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Development of Wearable-Agri-Robot ～Mechanism for Agricultural Work～

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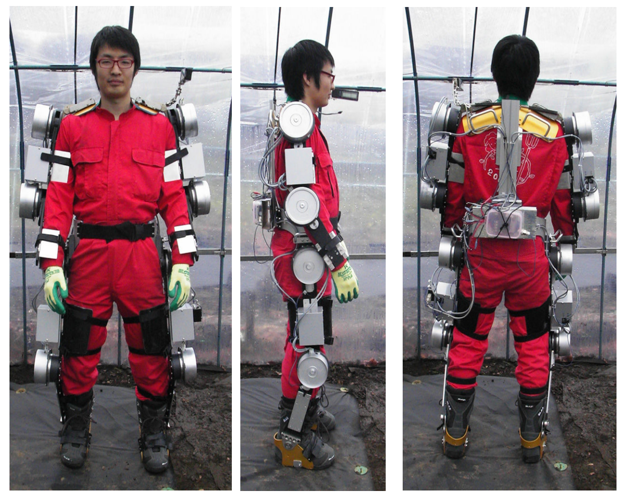
***Abstract*— Recently, It has become a rapidly aging society. Coupled with a decrease in the number of farmers, this has becomes a serious problem in agriculture. Agricultural work includes a great deal of heavy work and special work postures, imposing a large physical strain on farmers. Therefore, we developed the Wearable Agri-Robot, which was designed as an exoskeletal mechanism to assist in the wearer's work. This study evaluates the degree of freedom realized by forcusing on the range of motion of the joints. Using this method, we evaluated the articular structure of the Wearable Agri-Robot. We investigated the possibility of using it to assist in agricultural work by analyzing the motion required for thie type of work. In this work, we narrowed down the intended operations to the harvesting of Japanese radishes, and validated the effect of the Wearable Agri-Robot on the wearer using myoelectric potential measurement. As a result, it was ascertained that wearing the Wearable Agri-Robot could alleviate the burden on wearer by assisting with agricultural work.**



(a) (b) (c)

Fig.1 Wearable-Agri-Robot. (a) shows front view. (b) shows side view (c) shows back view

Ⅰ. Introduction

THERE are serious problems facing an aging society with a falling birthrate. We do not propose a concrete problem solving method. It is has been estimated that in our super-aging society one person in three was 65 years old or older in 2005. Although the present population of the agricultural work force is 3.12 million people, it decreases every year. In addition, about 59 % are 65 years old or older, with this ratio on the increase. This represents a remarkable increase in the load placed on the supporters of agriculture. Moreover, the food self-sufficiency rate for the major advanced countries is 130% for France, 119% for the United States, 91% for German, 74% for Britain, and 40% for Japan, according to an investigation by the Ministry of Agriculture, Forestry, and Fisheries. Japan has the lowest level. This fact shows the importance of improving agrigultural efficiency.

Numerous pieces of farm equipment have been introduced in an attempt to achieve this efficiency improvement. For instance, combines, etc. are used to cultivate and harvest rice fields. However, such large-scale farming machines are limited to large-scale farms, which only constitute a part of the crops. It is not more effective willingly by mechanization and enough in a small-scale farm, slope arable land, and the bottleneck in the house, etc. The same degree of advancement has not been made in the mechanization of the harvesting work for fruits and vegetables, such as the cucumbers, eggplants, and tomatoes or for the pruning hybridization, fruit thinning, and harvesting of fruit trees. Much work must still be done by hand.

Thus, we developed an exoskeleton type Wearable-Agri-Robot that can be used by an individual farmer. Agriculture labor involves the delicate work of pruning branches, judging the appropriate time for harvesting, etc. With the aim of assisting in this type of labor [1]-[3], the Exoskeleton type Wearable-Agri-Robot shown in Fig.1 was developed.

Ⅱ. WEARABLE-AGRI-ROBOT

A. Structure

The Wearable-Agri-Robot has a total of ten joints (shoulders, elbows, hip joints, knees, and ankles). DC motors unit are installed in each of these joints, with the exception of the ankles [4]-[25]. The operation interface is attached to the exoskeleton on the left side. Because input operations are performed using the voice, the hands are free. The status of the operation is displayed on a monitor at the same height as the line of vision. The controller and the battery for the motors are installed in the exoskeleton, achieving stand-alone operation.

The frame of the Wearable-Agri-Robot is constructed from aluminum and acrylonitrile-butadiene-styrene resin, which is lightweight and excellent in rigidity in bending. Velcro and a buckle are used to attach the Wearable-Agri-Robot [1]-[3]. The gross weight of the Wearable-Agri-Robot is 30 kg. However, those who install it do not feel this weight because the Wearable-Agri-Robot rests on the ground. Because it has a structure where the upper-body is combined with the lower half of the body, the installation by one person is difficult, though it only requires about five minutes. A special stand was produced for taking it off. The tire places to the stand, and carrying to outdoor is easy.

B. Control system

Those who install it wear the inner wear that can be each joint angle detection. Angle sensors and giro sensors were used for the angle detection. Pressure sensors were used for the motor control of the lower half of the body. Hall sensors were used for the motor control of the upper-body. Two method are used to control the Wearable-Agri-Robot. One reads movement reading installation person's movement from the distance of Wearable-Agri-Robot and the joint angle of those who install it as those who install it and is a mode to follow as for the motor. The second method memorizes the movement pattern and then uses a mode to reproduce it. So as not to interfere with the wearer’s movement, the follow control is performed. When work is performed where there is predetermined movement pattern, control is performed using the pattern reproduction mode. The control is matched to the situation by switching between modes based on the work

Ⅲ. EVALUTION

A. Model Designing

The joint structure was modeled from the structure and functions of a human body’s joints, and the ranges of motion of a human body’s joint were measured. Moreover, a 'degree of freedom achievement rate' that used the joints' ranges of motion was used as a method of evaluating the Wearable-Agri-Robot. The structure of the Wearable-Agri-Robot, which was designed and produced based on the joint model, was evaluated by using this 'Degree of freedom achievement rate.' In relation to the range of motion of the joint movements, the researcher who developed the model for the Wearable-Agri-Robot production was used as a testee and the range of motion of each joint was measured.

In addition, we compared these with anatomical values. The skeleton texture of a human body joint was modeled.

We made the best use of this model in the design of the Wearable-Agri-Robot. Fig. 2 shows the human body frame model and the Wearable-Agri-Rbot design model. The motors used in the Wearable-Agri-Robot chiefly aim at

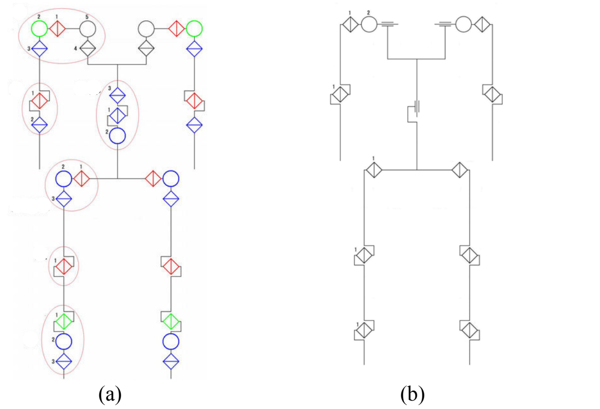


Fig.2 joint model (a) shows the human joint model. (b) shows the Wearable-Agri-Robot joint model

assisting with gravity by applying a force in the opposite

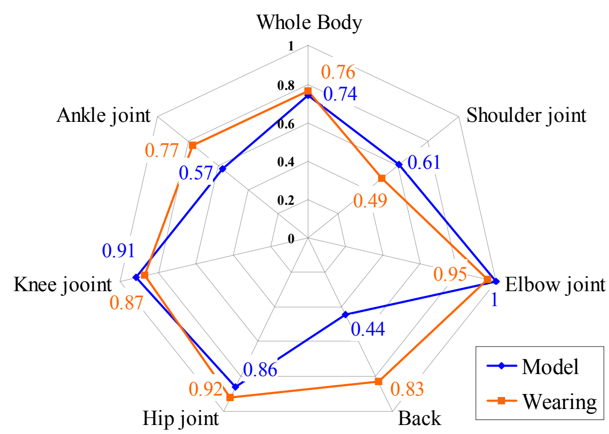


Fig.3 Comparison of Realization ratio of DOF.

direction. Therefore, the direction of the output changes for the motors in the shoulders, elbows, hip joints, and knees depend on the wearer’s posture. We should additionally reduce the error margin for the position of each joint and the position of the motor for operation.

B. Degree of freedom achievement rate

To evaluate it, we compared the degree of freedom experienced by the user before putting it on and the degree of freedom of operation after donning it. We paid attention to the degree of freedom for each joint of the human body and the range of motion of each joint of the Wearable-Agri-Robot to evaluate the degree of freedom achievement rate.

The range of motion of a joint of the human body was assumed to be θ. The range of motion of a joint of the Wearable-Agri-Robot was assumed to be φ. The gap corner of the rotation axis of the human body joint and the Wearable-Agri-Robot joint was assumed to be ψ. The degree of freedom achievement rate of the joint was assumed to be *'n'*. Thus, it can be defined by the expression:

$$n = \cos\psi \cdot g\left(\frac{\phi}{\theta}\right) \tag{1}$$

And

$$\begin{aligned} &\text{if} \quad (\frac{\phi}{\theta}) < 1 \qquad g(\frac{\phi}{\theta}) = \frac{\phi}{\theta} \\ &\text{if} \quad (\frac{\phi}{\theta}) \geq 1 \qquad g(\frac{\phi}{\theta}) = 1 \end{aligned} \tag{2}$$

For instance, the ratio of the range of motion in the joint was assumed to be *r,* which becomes the following for a joint that has winding, progress, the outward swing, the inward swing, the external rotation, the internal rotation, and three degrees of freedom.

$$n_S = r_1 \cos\psi_1 \cdot g(\frac{\phi_1}{\theta_1}) + r_2 \cos\psi_2 \cdot g(\frac{\phi_2}{\theta_2}) + r_3 \cos\psi_3 \cdot g(\frac{\phi_3}{\theta_3}) \tag{3}$$

The degree of freedom achievement rate for the entire Wearable-Agri-Robot was assumed to be N, and is defined by the next expression by using the ratio R of the range of motion between joints as the degree of freedom achievement rate n of each joint.

$$N = R_s n_s + R_e n_e + R_b n_b + R_h n_h + R_k n_k + R_a n_a \tag{4}$$

The affixing character is s respectively: shoulder, e: elbow, b: dorsal, h: hip joint, k: knee and a:

C. Evaluation

The results of measuring the joints' ranges of motion are shown in Table 1. The design model of the Wearable-Agri-Robot and the degree of freedom achievement rate for its use were calculated by using the definitional identity.

Fig. 3 is the numerical result of n and N. The degree of freedom achievement rates N_M and N_W for the whole body for the design model and after installing it indicated values close to 0.74 and 0.76, respectively. It was possible to reduce the physical exertion by 70% or more. Between the design model and the actual use, a difference was seen in the dorsal and foot joints. Its actual use fell below the design model in the shoulder joint. The other joints had almost the same values.

D. Causes of Observed Results

The difference in the foot joint was caused by movement of the wearer’s foot in the installation part. The movement of the dorsal joint was achieved by the elasticity of the frame. However, a slide mechanism was installed in the dorsal. This is because in the winding and the progress of dorsal, there is a distance in the rotation axis of the human body and Wearable-Agri-Robot. The length of the frame changed, and the displacement by the gap of the rotation axis was supplemented by the slide mechanism. However, because the item of the keep abreast of movement was not included in the definitional identity, it became the result the difference's there.

It is a winding as understood from Table.1 that the range of motion of the installation of the shoulder joint decreases especially for the design model. The reason for the metallic part of the Wearable-Agri-Robot that covered the collarbone was that it interfered and the arm did not go up to 90° or more when rotating the humerus. It is necessary to improve this interfering part. Thus, because it is an exoskeleton, the joint's range of motion is different. The problems with its use were clarified by the calculation of the degree of freedom achievement rate. Moreover, the range of motion becomes only an angle by the elasticity of the frame because it does not consider the rotation axis of the external rotation and the internal rotation of the shoulder joint of the Wearable-Agri-Robot. It can be said that it is necessary to consider the rotation axis of the external rotation and the internal rotation to improve the degree of freedom achievement rate.

Thus, we were able to confirm the part to hinder the part and operation where the operation of the human body had been almost achieved was able to be specified easily for a numerical value.

Table 1 Joint range of motion

Joint		Joint No.	Motion direction	Joint of the human body	Design model	Wearing Wearable Agri-Robot
Shoulder	Shoulder complex	1	Flexion	160	125	90
			Extension	40	40	40
		2	Abduction	130	110	80
			Adduction	25	30	20
		3	External rotation	50	10	15
			Internal rotation	65	10	10
	Shoulder girdle	4	Flexion	15	0	0
			Extension	15	0	0
		5	Elevation	15	0	0
			Depression	5	0	0
Elbow		1	Flexion	135	135	125
			Extension	0	0	0
		2	Supination	95	95	100
			Pronation	70	70	65
Back		1	Flexion	85	15	80
			Extension	20	15	30
		2	Side Flexion	40	20	20
		3	Rotation	60	40	50
Hip		1	Flexion	110	115	110
			Extension	15	20	15
		2	Abduction	45	30	25
			Adduction	20	20	20
		3	External rotation	30	20	30
			Internal rotation	30	20	30
Knee		1	Flexion	155	150	135
			Extension	0	0	0
Ankle		1	Dorsal flexion	20	75	15
			Plantar flexion	40	90	40
		2	Abduction	25	10	20
			Adduction	25	10	20
		3	External rotation	25	5	20
			Internal rotation	20	5	5

IV. ANALYSIS OF FARMING OPERATION

We wanted to determine what operations could assist with the labor of farming. To measure the joint angle under work conditions, we used a rotary sensor. The angle data of each joint of the shoulder, elbow, hip joint, and knee were measured. The investigation of the labor involved in farming was narrowed down to radish harvesting, cucumber harvesting, and fruit tree pruning, and we analyzed the work operation.

A .Radish Harvesting

Fig. 5(a) shows the angle of the lower limb joints when harvesting radishes. From this figure, it is understood that the movement of the joints of the lower extremities in the radish harvesting operation is a repetition of a certain movement pattern. It is the posture shown in Fig. 4(a).

The arm also periodically repeats the same operation, along with the movement of the lower limbs. Thus, it is thought that light work pain can be expected when using the Wearable-Agri-Robot because it is a repetition of a specific movement pattern, and work that requires the exertion of the lower limbs.

B. Cucumber Harvesting

In general, cucumbers are grown on a trellis. Mature cucumbers are harvested from this trellis. Fig. 5(b) shows the angle of the lower limb joints when harvesting cucumbers. Unlike the radish harvesting operation, it does not involve a repetitive movement pattern. This is because the positions of the harvestable cucumbers are not constant like the radishes. It is difficult to find cucumbers among the leaves because they grow at various heights from the top to the bottom of the trellis. Therefore, numerous bending exercises are involved, like the posture of half-sitting, and these postures appear at random. The operation also involves moving leaves with one hand so that the other may discover fruits, which makes irregular movements necessary.

There are a lot of bending exercises with the head bent forward in the harvesting operation for cucumbers, and the worker's load is large. However, it is thought that light pains from the Wearable-Agri-Robot are difficult to avoid because the rotational angles of the joints are uneven and there a lot of irregular movements.

C. Fruit tree pruning

As for fruit trees, cultivation is done from the height a little in general with a high shelf. Therefore, the height of the branches and fruits is over the head. Both hands are raised, and the face assumes an upward posture. Fig.5(c) shows the angle of the arm joint when working on fruit tree pruning. Tiredness collects from the shoulder to the humerus because it involves a posture of having the arms raised for a long time. As for lower limbs, their posture involves standing almost upright. It was extent to which the knee and the hip joint slightly wound for the movement. In the pruning work for fruit trees, when light pains of work can be attempted by supporting only the arm, we are guessed.

V . EVALUTION OF ADAPTABILITY

(a) (b) (c)

Fig.4 Harvesting operation (a) shows radish harvesting (b) shows cucumber harvesting (c) shows fruit tree pruning

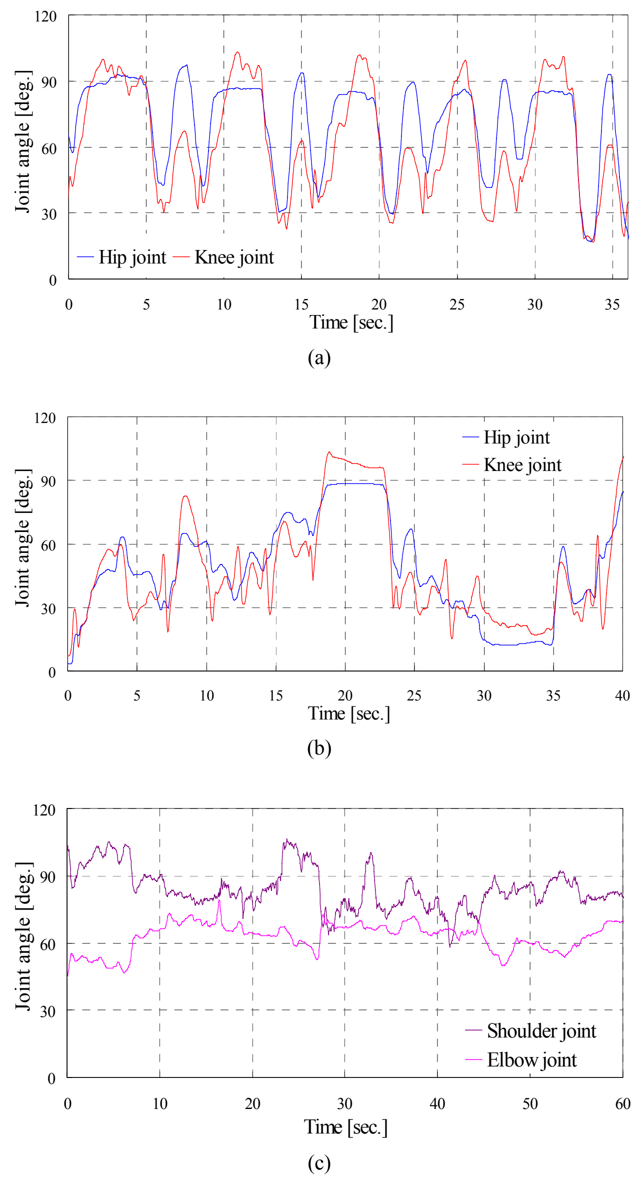


Fig.5 Joint angle. (a) shows harvesting operation of radish (b) shows harvesting operation of cucumber (c) shows pruning operation of fruit tree

The adaptability was based on the definition of the degree of freedom achievement rate. The usual range of motion for a joint of a worker's body performing farm labor was assumed to be θ_{adp}, the range of motion for a joint when wearing the Wearable-Agri-Robot was assumed to be φ_{adp}, and it can be defined by the next expression.

$$n_{adp} = g\left(\frac{\phi_{adp}}{\theta_{adp}}\right) \quad (5)$$

The n_{adp} of each joint and N_{adp} of the whole body were calculated, as well as the degree of freedom achievement rate. It was rare that joint movement under work reached the maximum range of motion although the degree of freedom achievement rate was requested by the maximum range of motion of the joint. The adaptability reached a value that was higher than the degree of freedom achievement rate. Fig.6 shows the numerical results for the adaptability.

The results were able to often operate near the circle in the radish harvesting work, and the adaptability of the whole body also reached 0.92, which was high value. The cucumber harvesting work had a value of 0.84 and the fruit tree pruning work reached 0.83, which were high values for the whole body. However, the value of the shoulder joint was low. In the cucumber harvesting work, the value of the dorsal was also low. It is understood from this that an improvement in the range of motion of the shoulder joint and dorsal are necessary.

We were able to determine the specific joint that became a problem in each type of farm labor.

VI. CONTROL SYSTEM

A. Ambulation

There are a lot of ambulation activities in the labor for farming. The goal was to make the Wearable-Agri-Robot follow the wearer's movements. In the follow-up control [4]-[25], the Wearable-Agri-Robot does not reduce man's body load. It was necessary to understand each joint angle for a human to make the Wearable-Agri-Robot follow the acquisition of these joint angles. The acquired angle sensor values were set as the target angles for the motors of each joint, and the location control of the motor was performed. PID control was used to control the motors. The walking rate went as high as 2.5 [m/sec], which is the usual walking rate for a man. DC motors and supersonic wave motors were used for the experiment.

B. Results of Experimenting with Walking

Fig. 7 shows the results of the walking experiment. Fig. 7 (a) shows the results with the DC motors. Fig.7 (b) shows the results with the supersonic wave motors. In Fig.7 (a) and (b), angular differences between the man and Wearable-Agri-Robot were hardly seen. However in Fig.7 (a) the Wearable-Agri-Robot was about 20 [msec] late compared to the man. The delay was about 120 [msec] in Fig.7 (b). It was possible to confirm that the response of the supersonic wave motor better than the response of the DC motor. The data communication time can be considered to be the cause of these delays. We should take the feedforward control for the repeating motion.

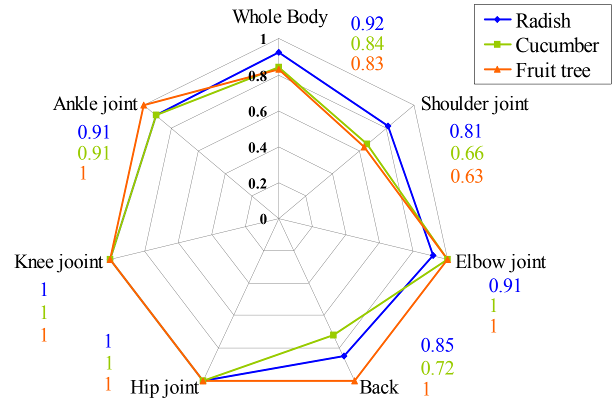


Fig.6 Comparison of Adaptability

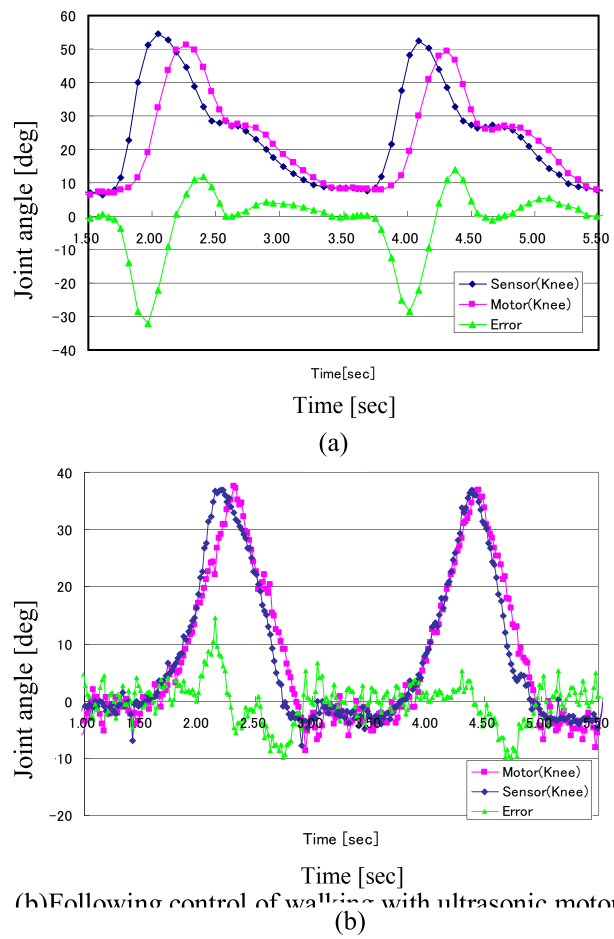


Fig.7 Following control of walking. (a) shows walking with DC motors (b) shows walking with ultrasonic motors

VII.CONCLUTION

Human body joints were modeled from the skeleton texture of the human body to make the labor for farming light pains, and Wearable-Agri-Robot was developed. An evaluation method was proposed concerning the structure of the Wearable-Agri-Robot, and the degree of freedom achievement rate and adaptability were defined as evaluation constants. The structure of each joint and the whole body were evaluated using this degree of freedom achievement rate and the effectiveness was shown. Moreover, an evaluation showed the adaptability farm labor.

An experiment was performed using supersonic wave motors and DC motors to control walking. It was possible to confirm that the response of the supersonic wave motor better than the response of the DC motor.

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