Analysis of human object lifting operation force using power assist device

Ken Kato¹, Ryojun Ikeura¹, Shigeyoshi Tsutsumi¹, Soichiro Hayakawa¹ and Hideki Sawai¹

¹Department of Mechanical Engineering Graduate School of Engineering, Mie-University, 1577 Kurimamachiya-cho, Tsu-shi, Mie, Japan.

Abstract. We carry various objects at the work site. At that time, you may have a heavy object, which requires muscular strength. However, setting such restrictions reduces the number of people who can participate in the work. Therefore, I think that it can be improved by using a power assist device. However, the power assist device has a problem in operability. When we use an assist device to lift an object, we feel sensation different than usual. At that time, we can feel discomfort and unstable. Analyze what kind of operation is performed when a person feels uncomfortable. For that purpose, we set a weight and some lifting conditions and conducted an experiment.

1. Introduction
In countries with a declining birthrate and an aging population, the working-age population is declining. In particular, it is difficult for elderly people to participate in heavy-duty work at production sites and transportation industries because their muscle strength declines with age. However, the power assist device makes it possible to encourage work participation by compensating for weakened muscle strength. Further, by using the power assist device, in addition to reducing the burden on the operator, improvement in work efficiency can be expected. The objective of this study consists making several subjects lift various objects of different weights and sizes. The lifting operation of an object begins with the person visually recognizing the weight of the object, and by predicting the weight of the object from past experience, the method of applying force is determined and the object is lifted. However, when the power assist device is used, the weight borne by the person is reduced, so that the actually expected weight and the perceived weight are different. Therefore, there is a possibility that the force applied by a person is mistaken, and the person may feel surprised or uncomfortable and cause unstable movement. The purpose of this research is to improve convenience and safety when using a power assist device. At this time, it is important not to cause a sense of discomfort. It is considered that one of the causes of the discomfort is that the weight that a person visually expects and the weight that the person actually feels is different. In order to confirm this factor and phenomenon, the change in human operation when there is a visual change is analyzed by operating the power assist device, assuming the conditions in an actual working site.
2. Analysis of lifting operation

2.1 Lifting operation focused on the appearance

Regarding the relationship between appearance and weight, “the size-weight illusion” [1] is well known, in which the larger the size of a homogeneous object, the heavier the weight. “Simulation of Industrial Arm-Type Power-Assist System Considering Human Model” [2] and “Controller Design Method for Robustness Improvement of Power-Assist Control” [3] are studies the research power assist devices. Furthermore, “Evaluation of Compensation Ratios in Power Assist System Based on Operational Sensation” [4], “Evaluation of operability and positioning accuracy for omni-directional mobile robot with force controlled power assist” [5], and “Evaluation of the Maneuverability of the Power-Assisted Mobile Robot Using Manipulability Ellipsoid” [6] are research on operability of power assist devices. In addition, Nagai et al. determined that the primary requirements for power assistance are those aimed at assisting power and movement. Then, those aimed at safety, security, and ease of use were classified as secondary requirements [7]. Moreover, in the previous study of this research, Tage et al. [8], by using the differential waveform of the lifting force, the lifting characteristics of a person in objects with different weights were shown, and the expected weight of an object was clarified. However, in their experiments, the mass was virtually changed by a power assist device to perform the lifting operation. In the actual work site, the person exerts more power by the appearance and the weight predicted from the person's past experience. In other words, it is necessary for the device to recognize the force exerted by the prediction from the appearance and to apply the assist.

Therefore, in this paper, in order to enable operations based on expectations from the appearance, we will investigate changes in how the operator exerts force by adding weights. In addition, we will consider the problems that occur when assisting the operation.

2.2 Experimental equipment

Figure 1 shows the experimental equipment used in this study. Figure 2 shows the structure of it. It mainly consists of weights, actuators, grips, force sensors, position sensors, amplifiers, control circuits, guides, connecting rods, and weights. The object realizes a movement constrained in the vertical direction by a guide. The force sensor uses a load cell and can measure the force of only one axis when lifting an object in the vertical direction. The position sensor is a gap sensor that measures the distance from the diagonally arranged iron plate located at the bottom of the device. The target is placed 5 cm vertically from the initial position of the device, and the subject is asked to perform a lifting operation.

The voice coil motor (VCM) is used for the actuator, and a force proportional to the input voltage can be output almost ideally. The input voltage can be changed by the control circuit, and it can be switched by the switch. The data is obtained by using an oscilloscope to record the force waveform and displacement waveform.
2.3 Control method

When an object has acceleration, there are three forces applied to the object: gravity, the lifting force applied by a person, and the assisting force output by VCM. The parameters used are shown in Table 1. Figure 3 shows the forces applied to the equipment.

| Parameter          | Symbol | Unit |
|--------------------|--------|------|
| Lift Force         | $f_h$  | N    |
| Position           | $x$    | m    |
| Assist force       | $f_a$  | N    |
| React force        | $R$    | N    |
| Mass of device     | $m$    | kg   |
| Target mass        | $m_d$  | kg   |
| Gravitational       | $g$    | m/s² |

The equation of motion of an object can be expressed as the following equation.

$$m\ddot{x} = f_h + f_a - mg$$

(1)

In this experiment, a lifting operation may be performed with a certain mass as a target. Let the target model be the following equation.

$$m\ddot{x} = f_h - m_dg$$

(2)

By eliminating the acceleration $\ddot{x}$ from the above equations (1) and (2) and solving for $f_a$, it can be solved as follows.
\[ f_a = \left( \frac{m}{m_d} - 1 \right) f_h \]  \hspace{1cm} (3)

It is possible to determine the assist force as in equation (3).

Using the amplifier circuit of the operational amplifier included in the analog control circuit, adjust the lifting force \( f_h \) of a person \( \left( m/m_d - 1 \right) \) times.

The above shows the state in which the object has acceleration. However, in reality, the lifting operation starts from the state where the object is in contact with the ground. Since it receives the reaction force from the desk, the formula becomes as follows.

\[ 0 = f_a + f_h - mg + R \]  \hspace{1cm} (4)

Substituting Eq. (3) into Eq. (4) gives the following equation.

\[ 0 = f_h - mg + \frac{m}{m_d} R \]  \hspace{1cm} (5)

Moreover, when Eq. (5) is solved for the reaction force \( R \), it becomes as follows.

\[ R = \frac{m}{m_d} (mg - f_h) \]  \hspace{1cm} (6)

The operation model when lifting an object with mass \( m_d \) can be expressed as the following equation.

\[ 0 = f_h - mg + R \]  \hspace{1cm} (7)

In the case of equation (6), the reaction force \( R \) is \( m/m_d \) times. However, the person cannot feel the reaction force. In both equations (6) and (7), the object is lifted when a person exerts \( mg \).

In this experiment, the mass of the object is set to the target mass by mass compensation as in the above control.

---

Figure 3. Forces applied to the equipment
2.4 Experimental methods

In this experiment, the assisting force is applied vertically downward in state I, as shown in figure 4. State II is the state in which two weights are added and the assisting force is applied vertically upward. In addition, the assist device was set so that the mass would be the same as in states I and II. The lifting speed is the speed at which the operator naturally lifts a heavy object. There are 3 subjects and 1 instructor.

![Figure 4. Change from state I to state II](image)

An experiment is conducted to confirm that the expected weight changes due to a visual change using this experimental device. First, state 1 is performed, in which the subjects lift an object several times. After they get used to it, state 2 is performed, in which the appearance of the object change and the subjects lift the object once. The lifting waveforms are recorded in both states. This process is repeated 3 times per subject. The subject exchanges the weight when changing from state I to state II, and asks the subject to confirm that the weight is actually heavy. It is assumed that this is made heavier by putting a weight on it, but in reality, it is done with the intention of confirming the change in operation when the mass is the same by using a power assist device.

3. Experimental results

First, as an experimental result, the lifting force $f_h$ of a person is normalized by the maximum value and the time. As an example, the waveform of the lifting force of subject A is shown in Fig.5. The red line shows the first lift data for state 2. The blue line shows the second lift data and the green line shows the third lift data. The black line in the figure represents the minimum jerk trajectory [9]. The minimum jerk trajectory is the ideal waveform shown when the optimized motion is performed. In other words, it is assumed that the weight predicted by a person matches the weight felt when actually lifted, and smooth lifting can be performed without any difference in sensation. In addition, when the subject got used to the device and there was no change in the objects appearance. The waveform was almost the same as the black line.
None of the 3 samples matched the ideal lifting waveform. The lifting operation was analyzed in detail by differentiating the data shown in Fig. 5 and observing how the force is applied. Fig. 6 is a derivative of the result of subject A. The colors of the lines are the same as before. In this sample, the lifting waveforms presented a shift to the right when compared to the ideal waveform. Also, the position of the maximum value of the lifting force derivative was not constant.

By looking at the shape of the waveform from the starting point of lifting to the maximum value, it is possible to know whether the weight of the object to be lifted can be accurately grasped. When the peak of the subject’s lifting is to the left of the peak of the minimum jerk trajectory, the subject estimates that the object is heavy, and it can be said that the force, before the object is lifted, is applied earlier than usual. On the contrary, when it is on the right, the subject estimates that the object has a light weight, and it is considered that the force, until the object is lifted, is reached later than usual.

Table 2 shows the amount of deviation of the peak from the minimum jerk trajectory of each trial for each subject. In the three trials in state 2, the applied force by the subjects hardly matches the minimum jerk trajectory, and the lifting force differential varies greatly from trial to trial.

![Figure 5. Normalized lifting force](image5)

![Figure 6. Normalized lifting force differential](image6)
Also, to show how smooth the lifting operation performed by each subject is, Fig.7 shows renormalized waveforms in the time direction to align the vertices of Fig.6. From here, the integration value of the amount of deviation between the minimum jerk trajectory and the line of each color is calculated. It can be seen that the larger the integration value, the wider the difference in how the force is applied from the minimum jerk trajectory.

Table 2. Vertex difference

|   | A   | B   | C   |
|---|-----|-----|-----|
| 1 | 0.1373 | -0.1400 | -0.0025 |
| 2 | 0.1193 | 0.1500 | -0.1157 |
| 3 | 0.2691 | 0.0437 | 0.0720 |

Figure 7. Align the vertices in Fig.6 by renormalizing in the time direction

Table 3 shows the results of the integration values for each subject. When a relatively small value appears, a large value may appear again at the next lifting. It was found that none of the subjects’ lifting operations converged into the minimum jerk trajectory. This experiment was performed only three times, but it seems that the subject will become accustomed to the lifting operation as the number of times increases, and the integration value will decrease and converge to the minimum jerk trajectory. Based on the above, the operating force was analyzed. This time, we focused on the lifting force and conducted the experiment. As a result of analyzing the normalized lifting force and its derivative, it can be said that there was no clear tendency in the change of the subjects’ operation after performing several trials.

Table 3. Integral value calculated by the sum of integrated areas

|   | A   | B   | C   |
|---|-----|-----|-----|
| 1 | 0.2170 | 0.2329 | 0.0553 |
| 2 | 0.0975 | 0.2467 | 0.1961 |
| 3 | 0.3187 | 0.0826 | 0.1311 |
4. Conclusion

In this study, it is assumed that the weight of the object to be lifted by using the power assist device changes depending on its appearance, but the weight during operation does not change. An experiment was conducted in order to clarify the effect of visual factors that cause discomfort when the lifting operation is performed. From the results of the experiment, it was confirmed that the device exerted an assisting force, and when a visual change occurs, a person can sometimes produce a stable movement, and other times an unstable movement. However, no certain tendency was found.

In order to make the assist device easier for humans to handle, it is necessary to find out the tendency of human operation and control the device. Therefore, it is necessary to identify the cause of the variation in the numerical values for each subject, investigate the possibility that other factors are involved in addition to the visual sense, and further analyze the operation of humans. In addition, it is necessary to investigate the process of getting used to the feeling of discomfort.

Acknowledgement

The research has been carried out under the Malaysian Technical University Network (MTUN) Research Grant by Ministry of Higher Education of Malaysia (MOHE) under a grant number of (9028-00005)&(9002-00089) with the research collaboration with thanks to Center of Excellence Automotive & Motorsport and Faculty of Mechanical Engineering Technology, University Malaysia Perlis (Malaysia) for their productive discussions and input to the research.

References

[1] Flanagan J R and Beltzner M A 2000 Independence of perceptual and sensorimotor predictions in the size-weight illusion Nature Neuroscience 3(7) pp 737-741
[2] Doi T, Yamada H 2009 Simulation of Industrial Arm-Type Power-Assist System Considering Human Model Transactions of JSME, Series C 75(752) pp 970-976
[3] Hara S 2004 Controller Design Method for Robustness Improvement of Power-Assist Control Transactions of T. IEE Japan, Series C 70(690) pp 419-426
[4] Hayashibara Y, Tanie K, Arai H and Tokashiki H 1997 Evaluation of Compensation Ratios in Power Assist System Based on Operational Sensation Transactions of T. IEE Japan, Series C 117(5) pp 534-539
[5] Kawakami D, Miyoshi T 2018 Evaluation of operability and positioning accuracy for omni-directional mobile robot with force controlled power assist Proceedings of the Automatic Control Federation Conference 61 pp 809-813
[6] Ueno Y, Kitagawa H, Terashima K 2015 Evaluation of the Maneuverability of the Power-Assisted Mobile Robot Using Manipulability Ellipsoid Journal of the Robotics Society of Japan 33(7) pp 531-537
[7] Nagai K and Nakanishi I 2000 Mechanism and Control of Rehabilitation Robots and Assistive Devices with Power Assisting Function Institute of Systems, Control and Information Engineers 44(12) pp 688-695
[8] Tage A, Serikawa S, Ikeura R, Sawai H, Tsutsumi S and Hayakawa S 2018 Analysis of characteristics of human lifting operation leading to discomfort caused by the difference between assumed mass and perceived mass Transactions of IEEE International Conference on Robotics and Biomimetics 1 pp 752-758
[9] T Flash and N Hogan 1985 The coordination of arm movements: an experimentally confirmed mathematical model The Journal of Neuroscience 5(7) pp 1688-1703