 m for females based on statistical data.  $L_A$ ,  $L_C$ , and  $L_D$  are the length from top of the desk to elbow height, the upper arm length, and the forearm length, respectively. Hence, the length of  $L_E$  is

$$L_E = \sqrt{L_A^2 + L_B^2} \quad (1)$$

Thereby, the maximum extension angle of elbow  $\theta_{max}$  is obtained as below.

$$\theta_{max} = \beta - \alpha$$

$$\alpha = \arccos \frac{L_D^2 + L_E^2 - L_C^2}{2L_D L_E}, \quad \beta = \arccos \frac{L_B}{L_E} \quad (2)$$

The parameters used in the equations are defined in Table 3. As a result, the maximum extension angle is calculated as 29 deg. Consequently, the overall movable range requirement of joint 3 was determined as 99 deg.

From these results, the movable range requirements of the device can be determined. Table 4 presents the required specifications of each joint derived from Fig. 3. The direction shown in the table is based on the right-handed coordinate system in Fig. 1.

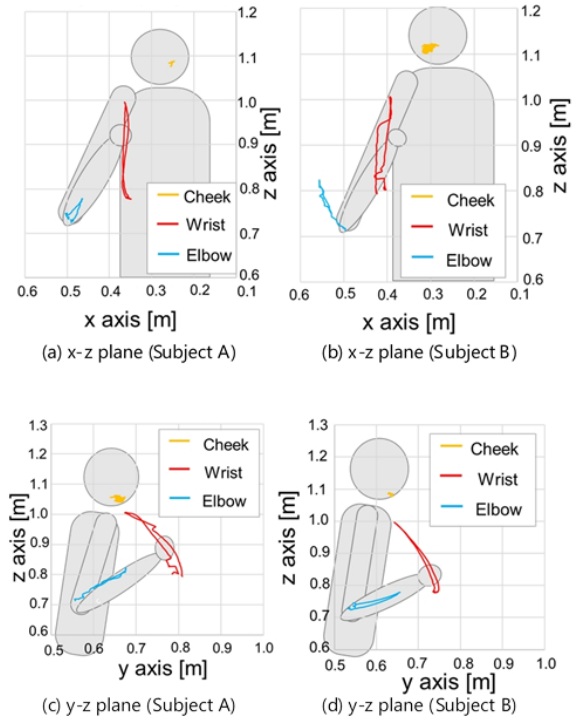


FIGURE 3. Measuring results. (a), (b) Motion trajectory on the x-z plane. (c), (d) Motion trajectory on the y-z plane.

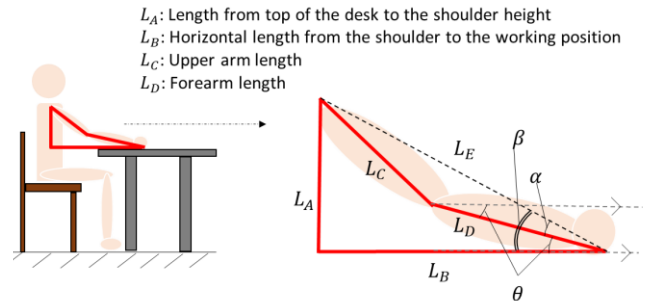


FIGURE 4. Geometric relationship around the human elbow joint.

TABLE 3. Parameters defined in figure 4.

	Age	$L_A$	$L_C$	$L_D$	$\theta$
Male	50-59	0.304 m	0.308 m	0.246 m	13 deg
	60-69	0.328 m	0.300 m	0.241 m	27 deg
	70-79	0.328 m	0.300 m	0.239 m	28 deg
Female	50-59	0.309 m	0.280 m	0.222 m	25 deg
	60-69	0.306 m	0.281 m	0.223 m	23 deg
	70-79	0.304 m	0.274 m	0.218 m	29 deg

### B. FOREARM ROTATION MECHANISM

To ensure the device is lightweight and compact, a guide mechanism type pneumatic cylinder (guide cylinder) and rack and pinion are used as the rotation mechanism for joint 3. The mechanism of joint 3 is shown in Fig. 5. The rack slides along the y-axis by the movement of the piston of the guide cylinder.

TABLE 4. Movable range requirements of joints to achieve meal action.

Joint no.	Direction	Requirements
1	Parallel to y-axis	> 10 mm
2	Around x-axis	+31 deg
3	Around x-axis	From -29 to +70 deg
4	Around z-axis	±10 deg
5	Around z-axis	±6 deg

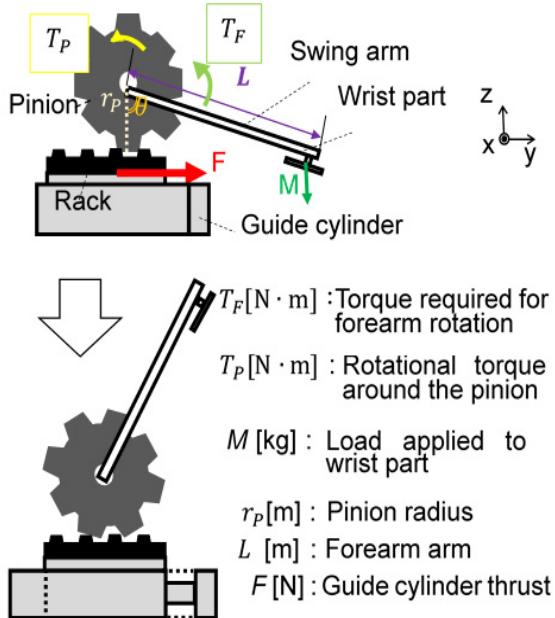


FIGURE 5. Model of the forearm rotating mechanism. It consists of a guide cylinder, a rack and pinion, and a swing arm.

Simultaneously, the forearm placed on the swing arm rotates around the x-axis with the pinion.

To support the forearm movement, the swing arm part should be rotatable when the upper limb weight of the user is applied. Additionally, the movable range of the swing arm should be designed to satisfy the requirements described in Table 4. Based on statistical data on the forearm length and upper limb weight of elderly people, the assumed forearm length of the users was set as 0.26 m considering gender differences, of which the maximum variation is 0.03 m. The assumed weight acting at the wrist part of the mechanism was experimentally determined as 1.0 kg from the previous study [4].

The maximum rotation torque around the pinion  $T_{Pmax}$  is

$$T_{Pmax} = r_p F \tag{3}$$

where  $r_p$  is the pinion radius, and  $F$  is the thrust force generated by the guide cylinder. The maximum torque necessary to rotate the forearm of the device  $T_F$  is

$$T_F = MgL \tag{4}$$

where  $M$ ,  $g$ , and  $L$  are the load applied to the wrist part, the gravitational acceleration of  $9.81 \text{ m/s}^2$ , and the length

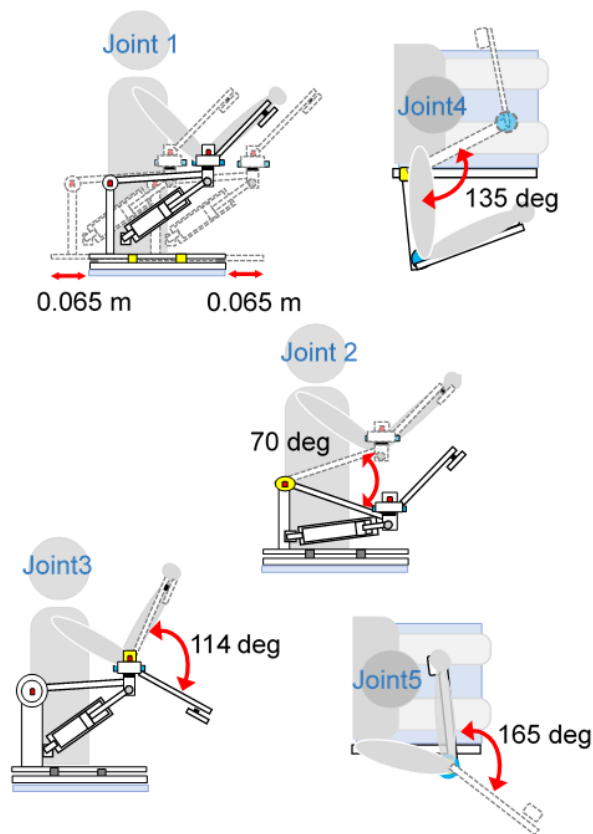


FIGURE 6. Movable range of each joint of the device.

of the swing arm, respectively. In the state of the original posture, the swing arm angle,  $\theta$ , is 90 deg. When  $T_P \geq T_F$  holds, the forearm flexes. Here,  $T_F = 2.55 \text{ Nm}$  was obtained from the calculation of the swing arm length and the load applied to the wrist part. In addition, the guide cylinder stroke  $D$  is

$$D = 2r_p\pi \left( \frac{\theta}{360} \right). \tag{5}$$

From the equations above, we examined the parameters satisfying the equations and the relational expression of  $T_P \geq T_F$ . The obtained specifications for guide cylinder and rack and pinion are presented in Table 5.

Table 6 and Figure 6 illustrate the specified torque and movable range of the designed joints. The requirements for the movable range of each joint specified in Table 4 are fully satisfied. The weight of the device is 5.5 kg (2.8 kg for the seat part and 2.7 kg for the supporting part).

#### IV. CONTROLLER DESIGN

##### A. METHODS FOR MEAL SUPPORTING FUNCTION

As described earlier, the device is designed not only for supporting the meal action, it is also designed to maintain muscular strength using the residual muscular strength of the user. To realize the latter objective, the isometric contraction force generated by a target muscle must satisfy: “muscular



TABLE 5. Specifications of the guide cylinder, rack and pinion.

Guide cylinder (MGA16x30L; Koganei Co., Ltd.)	Stroke	30 mm
	Inner diameter	32 mm
	Thrust (at 0.3MPa)	241 N
Pinion (GEAB1.0-30- 12B-8-KC90; Misumi Group Inc.)	Gear shape	Spur gear
	Number of teeth	30
Rack (RGEASL1.0ST- 40-A10-B20; Misumi Group Inc.)	Diameter	30 mm
	Length	40 mm

TABLE 6. Specifications for swing arm.

	Torque	Movable range
Required	> 2.45 Nm	> 99 deg (-29 to +70 deg)
Specified	3.62 Nm	114 deg

TABLE 7. Specified parameters of pid controllers.

	Requirements	Parameters
Upper arm	Keeping in the same angle	$K_p = 0.75$ $K_i = 1.20$ $K_d = 0.20$
Forearm	Tracking the target angle with; Dead time of 0.2 s Settling time of 1.0 s	$K_p = 0.70$ $K_i = 0.34$ $K_d = 0.42$

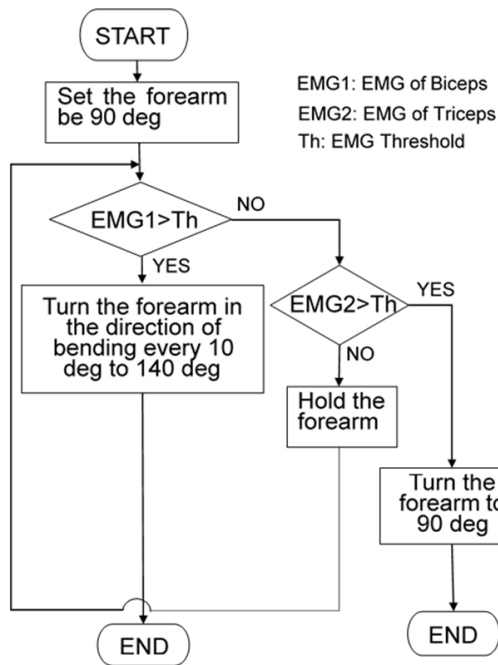


FIGURE 7. Flowchart of the forearm control in meal supporting function.

strength more than 30% of maximum muscular strength” [19]. In this study, the target muscles are biceps brachii and triceps brachii, which are the main muscles acting while the elbow is flexing or extending. Moreover, the correlation between muscular strength and electromyogram (EMG)

signal has been confirmed [20]. Accordingly, we constructed a control system that is triggered by EMG signals.

Figure 7 illustrates the flowchart of the device operation. The EMG signals of each target muscle are measured by the EMG sensor placed on the surface of the muscles. In this experiment, the original posture of the device is defined as in Fig. 2. Initially, both angles of joint 2 (upper arm joint) and joint 3 (forearm joint) are controlled to be horizontal (90 deg). If neither of the EMG signals exceed the threshold, the forearm joint angle holds in the same angle. If the EMG signal of the flexion side muscle (biceps brachii) exceeds the threshold, then the target angle of the joint increases by 10 deg. (Naturally, the target increase angle of the joint can be freely set.) When the joint angle reaches the target angle, the target angle increases by 10 deg up to 160 deg. Contrarily, if the EMG signal of the extension side muscle (triceps brachii) exceeds the threshold, then the target angle is set to 90 deg. The upper arm joint is held at the same angle during the meal supporting function. The threshold is set as 30% of the maximum value of the EMG signal of each muscle that can be performed on each subject.

In this device, each joint flexes by the pneumatic cylinder and extends by the weight of the arm. Joint angles are controlled respectively by the PID controller. The requirements and specified parameters of the controllers are shown in Table 7. The parameters of  $K_p$ ,  $K_i$ , and  $K_d$  were experimentally determined to satisfy the requirements in the table. The requirements of dead time and settling time were tentatively determined so that the meal supporting action could be performed. These values can be set arbitrarily according to the user’s physical ability. Since it is generally said that it takes about 0.2 s for a person to start moving muscles after thinking about motion, the dead time was specified as 0.2 s.

B. EXPERIMENTAL SETUP

In this section, we describe experiments conducted to assess the meal supporting function. The experimental setup is shown in Fig. 8. Compressed air is provided from the air compressor (YC-4; Yaezaki Kuatsu Co., Ltd.) to the electro-pneumatic regulator 1 and 2 (ETR200-1; Koganei corp.). A control signal from the PC is sent to each regulator via the I/O board (MF634; Humusoft Corp.). Air pressure proportional to the signal is transmitted from the electro-pneumatic regulator to the air cylinder for the upper arm (DA25x100; Koganei Corp.) and that for the forearm (MGA16x30L; Koganei Corp.). The cylinder rod expands and contracts according to the internal pressure. Each arm rotates around the x-axis with the expansion or contraction of the cylinder rod.

Rotation of joints 2 and 3, i.e., the rotation angle around the x-axis of the upper arm and forearm, was measured by the position sensor (RDC 503013 A; Alps Electric Co., Ltd.) and is fed back via the I/O board. Electrodes of EMG sensors (ID 2 PAD; Oisaka Electronic Equipment Ltd.), were attached to the biceps brachii and triceps brachii [21]. The signals of the EMG sensors were sent to a PC for processing.

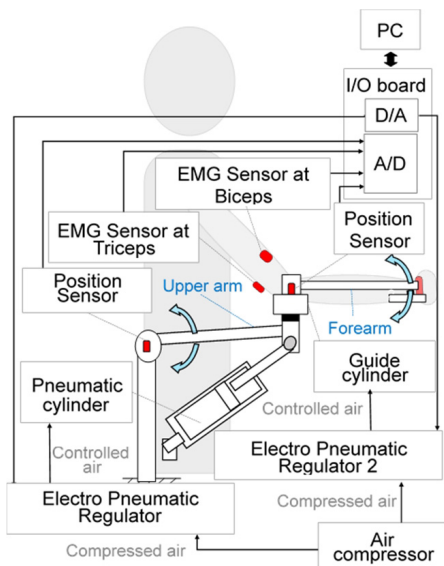


FIGURE 8. Experimental setup.

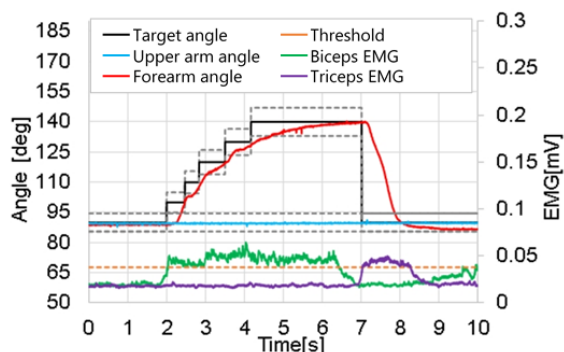


FIGURE 9. Experimental result for confirming the meal supporting function (healthy young person).

Subjects were five healthy young people ( $24.0 \pm 1.0$  years old; 2 males and 3 females). The action task is to move the food to the mouth and to return the arm to the original position.

### C. EXPERIMENTAL RESULTS

Similar results were obtained for the five subjects in this experiment. Hence, the result of one of the subjects is shown in Fig. 9. The horizontal axis represents time and the left vertical axis represents the angle. The right vertical axis represents the EMG signal. The red line and the light blue line depict the measured angles of the forearm and the upper arm, respectively. The green line and purple line represent the EMG signals of the biceps brachii and the triceps brachii, respectively.

According to Fig. 9, when the EMG signal of the biceps brachii exceeded the threshold at 2.0 s, the target angle of the forearm joint began to increase. The target angle continued to increase by 10 deg during the period that the EMG signal exceeded the threshold. The target angle fell to 90 deg when

the EMG signal of the triceps brachii exceeded the threshold at 7.0 s. These results demonstrate that the forearm of the subject is operated according to the EMG signals of the biceps brachii and triceps brachii. The target value was adjusted without overshooting at the dead time of 0.2 s and the settling time of 0.5 s. It was confirmed that in both the cases of rising and falling, its operation satisfied the required specifications. The result also shows that the upper arm joint was held at a constant angle irrespective of the forearm motion. As a result, in the meal supporting function, it was confirmed that both the upper arm and the forearm work to satisfy the required specifications.

## V. EVALUATION OF MEAL SUPPORTING FUNCTION

### A. EXPERIMENTAL METHOD

Using the meal supporting function we designed in the previous section, we conducted an experiment for evaluation with healthy elderly people. Then, each participant answered an evaluation questionnaire to describe the operation feeling of the device.

Subjects were five healthy elderly people ( $75.0 \pm 3.2$  years old; three males and two females). The physical characteristics of these subjects were average measures [17] for people aged in their 70s. For the operation task, three individual meal actions were taken as one set: the food is scooped by a spoon; then, the arm is returned to the original position after taking the food to the mouth. The experimental environment resembles Fig. 7. Furthermore, as shown in the preceding section, the angle of the upper arm joint was held at 90 deg during operation. The forearm part is assumed to be operated according to the operation flow of Fig. 8.

### B. EXPERIMENTAL RESULTS

Similar results were obtained for all subjects in this experiment. The results of one of the subjects are presented in Fig. 10. The horizontal axis, the left vertical axis, and the right vertical axis represent time, joint angles, and EMG signals, respectively. The red line and the light blue line depict the measured angle of the forearm joint and the upper arm joint, respectively. The green line and purple line represent the EMG signals of the biceps brachii and the triceps brachii, respectively.

The experimental result presented in Fig. 10 demonstrates that the forearm part operates depending on the EMG signals of the biceps brachii and triceps brachii. In the first and second sets of the operation, the forearm joint angle decreased immediately because the EMG signal of the triceps brachii exceeded the threshold almost simultaneously with the moment the forearm lifted. However, in the third set, the forearm joint angle was held even after the forearm had risen and the EMG signal of the biceps brachii decreased below the threshold. Therefore, the result shows it is possible to raise and lower the forearm part according to EMG signals of subjects at the desired timing of the examinee. Additionally, it is shown that, although the angle of the upper arm joint

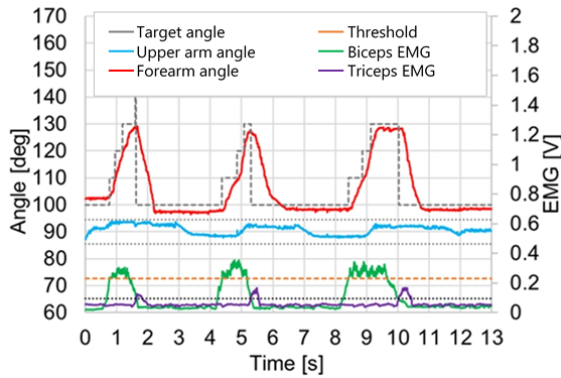


FIGURE 10. Experimental result for evaluating the meal supporting function (healthy elderly person).

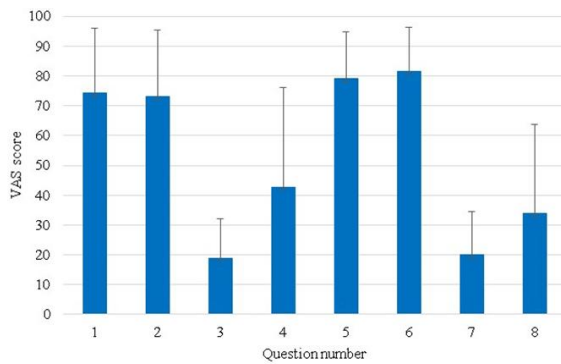


FIGURE 11. VAS score of question response.

was unsteady, it was held at 90 deg without deviating from the allowable range.

These results show that even elderly people, who are less muscular than younger people and whose EMG signals may be harder to measure due to slackening of the skin, could operate the device with the input of EMG signals.

### C. EVALUATION QUESTIONNAIRE

The evaluation questionnaires conducted after the experiment are described in this section. The Visual Analogue Scale (VAS) was used as an evaluation method for this study. Questionnaire items related to the meal supporting function are presented in Table 8. The evaluation was made with 0 points at the left end and 100 points at the right end.

The result of the questionnaires administered after the experiment is presented in Fig. 11. The abscissa shows the question number; the ordinate shows the VAS score. The result showed that some subjects felt difficulty moving to their desired position and direction. A possible reason for this is that they were not accustomed to using the device. However, regarding the operating speed, great differences were found in the evaluation of each subject.

The experimental result and the questionnaire result illustrate that the meal supporting function could be accomplished using this device. The operating speed and other points remain as future tasks for further examination.

TABLE 8. Questions for operation feelings.

No.	Questions	
	Left end No	Right end Yes
1	Have you been able to move your upper arm to the position you want to move?	
2	Have you been able to move your upper arm in the direction you want to move?	
3	Did you feel that your upper arm’s motion is being hindered by the resistance force you receive from the device?	
4	When you use this device, did you feel that your own upper arm motion is slow?	
5	Have you been able to move your forearm to the position you want to move?	
6	Have you been able to move your forearm in the direction you want to move?	
7	Did you feel that your forearm’s motion is being hindered by the resistance force you receive from the device?	
8	When you use this device, did you feel that your own forearm motion is slow?	

### VI. CONCLUSION

As described in this paper, we added a meal supporting function to the upper limb supporting device we developed previously. The meal supporting function aims to support the action of scooping food using a spoon or the like and returning the forearm to its original position.

In the previous device, a passive gas spring was used around the elbow because the function for the forearm joint angle was only to maintain its position. However, the active movement of the forearm is required for the meal supporting function. In this study, we designed a new forearm mechanism with an actuator and a control system, and conducted an evaluation experiment with healthy elderly people.

Firstly, the mechanism was designed based on statistical data of the human body, including limb length and weight, and the range of joint motion necessary for eating. The range of motion was determined from experimental data we measured. Secondly, the controller was designed so that the forearm joint is flexed or extended using the user’s electromyogram (EMG) signal as a trigger, and the hand approaches the mouth. The upper arm joint is kept in its position during operation. The threshold of the trigger is set to 30% of the user’s maximum EMG, and the device demands some muscle loading from the user. A previous study suggested that the residual muscle strength of the user can be thereby maintained. Finally, an evaluation experiment was conducted on the feasibility and operability of the movement by healthy elderly people.

As a result, it was confirmed that the device can be driven using selected timings and reach the target posture, even for elderly people whose EMG signals are difficult to measure. Operability was evaluated by the Visual Analogue Scale. The result of the questionnaires suggests that the device can support the meal action of the user. However, regarding the operating speed, significant differences were found in the

evaluation of each subject. It will thus be necessary to adjust the tracking performance of the controller according to the motor ability.

Currently, the device supports the upper arm and the forearm for meal action. However, some patients need more support for their wrist to bring the hand closer to the mouth. Therefore, support of pronation and supination will be the aim for future study.

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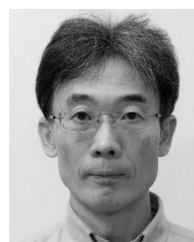
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