Development of an Upper Limb Power Assist System Using Pneumatic Actuators for Farming Lift-up Motion*

Eiichi YAGI**, Daisuke HARADA*** and Masaaki KOBAYASHI****

**Faculty of Systems Engineering, Wakayama University, 930 Sakaedani, Wakayama-shi, Wakayama, 640-8510 Japan
E-mail:eyagi@sys.wakayama-u.ac.jp
***Murata Machinery, Ltd., 2 Hasidumenakajima, Inuyama-shi, Aichi, 484-8502 Japan
E-mail:daisuke.harada@nan.muratec.co.jp
**** Kawasaki Heavy Industries, Ltd., 2680, Oka, Inami-cho, Kako-gun, Hyogo, 675-1113 Japan
E-mail:kobayashi_masaaki@khi.co.jp

Abstract
A power assist system has lately attracted considerable attention to lifting-up an object without low back pain. We have been developing power assist systems with pneumatic actuators for the elbow and shoulder to farming support of lifting-up a bag of rice weighing 30kg. This paper describes the mechanism and control method of this power assist system. The pneumatic rotary actuator supports shoulder motion, and the air cylinder supports elbow motion. In this control method, the surface electromyogram (EMG) signals are used as input information of the controller. The joint support torques of human are calculated based on the antigravity term of necessary joint torques, which are estimated on the dynamics of a human approximated link model. The experimental results show the effectiveness of the proposed mechanism and control method of the power assist system.

Key words: Power Assist System, Wearable Robot System, Exoskeleton, Pneumatic Actuator, EMG, Elbow Motion, Shoulder Motion, Farming, Lift-up Motion

1. Introduction
As average age goes up and birth rate decreases in the developed countries, senior workers at the agricultural industry must continue to work because of the lack of young workers. However, in spite of its intensive work such as collecting and transferring crops, the works at the agricultural industry in Japan have only been partly mechanized because of the size of each farm. Therefore, we aim to develop a power assist suit to lessen the physical load to workers at small sized farmlands.

In the last several years, many research institutions have developed power assist suits. These include, for example, the robot suit with electrical motors and reducers, HAL(1), the suit with rubber bellows type pneumatic actuators(2), the exoskeletal assist robot with electrical motors and reducers(3)(4), and the wearable walking support system with a ball screws and electrical motors(5). In addition, the muscle suit with pneumatic actuators(6), the mechanism with the pneumatic actuators(7), and the exoskeleton assist legs with hydraulic actuators for military uses(8) have been developed. For the agricultural purpose, there is a study on a power assist suit with ultrasonic motors(9).
Because of the soft motion resulting from the compression of pneumatic actuators, we have been developing an elbow power assist system with practical pneumatic cylinders that are light-weighed and have sufficiently large power and stroke\(^\text{(10)}\). The feature of a pneumatic robot is the compliance caused by the compression of air, and it was reported that its compliance is effective for reducing impact and creating soft motion\(^\text{(11)}\).

Considering these situations, we have developed an upper body power assist system for the elbow and shoulder to assist heavy lifting-up work at the agricultural industry. Using pneumatic cylinders and pneumatic rotary actuators, the system can assist lifting-up work of 30 kg load with sufficient power and stroke. Since the system with electrical motors and high-gear-ratio reducers is non-backdrivable, the joints are not elastic. In this study, the elasticity of the joints created by the compression of air plays an important role to prevent injury. Also, the system is lighter than the system without reducers by electrical motors such as ultrasonic motors.

About control, the learning theories such as neural networks were used to estimate the intended torque from electromyogram signals. This method, however, leads to diverted results by individuality and fatigue level. Therefore, calibration is necessary for accurate estimation, and sometimes it is problematic. Even when we use electromyogram signals as triggers, the followed procedures are based on predefined motion patterns. Therefore, it needs a database, and the problem of assist discontinuity exists. In this study, we use electromyogram signals as triggers, and the necessary joint torques are approximated with statics calculation by using the human model consisting of multi-jointed rigid links with measured joint angles and loads. With this technique, the system can assist a user without causing uncomfortable feelings. The reason why statics calculation is effective is that the system is intended for senior agricultural workers. The most part of joint torques are not from inertial effects by acceleration and velocity, but from gravity.

2. Upper limb power assist system

The prototype of an upper limb power assist system for the assist of lift-up motion was constructed. The mass of the total system, including the computer for control and the compressor, is about 10 kg. Figure 1 shows the photograph of the mechanism attached to a user, and Fig.2 shows the configurations of the power assist system.

![Fig.1 Overview of power assist system](image)

2.1 Assist mechanism for elbow joints

The assist mechanism for elbow joints is actuated by pneumatic cylinders. A compact light-weighted link mechanism was adopted. The part where the pneumatic cylinder is attached was improved from the previous prototype to alleviate the interference at the shoulder joint. The pneumatic cylinder has an inner diameter of 20 mm and a stroke of 125 mm.
2.2 Assist mechanism for shoulder joints

Pneumatic rotary actuators were used to the assist mechanism for shoulder joints so that the mechanism can be compact and create necessary torques. The pneumatic rotary actuator is of a double vane type and has an inner diameter of 50 mm and a stroke of 100 deg. The mechanism only assists the shoulder motion for lifting-up. Passive joints are adopted for other 2 degrees of freedom.

2.3 Specifications of power assist system

Table 1 shows the specifications of the power assist system. The torque of the elbow joint depends on the rotating angle caused by the link mechanism. Therefore, the torques of the elbow joint in Table 1 represent the peak torques at the pressures.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Elbow</th>
<th>Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator</td>
<td>Air cylinder</td>
<td>Rotary actuator</td>
</tr>
<tr>
<td>Mass of Actuator[kg]</td>
<td>0.22</td>
<td>0.82</td>
</tr>
<tr>
<td>Torque range[Nm]</td>
<td>4.40～13.2</td>
<td>4.02～14.3</td>
</tr>
<tr>
<td>(Pressure range [MPa])</td>
<td>(0.2～0.6)</td>
<td>(0.2～0.6)</td>
</tr>
<tr>
<td>Movable range[deg]</td>
<td>0～120</td>
<td>0～100</td>
</tr>
</tbody>
</table>

2.4 Pneumatic devices

Figure 3 shows the Pneumatic actuator system. The pneumatic devices used in the system are the pneumatic cylinders, flow control valves, and electro-pneumatic regulators for the elbow mechanism. For the shoulder mechanism, the pneumatic rotary actuators, flow control valves, and electro-pneumatic regulators are used. An oil mist filter and an air filter are at the back. A computer for control and a compressor are not attached to the body, though we are planning to attach them at the back at the product stage. The compressor turns on at a pressure of 0.5 MPa and off at 0.7 MPa.

2.5 Drive of actuators

The method to drive these pneumatic cylinders and rotary actuators are to produce pressure difference between the two ports where the air is flown by using electro-pneumatic regulators. Because they balance the pressure, the actuators stop at the neutral position, and when the pressure to the two ports is not so high, the actuators becomes sufficiently soft. The stiffness of the pneumatic actuators can be changed by changing the air pressure. In this system, the pressure range of the electro-pneumatic regulators is set to 0.1 to 0.5 MPa.
2.6 Measurement of EMG

EMG (Electromyogram) is the voltage that is produced when a muscle contracts. In this study, surface electromyogram from voltage sensors attached at the skin is used because by that, the sensors do not have to be within a body. Three-pole-type voltage sensors are used. Figure 4 shows the poles of the sensor. The high pass filter that attenuates the frequencies below 10 Hz and the noise cut filter that attenuates around 50 to 60 Hz are used, and the signals are amplified by 1000 times for use.

2.7 Estimation of load

The load at the elbow joints is estimated using the signals from strain gages attached at the end of arms. The picture of the part where gages are attached is shown in Fig.5. The output signals from the gages corresponding to the load are measured. The measuring method used is first to measure the voltage without a load. Then, a user lifts a bag weighing 10, 20, and 30 kg to a height of 0.6 m. Finally, the user releases the bag while measuring the voltage corresponding to the output of the strain gages. The sampling period is 10 ms. Two seconds after starting the measurement, the bag was started lifting, and after four seconds past, the bag was released. The output of the strain gages was balanced without a load.

Even though the change of voltage during the load changes is observed, the pattern of the change significantly differs from time to time. Therefore, the measured raw voltage cannot be used. Thus, RMS (Root Mean Square) of the voltage was calculated and used to obtain the trends of the signals. Equation (1) is used to calculate RMS, where N is the number of segments and \( v_i \) is the ith voltage.

\[
RMS = \sqrt{\frac{1}{N} \sum_{i=0}^{N} v_i^2}
\]  

(1)
For the measurement, 100 is used for the number of segments, N, and RMS was calculated for a period of 1000 ms. Figure 6 shows a graph of processed data. The solid line is the data without a load, and the dashed line is the data at 10 kg, and the dashed-dotted line is the data at 20 kg, and dotted line is the data at 30 kg. From Fig.6, the voltages corresponding to each load are characterized and can be used to estimate the load.

2.8 Control of power assist

The control method of the power assist system is shown in Fig.7. The loads are estimated using the signals from the strain gage attached at the end of arms. At the same time, joint angles are measured by potentiometers at the joints, and the retaining torques are calculated. The system estimates the intended motion of a user by using the electromyogram signals and the retaining torques. Then, necessary torques for that motion are imposed.

By this control method, the system can assist the user, and even when the user drops a bag, and that changes the necessary torques, the system can impose a recalculated necessary torques.

For a controller, a laptop computer that has a CPU of 1.2 GHz and a main memory of 512 MB is used. In order to obtain the signals from the electromyogram sensors, potentiometers, and strain gages, the controller is equipped with 16-bit-resolution A/D converters that have a range of ±10 V. For control output, 16-bit-resolution D/A converters that have a range of ±10 V are used. The control period is 10 ms.
2.9 Calculation of retaining torques

Since the degrees of freedom of human muscle-bone system are redundant, it is difficult to analytically resolve the torque equations at human joints created by muscles. In this study, the torque equations are resolved using a human model with a multi-jointed rigid link mechanism. Figure 8 represents the human model, and Eq.(2) are the torque equations resolved with the model.

The parameters in Eq.(2) are shown in Table 1. By using pre-measured body dimensions of a user, estimated loads, and joint angles, the system calculates the retaining torques at all the joints. By these retaining torques, the system assists the user.

\[
\begin{align*}
T_5 &= M_5 L_5 g \cos(\theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_5) \\
T_4 &= (M_4 L_4 + M_5 L_4) g \cos(\theta_1 + \theta_2 + \theta_3 + \theta_4) + T_5 \\
T_3 &= \left\{ M_3 L_3 + (M_4 + M_5) L_3 \right\} g \cos(\theta_1 + \theta_2 + \theta_3) + T_4 \\
T_2 &= \left\{ M_2 L_2 + (M_3 + M_4 + M_5) L_2 \right\} g \cos(\theta_1 + \theta_2) + T_3 \\
T_1 &= \left\{ M_1 L_1 + (M_2 + M_3 + M_4 + M_5) L_1 \right\} g \cos(\theta_1 + T_2)
\end{align*}
\]

Table 2 Link parameters

<table>
<thead>
<tr>
<th>Joint No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Torque[N\cdot m]</td>
<td>$T_1$</td>
<td>$T_2$</td>
<td>$T_3$</td>
<td>$T_4$</td>
<td>$T_5$</td>
</tr>
<tr>
<td>Mass[kg]</td>
<td>$M_1$</td>
<td>$M_2$</td>
<td>$M_3$</td>
<td>$M_4$</td>
<td>$M_5$</td>
</tr>
<tr>
<td>Link Length[m]</td>
<td>$L_1$</td>
<td>$L_2$</td>
<td>$L_3$</td>
<td>$L_4$</td>
<td>$L_5$</td>
</tr>
<tr>
<td>Length to COG[m]</td>
<td>$L_{g1}$</td>
<td>$L_{g2}$</td>
<td>$L_{g3}$</td>
<td>$L_{g4}$</td>
<td>$L_{g5}$</td>
</tr>
<tr>
<td>Joint Angle[deg]</td>
<td>$\theta_1$</td>
<td>$\theta_2$</td>
<td>$\theta_3$</td>
<td>$\theta_4$</td>
<td>$\theta_5$</td>
</tr>
</tbody>
</table>

(a) Raw EMG signal
(b) RMS EMG signal
Fig.9 EMG signals on biceps brachii
Fig.10 EMG signals on anterior deltoideus
2.10 Motion trigger signals

One of the important tasks for power assist control is to predict the motion of a user. The reason for this is that if an assist mechanism does not start moving just after a user moves, the user feels uncomfortable. In this study, electromyogram signals are used for detecting the motion of users. For the motion of elbow extension and flexion, a biceps brachii and triceps brachii muscles are measured. For the motion of shoulder extension and flexion, a front and rear parts of a deltoid muscle are measured.

Electromyogram signals are often disturbed by noises. Therefore, it is difficult to use raw signals. Thus, RMS of the signals is obtained to use the signals\(^{(4)}\). Again, Eq.(1) is used. Figure 9 shows the raw and RMS-processed signals of the biceps brachii muscle when the user flexes the elbow for 1 s, retains the position for 1 sec, and extends the elbow for 1 sec. Figure 9(a) shows the raw signal, and Fig.9 (b) shows the RMS-processed signal with a segment number, N, of 20 for a period of 200 ms. While the elbow was moved, the electromyogram signal of the biceps brachii muscle increases. This situation is more particular in the RMS-processed signal. When the change of the RMS-processed signal exceeds 0.2 mV within 200 ms, an elbow motion assumes to be activated.

Figure 10 shows the raw and RMS-processed signals of the front part of the deltoid muscle when the user flexes the shoulder. Figure 10(a) shows the raw signal, and Fig.10(b) shows the RMS-processed signal. While the shoulder was moved, the electromyogram signal of the front part of the deltoid muscle increases. This situation is more particular in the RMS-processed signal. Therefore, with this RMS-processed signal, a shoulder motion assumes to be activated.

3. Experiment

3.1 Purpose of experiment

One of the intensive works at the agricultural industry is to lift up a bag of 30-kg rice to a wheel-barrow, which is 0.6 m high. To verify the effectiveness of the system, experiment was conducted. By doing lift-up motion to the shelf, which is as high as a wheel-barrow while wearing the assist mechanism, we checked whether assist torques were appropriate and triggers by the RMS-processed electromyogram signals at a biceps brachii, triceps brachii, and front part of a deltoid muscles were functioning. In addition, whether assist was appropriate or not was verified by comparing the electromyogram signals with and without assist.

3.2 Method of experiment

A user wearing the assist mechanism lifted up a 30-kg-bag of rice. The height of lift-up motion was 0.6 m, which is as high as the rice shelf generally used. The joint angles, assist torques, voltages from strain gages for estimating loads, and RMS-processed electromyogram signals were measured. The electromyogram signals with and without assist were also measured.

The person who played a user role at the experiment was a grown-up male with a weight of 75 kg. The values in Table 3, which corresponds to Table 2, were used for Eq.(2). In this mechanism, only the elbow angle \( \theta_5 \) and shoulder angle \( \theta_4 \) were measured. We assumed the lift-up posture as straight stand-up. Considering this, the ankle angle \( \theta_3 \), knee angle \( \theta_2 \), and torso angle \( \theta_1 \) were respectively set to 70, 35, and -40 deg to calculate the retaining torques.

<table>
<thead>
<tr>
<th>Joint No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass[kg]</td>
<td>5.33</td>
<td>8.70</td>
<td>18.8</td>
<td>2.55</td>
<td>2.33</td>
</tr>
<tr>
<td>Link Length[m]</td>
<td>0.44</td>
<td>0.49</td>
<td>0.42</td>
<td>0.30</td>
<td>0.25</td>
</tr>
<tr>
<td>Length to COG[m]</td>
<td>0.22</td>
<td>0.25</td>
<td>0.21</td>
<td>0.15</td>
<td>0.13</td>
</tr>
</tbody>
</table>
3.3 Verifying lift-up motion

Figure 11(a) to (d) shows the procedure of lift-up with the assist mechanism. After grabbing a rice bag, it took 2 s to lift the bag to a height of 0.6 m. Then, the user held the bag at the same height for 1 s. Finally, using 2 s, the user put the bag on the shelf and released the bag. The mechanism could follow the lift-up motion of the user without causing uncomfortable feeling.

The time of this experiment is much longer than that of real lift-up motion. The reason why the experimental time is much longer is that the system is intended for the slow motion of senior agricultural workers. Because of the slow motion, most part of joint torques is not from inertial effects by acceleration and velocity, but from gravity.

3.4 Measurement of joint angles

Measured joint angles were analyzed. Figure 12(a) and (b) respectively show the elbow and shoulder angles during the motion shown in Fig.11. For the sign convention of the elbow angle, extension is assigned as negative direction. Figure 12(a) indicates that until 2 s, the user flexed the elbow; thus, the angle increased. After that, while the user was holding the bag for 1 s, the joint held on the same angle. Finally, while the user was extending the elbow, the angle decreased even though it seemed instantaneously increasing by the noise. About the shoulder, extension is assigned as negative direction, too.
Figure 12(b) shows that the shoulder little moved. The reason for this is that the height, 0.6 m, of lift-up was not high enough to use shoulders. The user could lift the bag only with the forearm and torso motion.

3.5 Verifying assist torque

Figure 13 shows output torques of the power assist system during the motion in Fig.11. Figure 13(a) and (b) respectively show the elbow assist torque and shoulder assist torque, and in both torques, extension is assigned as negative direction. In this experiment, the mechanism assisted the half of the elbow retaining torque, $T_5$, and half of the shoulder retaining torque, $T_4$, calculated by Eq.(2).

The inertia torque of the elbow joint, $\tau_5$, was 0.005 times as small as the retaining torque, $T_5$, as later calculated. Therefore, for the practical consideration, we use a 0.005-times torque of the retaining torque for the inertia torque triggered by the motion trigger signals mentioned in the next section. The same method was applied to the shoulder inertia torque. Because farming support for elderly people is the target of this system, motion speed and acceleration are not as large as those of average people; thus, gravity prevails. With the experiment, appropriateness of the assist torques of the elbow and shoulder joints was verified, and smoothness of the motion was confirmed. Equation (3) is used to calculate the inertia torque of the elbow joint.

\[
\tau_5 = M_5 L_5^2 \alpha_5
\]  

Now, we calculate approximate elbow inertia torque. The mass of the load and the arm, $M_5$, is 17.3 kg, and the length to the c.g. of the arm, $L_5$, is 0.13 m, and angular acceleration, $\alpha_5$, is 0.35 \(\text{rad/s}^2\). Then, from Eq.(3), $\tau_5$ becomes 0.10 Nm. The retaining elbow torque, $T_5$, can be calculated by Eq.(2). When an elbow angle, $\theta_5$, is 113 deg and shoulder angle, $\theta_4$, is -180 deg, the retaining torque becomes 21 Nm. The inertia torque is 0.005 times as much as the retaining torque; it is sufficiently small. A centripetal and Coriolis forces are also sufficiently small. Therefore, they are neglected for the elbow. They are neglected for the shoulder as well.

The motion sometimes becomes different from the motion that is intended by a user. For example, if a user tries to lift a heavy object, the arm can be dragged down due to the lack of force. Therefore, measured joint angular velocities and accelerations cannot be used for assist motion. In addition to this reason, due to the problem of noise and drift, angular accelerations are not used.

Because we assume that the joint angles of the lower limbs are constant, the calculated retaining torques sometimes exceeds necessary torques. However, the fact that the EMG signals with assist are smaller than those without assist as later shown verified the effectiveness of the assist.

3.6 Verifying trigger signals

As in Fig.9, the electromyogram signal of the biceps brachii muscle can be used for the trigger signal to the flexion of the elbow. Also, the electromyogram signal of a front part of the deltoid muscle can be used for the trigger signal to the flexion of the shoulder as in Fig.10. However, the triceps brachii and a rear part of a deltoid muscle are not much used when a user set an object down. Therefore, these electromyogram signals are sometimes not sufficient enough for the trigger signals.

Thus, in case of this insufficient electromyogram signals, the system uses the change of each measured joint angle to detect a motion of a user. When the elbow joint angle increases, the system assumes flexion, and when it decreases, the system assumes extension, and when it does not change, the system assumes a holding state. For the
shoulder joint, the same method is applied. With this technique, faltered movement at the beginning of motion almost disappears, and a user does not feel uncomfortable.

3.7 Verifying effectiveness of assist

In order to verify the effectiveness of the power assist system, electromyogram signals with and without assist were compared. Figure 14 shows the raw electromyogram signal at the biceps brachii muscle. Figure 14(a) and (b) respectively show the signal with and without assist. Figure 15 shows the raw electromyogram signal at the front part of the deltoid muscle. Figure 15(a) and (b) respectively show the signal with and without assist.

Comparing these signals, the signal with assist is smaller than that without assist in case of both the biceps brachii muscle and the front part of the deltoid muscle that are required for lift-up motions. Therefore, the effectiveness of assist was verified. For the triceps brachii muscle and the rear part of the deltoid muscle, assist is not required, and a user can set an object down without effort. Therefore, we did not compare the signals of these muscles.

4. Conclusion

In this study, for the purpose of developing an upper limb power assist system to support lift-up motions for farming work, we have constructed the prototype of a power assist mechanism and proposed a control method for this mechanism. Using pneumatic cylinders and pneumatic rotary actuators, the upper limb power assist system that assists the motion of elbows and shoulders was developed. The assist mechanism for the elbow joint has the range of 0 to 120 deg, which is the same as that of human elbow. The assist mechanism for the shoulder joint assists the extension-flexion motion, which is lift-up direction, at the range of 0 to 100 deg. Other rotational 2 degrees of freedom at the shoulder consist of passive joints. Wearing the prototype, a user can lift an object without uncomfortable feelings. The system is intended for senior agricultural workers to lift up a heavy weight.

(a) With assist
(b) Without assist

Fig.14 Raw EMG signals on biceps brachii

(a) With assist
(b) Without assist

Fig.15 Raw EMG signals on anterior deltoideus
Therefore, the velocity of the lift-up motion is not so large. Thus, we can use the pneumatic actuators with the long delay-time, e.g., 0.03 s. Comparing EMG signals, the signals with assist are smaller than those without assist. Thus, the effectiveness of the assist was verified. When the pressure to the two ports is not so high, the actuators become sufficiently soft. The stiffness of the joints can be changed by changing the air pressure. The elasticity of the joints created by the compression of air plays an important role to prevent injury.

For the control method, necessary torques are calculated by assuming human bodies as multi-jointed rigid links. By this method, appropriate assist is achieved even when load and a posture of a user change. One of the important aspects of power assist control is that the system must detect user’s intention and predict following motion because if an assist mechanism moves after the user moves, the user feels uncomfortable. In this study, electromyogram signals are used as trigger signals, and measured joint angles are simultaneously used to predict the user’s motion. During the experiment, appropriate assist torques during lift-up and the effectiveness of assist were verified with a twenty-years-old person. In case of elderly people, to whom this system targets, electromyogram signal characteristics often change. Therefore, we will validate this method, in which electromyogram signals are used as trigger signals, with the elderly people. In addition, we are planning a study on a total power assist system including lower limb assist.

References