2011 IEEE International Conference on Rehabilitation Robotics
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011

Exoskeletal Meal Assistance System (EMAS II) for Progressive Muscle Dystrophy Patient

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***Abstract*—This paper introduces a 4-DOFs exoskeletal meal assistance system (EMAS II) for progressive muscle dystrophy patient. It is generally better for the patient to use his/her hands by himself in daily life because active works maintain level of residual functions, health and initiative of him/her. The EMAS II that has a new joystick-type user interface device and three-DOFs on a shoulder part is enhanced for an easier operation and more comfortable support on eating, as the succeeding model of the previous system that has two-DOFs on a shoulder. In order to control the 4-DOFs system by the simple user interface device, the EMAS II simulates upper limb motion patterns of a healthy person. The motion patterns are modeled by extracting correlations between the height of a user's wrist joint and that of the user's elbow joint at the table. Moreover, the EMAS II automatically brings user's hand up to his/her mouth or back to a table when he/she pushes a preset switch on the interface device. Therefore a user has only to control a position of his/her wrist to pick or scoop foods and then flip the switch to start automatic mode, while a height of the elbow joint is automatically controlled by the EMAS II itself. The results of experiments, where a healthy subject regarded as a muscle dystrophy patient eats a meal with EMAS II, show that the subject finished her meal in a natural way in 18 minutes 40 seconds which was within a recommended time of 30 minutes.**

I. INTRODUCTION

Today, there are about 20,000 patients affected by muscular diseases in Japan. Progressive muscle dystrophy patients usually suffer from difficulties in their activities of daily lives (ADL) and require caregivers support. In order to reduce the caregiver's burden, the patients need a support device for their ADL. For example, an electric wheel chair works for patient's mobility without caregiver's help. A meal support device is also required since caregivers will have to assist the meal of patients thrice daily. In order to reduce the burden on the caregivers and to improve the quality of life (QOL) of the patients, various meal assistance devices have been developed in recent years. Examples of those famous consumer devices are Handy-1[1] and MySpoon[2]. These devices can be used by the advanced stage patients, as even with limited residual functions, they can control these devices. However, the Handy-1 and Myspoon does not use patient's arms and the disuse of the arms is not desirable from viewpoint of a musculoskeletal system. Mean while there are some passive arm support devices such as the Armon[3]. It is a spring-balanced arm support and users can use their residual functions without being affected by the force of gravity. However, the people who can use it are limited to the patient with mild symptoms. In addition, the ABLE[4], the Muscle Suit[5] and the BONES[6] assist the user's arm movement for rehabilitation, but they are too large to be applied in the daily activities. When we develop assistive systems for people of progressive weakening or paralysis, we should design a versatile support system which has adjustable support level and can improve the patients' physical condition.

We developed an exoskeletal meal assistance system (EMAS I) that has three degrees of freedom on an upper arm. Its exoskeleton part is light and small by adopting a wire-driven system and it can be used in meal assistance. However, it limits the posture of a supported upper arm. The assist system simulates a healthy person's motion in most frequently used area, but it cannot do it in all range of motion.

This paper therefore proposes EMAS II that has four degrees of freedom that helps progressive muscle dystrophy patient eating in a natural way as the succeeding model of the EMAS I. Some types of muscle dystrophy start from the proximal parts and spread to the distal parts. In this study, we focus on the patients whose arm muscles are too weak to move although they can move their wrists and hands because distal parts' functions tend to remain if they are at an advanced stage. The EMAS II operated by a joystick interface device assists the shoulder and elbow joints. In the following sections, the detailed mechanisms and its fundamental performances of the EMAS II are introduced.

II. EXOSKELETAL MEAL ASSISTANCE SYSTEM (EMAS II)

A. System architecture

The EMAS II consists of exoskeleton parts attached on upper arm and forearm of a user, a joystick-type user interface device, a motor unit and a control device as shown in Fig. 1 and Fig. 2. The torque of four motors is transmitted to the shoulder and elbow joints through each wire. The wire drive mechanism enables the exoskeleton parts to be smaller and lighter. Overall components except for the user interface device are fixed on a chair or a wheelchair that muscle dystrophy patients spend most of their time on. The user interface device that is located on a table in front of a user sends the control signals through ZigBee wireless communication device. This interface has two joysticks, which control position of the wrist part and start/stop an automatic control. The user operates

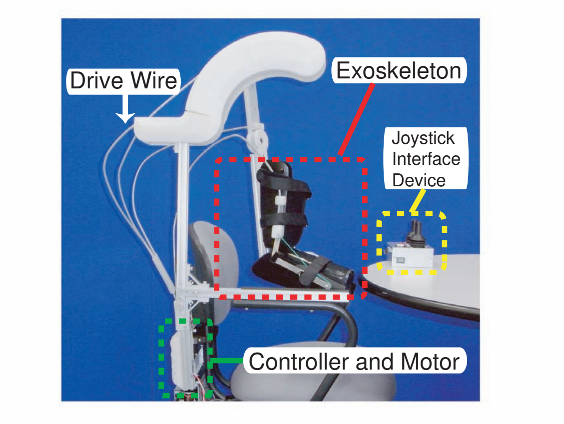


Fig. 1. Sideview of the EMAS II

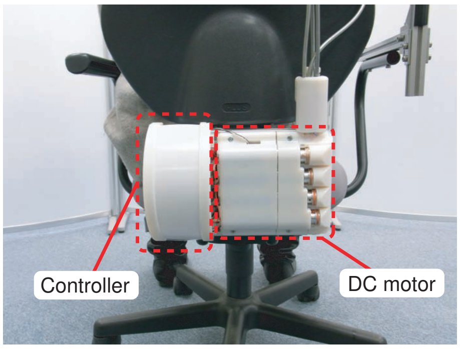


Fig. 2. Backview of the EMAS II

his/her right arm by his/her left hand with the user interface device.

B. Mechanisms

The EMAS II assists the motion of shoulder joint and elbow joint. A shoulder has three degrees of freedom, flexion/extension, medial/lateral rotation and abduction/adduction. An elbow has one degree, flexion/extension. Arrangement of joint ID, motion, θ direction, power source are shown in Fig. 3 and Table I.

In the meal situation, each motor is used to drive one direction of the joints; J_1, J_3 and J_4, and then the gravity force is used to drive the opposite direction of the joints. On the contrary, the gravity force does not affect a rotation of the joint J_2, so that a torsion spring is attached to J_2 for shoulder lateral rotation.

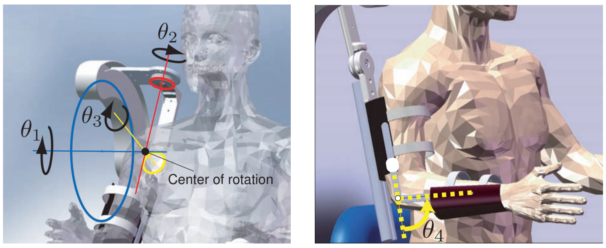


Fig. 3. Definition of coordinate system of shoulder and variables

TABLE I
ARRANGEMENT OF JOINT ID, MOTION, θ DIRECTION, POWER SOURCE

	Joint ID	Motion	θ direction	Power source
shoulder	J_1	flexion	θ_1^+	motor 1
		extension	θ_1^-	gravity
	J_2	medial rotation	θ_2^+	motor 2
		lateral rotation	θ_2^-	spring
	J_3	abduction	θ_3^+	motor 3
		adduction	θ_3^-	gravity
elbow	J_4	flexion	θ_4^+	motor 4
		extension	θ_4^-	gravity

TABLE II
RANEG OF MOTION

	The EMAS II Min. Angle [degree]	The EMAS II Max. Angle [degree]	The EMAS II Range of Motion [degree]	Human for ADL Range of Motion [degree]
θ_1	0	70	70	100
θ_2	0	80	80	110
θ_3	0	90	90	135
θ_4	20	130	110	150

Range of motion for ADL[7] are summarized in Table II. The origin of an angular vector $[\theta_1, \theta_2, \theta_3, \theta_4] = [0, 0, 0, 0]$ is the arm's neutral position. In order to avoid the singularity, the minimum angle of θ_4 is set at 20 degree. The maximum joint torques for ADL[7] are also summarized in Table III.

C. Motion Analysis

1) Experiment with Motion Capture System: Aiming for intuitive operation, the EMAS II solves inverse kinematics using data of the user's wrist joint position and a constrain condition. The user has only to control the position of his/her wrist joint without considering angles of the four joints. In order to solve the inverse kinematics problem, the condition of constraint is needed. So far, a lot of research for analysis of the human arm motions have been done[8]. However, none of them were measured for meal assistance, so this study focuses on motions of the human arm during a meal. A global Cartesian coordinate system is defined as shown in Fig. 4 for the data of posture and position of the human arm.

The meal motions were captured using the PhaseSpace IMPULSE system of PhaseSpace Inc. Nine markers were attached to the EMAS II and a subject, and eight cameras

TABLE III
MAXIMUM JOINT TORQUES

	The EMAS II [Nm]	Unimpaired Arm [Nm]
θ_1	142	53.50
θ_2	22.9	53.9
θ_3	15.0	53.6
θ_4	38.5	81.0

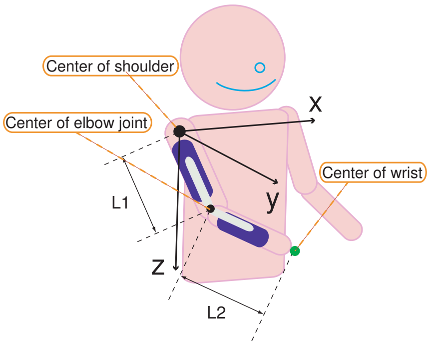


Fig. 4. Coordinate system of working space

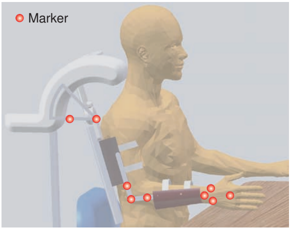


Fig. 5. Arrangement of markers for the motion capture system

Fig. 6. A subject during the meal motion analysis

tracked them (Fig. 5 and Fig. 6). The capturing rate was 120 frames per second. During the experiment, a subject who was wearing the EMAS II picked up foods from two plates on a table and ate them in five times each. The plates were put in a row in front of the subject and the height of the table was 690 [mm]. This experiment was done by three subjects (Subject 1, 2 and 3), one was a woman aged twenty-two and two were men aged twenty-two and thirty. All subjects were physically unimpaired and right-dominant.

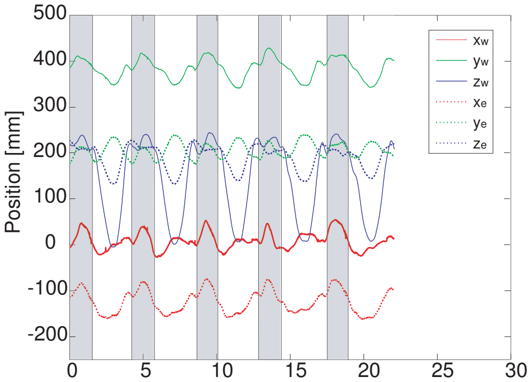
2) Results: Figure 7 shows one example of the motion measurement, where Subject 2 eating food in the left plate, where (x_w, y_w, z_w) is the position of the wrist joint and (x_e, y_e, z_e) is the position of the elbow joint. The gray areas in the Fig. 7 mean that the subject is spooning the food, and the white areas mean his/her arm movement between his/her mouth and the table. We focus on the white areas because slight movement of the elbow joint is observed during spooning. According to the measured data, the correlation between the height of the wrist joint and that of the elbow joint is extracted and then each correlation is approximated by a quadratic polynomial as shown in Fig. 8 using a least-square method.

The correlation concretely is expressed by

$$z_e = -0.0008z_w^2 + 0.5316z_w + 171.23, \tag{1}$$

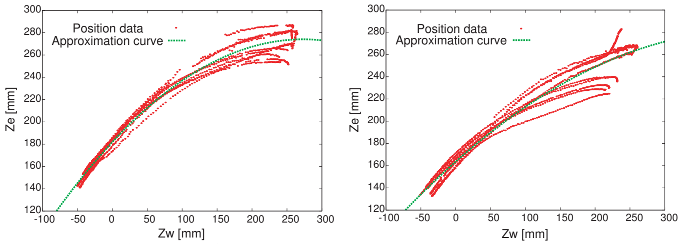
which is shown in Fig. 9.

Using this correlation model, two postures of the arm are obtained when the position of the wrist joint is fixed. Then, the EMAS II selects one of two which is in the range of motion (Table II).

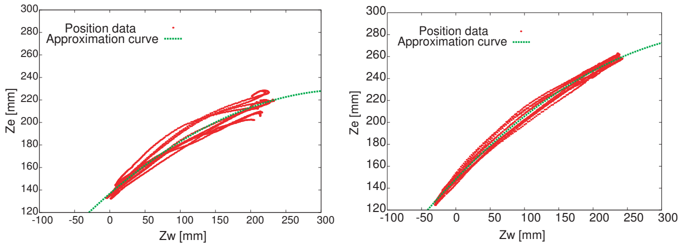


(c) Subject 2: Left Plate

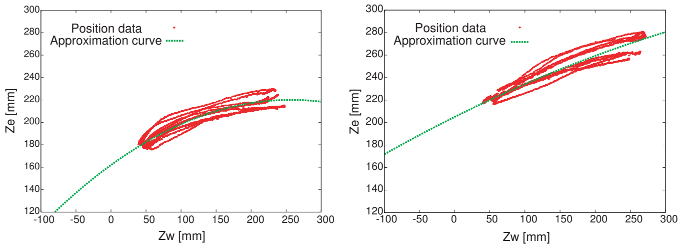
Fig. 7. Typical result of the meal motion analysis



(a) Subject 1: Left Plate (b) Subject 1: Right Plate



(c) Subject 2: Left Plate (d) Subject 2: Right Plate



(e) Subject 3: Left Plate (f) Subject 3: Right Plate

Fig. 8. The height of the wrist joint and the elbow joint

3) Inverse Kinematics: Based on arm mechanism and the correlation model mentioned above, the joint angles $\theta_1, \theta_2, \theta_3, \theta_4$ are calculated by,

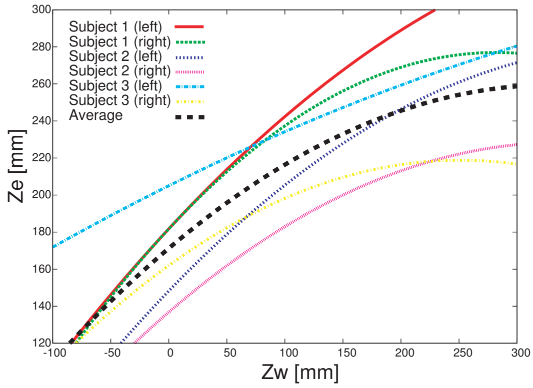


Fig. 9. Approximation curves of relationship between the height of the wrist joint and that of the elbow joint

TABLE IV
ERROR OF ELBOW POSITION

Subject	Plate	RMS of Error [mm]
Subject 1	Left	33.12
Subject 1	Right	19.66
Subject 2	Left	58.58
Subject 2	Right	27.79
Subject 3	Left	51.51
Subject 3	Right	30.31
Mean		36.83

$$\theta_1 = \cos^{-1}\left(\frac{y_w - \left(1+\frac{L_2}{L_1}\cos\theta_4\right)y_e}{L_2\cos\theta_2\sin\theta_4}\right), \qquad (2)$$

$$\theta_2 = \sin^{-1}\left(\frac{x_w - \left(1+\frac{L_2}{L_1}\cos\theta_4\right)x_e}{L_2\sin\theta_4}\right), \qquad (3)$$

$$\theta_3 = \sin^{-1}\left(-\frac{x_e}{L_1\cos\theta_2}\right), and \qquad (4)$$

$$\theta_4 = \cos^{-1}\left(-\frac{L_1^2+L_2^2-({x_w}^2+{y_w}^2+{z_w}^2)}{2L_1L_2}\right), \qquad (5)$$

where L_1 is the length of the upper arm and L_2 is that of the forearm, respectively.

The precision of the model is evaluated by comparing the measured position of an elbow joint and the predicted position based on the model. RMS of errors of them are shown in Table IV. The results show that an mean error is 37 [mm].

D. Control approach

The EMAS II has two control modes: manual control and automatic control.

In the manual control mode, the position of user's wrist joint is operated by him/her through the joystick interface device. The operations of the two joysticks correspond directory to position of the wrist joint in the manual control mode as shown in Fig. 10. The control flow in this mode is shown in Fig. 11, where $(x^{ref}, y^{ref}, z^{ref})$ is the reference of the wrist joint, and $(\theta_1^{ref}, \theta_2^{ref}, \theta_3^{ref}, \theta_4^{ref})$ is the reference of the joint angles.

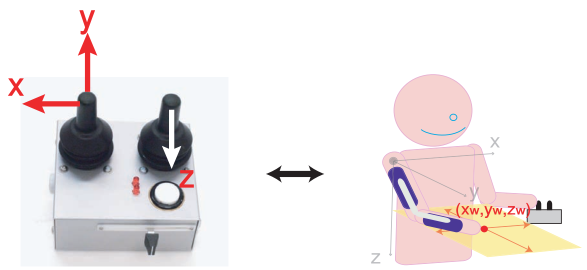


Fig. 10. Corresponding motions in the manual control

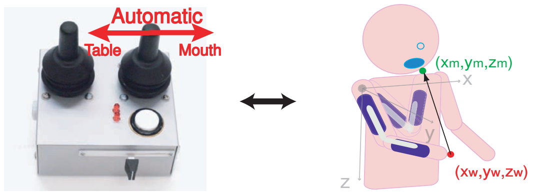


Fig. 12. Corresponding motions in the automatic control

A user can control his/her wrist joint position freely in the manual control mode. That is, it is possible to finish a meal only by using the manual control mode. However, a position of user's mouth is almost fixed and a reciprocating motion between user's mouse and a table is repeated so many times during a meal. The automatic control mode is therefore developed in order to improve utility and efficiency of system operation. In the automatic control mode, the EMAS II moves the wrist part from arbitrary position to user's mouth linearly and then move it back to where it comes from. The position of the mouth has to be programmed in advance. The corresponding motions are shown in Fig. 12. The control flow in this mode is shown in Fig. 11. Using this control mode, the user has only to incline the joystick to start the automatic mode after picking or spooning food.

III. EXPERIMENTS AND RESULTS

In order to verify the feasibility of the EMAS II for meal assistance, we conducted two different kinds of experiments.

A. Experiment procedure

1) Measurement of position accuracy: In order to clarify the position errors of the EMAS II, the position of the wrist part was measured using the motion capture system. During this experiment, two bottles filled up with one liter of water were loaded to the EMAS II in order to mimic weight of a muscle dystrophy patient (Fig. 14). The EMAS II repeated reciprocation of the wrsit part between table and mouth for 10 times. As the index, the position error of the wrist joint is considered. Let $(x^{enc}, y^{enc}, z^{enc})$ denote the wrist position calculated from the motor encoders, $(x^{cap}, y^{cap}, z^{cap})$ denote the wrist position calculated using data from the motion capture system, then the E^{enc} and E^{cap} were defined as

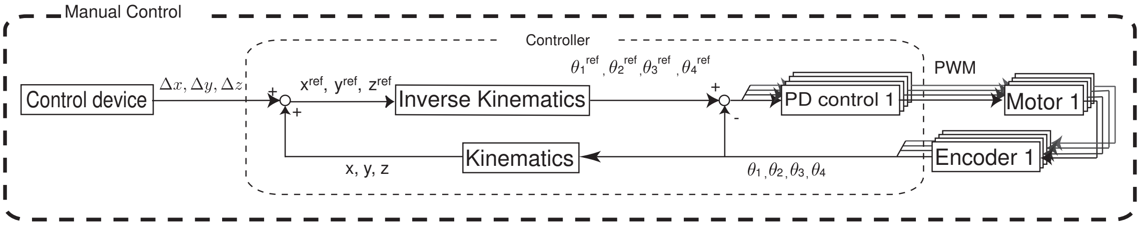


Fig. 11. Control flow of the manual control

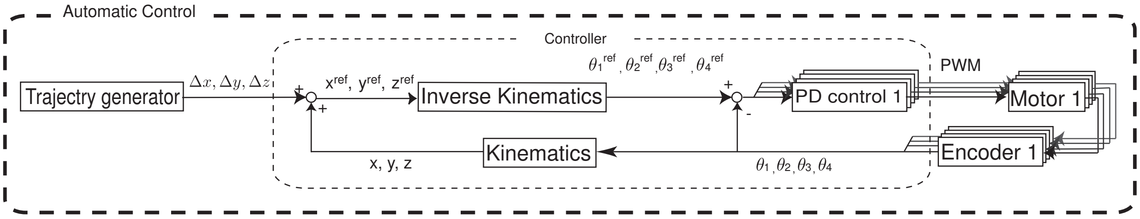


Fig. 13. Control flow of the automatic control

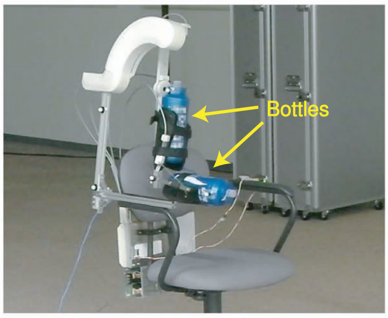


Fig. 14. The EMAS II with bottles

TABLE V
FOODS FOR THE EXPERIMENT

Curry	130 [g]	Rice	200 [g]	Potato salad	120 [g]
Yoghurt	70 [g]	Water	200 [ml]		

follows,

$$E^{enc} = \sqrt{(x^{ref} - x^{enc})^2 + (y^{ref} - y^{enc})^2 + (z^{ref} - z^{enc})^2}, \quad (6)$$

$$E^{cap} = \sqrt{(x^{ref} - x^{cap})^2 + (y^{ref} - y^{cap})^2 + (z^{ref} - z^{cap})^2}. \quad (7)$$

2) Meal assistance experiment with healthy person: A healthy subject regarded as a muscle dystrophy patient ate a meal with the EMAS II. List of foods for an experiment was shown in Table V.

Each plate was fixed to a tray of 420-by-295 [mm] on a table. The height of the table was 700 [mm], which meets the Japanese Industrial Standards (JIS). The subject was asked to pick foods from two plates with equal frequency. In order to verify usability of the user interface device and the assistive system, the time spent on meal was selected as an index. It is recommended to finish a meal within 30 minutes, because a sense of satiety is automatically induced in 30 minutes.

B. Results of the experiments

1) Results of the measurement of accuracy of position: Figure 15 shows the three kinds of wrist joint trajectories, reference wrist position, the actual wrist position calculated from the encoders of the motors and the actual wrist position measured by the motion capture system. The wrist position data from the motion capture system were offset so that their mean values correspond to each other because the coordinate origins of the EMAS II and the motion capture system were different. Rapid change of the reference position can be found at intervals, but that comes from the change of the control mode and is not a problem. Figure 16 shows that the wrist joint positioning error E^{cap} was 39.0 [mm] at most, the mean of E^{cap} was 17.6 [mm] and standard deviation of E^{cap} was 11.0 [mm]. Meanwhile, the error E^{enc} was 39.6 [mm] at most, the mean of E^{enc} was 16.6 [mm] and standard deviation of E^{enc} was 13.0 [mm]. The sources of errors were steady-state error of the PD control and the effect of friction and expansion of the cables. However, it will be little problem to eat a meal because the user can adjust the position by manual control mode.

2) Results of the meal assistance experiment with healthy person: Figure 17 shows the each action during the first cycle of eating in the second experiment:

Action 1 Pick up a spoon in manual control mode Fig. 17(a)

Action 2 Operate the hand position to pick a food on a plate in manual control mode Fig. 17(b)

Action 3 Bring the spoon up to the mouth in automatic control mode Fig. 17(c)

Action 4 Bring the spoon back to the same plate as before in automatic control mode Fig. 17(d)

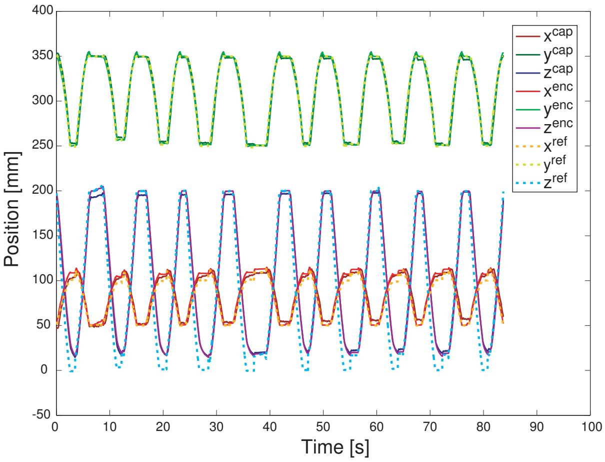


Fig. 15. Wrist joint position

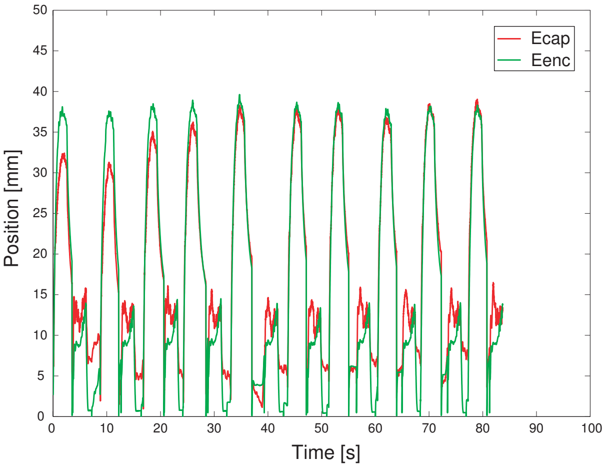


Fig. 16. Position error of the wrist joint

(a)Action 1
(Pick up a spoon)

(b)Action 2
(Operate the hand position)

(c)Action 3
(Bring the spoon up to the mouth)

(d)Action 4
(Bring the spoon back to the plate)

Fig. 17. Each action of eating

The time spent on a meal was 18 minutes 40 seconds, which was within the target time of 30 minutes. Through this experiment, we confirmed that the EMAS II is available for meal assistance.

IV. SUMMARY AND DISCUSSION

This paper introduced the EMAS II that helps the progressive muscle dystrophy patients eating meals. The user is assumed to have enough capabilities to control his hand and wrist joint. The EMAS II requires patient's operations, by using their residual functions. The left hand and wrist joint operate the joystick-type user interface device; whereas the right hand and wrist joint pick or scoop foods. The user's involvement in meal activities contributes not only to maintain their musculoskeletal conditions but also to keep fundamental dignity of individuals.

The correlation between the height of the wrist joint and that of the elbow joint are formulated based on the motion analysis of a healthy person, and then natural arm motions using multiple degrees of freedom of the EMAS II was achieved based on the formula. Through a pilot experiment, it is confirmed that the healthy person who imitated a muscle dystrophy patient finished her meal in 20 minutes. We plan to have a clinical trial of the EMAS II, which involves muscle dystrophy patients. The next step will be the development of EMAS III, which assists a wrist joint as well as an arm.

ACKNOWLEDGMENT

The authors would like to thank Prof. Fumihide Tanaka who kindly supported human motion measurement.

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