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Relationship between characteristics of human lifting motion and predicted mass

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***Abstract* - When a human performs a lifting operation using the power assist device at the production site, if the operator's weight perception is different from what he/she assumed, the operation may be different from the assumed one, which may cause discomfort. The discomfort in the situation of using the assist device can be prevented by bringing the predicted mass and the perceived mass closer. In order to do that, it is necessary for the assist device to estimate the predicted mass before human perceives weight. Therefore, in this report, we examine the quantitative relationship between the characteristics of human lifting motion before the object is lifted and the predicted mass. For that purpose, we prepared some mass and lifting time and carried out lifting experiments based on them.**

Index Terms - Power assist device, Weight perception, Predicted mass, Lifting motion, Motion Analysis,

I. INTRODUCTION

There are many opportunities to carry heavy objects at the production sites, and the workers at these work places bear heavy burden on their body. In response to this problem, the introduction of the power assist device which amplifies the human muscular strength and supports the carrying tasks can be expected to reduce the burden on the workers and improve their work efficiency. Furthermore, it enables the people with low muscular strength and the elderly to participate in heavy muscle works.

When human lifts an object, he/she first predicts the mass from its appearance and his/her past experiences. Next, he/she applies the lifting force based on the predicted mass, and feels the actual mass as the object leaves from the ground. In the lifting operation using the power assist device, there is a problem that it is difficult to predict the mass. In addition, the human isn't always able to accurately judge the object mass. For example, when people have two objects with the same mass in different sizes, we embrace the illusion called size-weight illusion that we perceive the smaller one feels heavier than the larger one [1]. From these reasons, the lifting operation using the power assist device tends to cause the difference between the predicted mass and the perceived mass, and it may develop into uncomfortable or sudden move operation. Our study treats this problem as the weight perception problem.

Researches on power assist devices carry out wide-ranging studies such as the arm type power assist device "Extender" [2], control methods with different assist rations for gravity load and dynamic load [3], and the application of impedance control [4] [5] [6]. However, the weight perception problem has not been solved yet. In order to elucidate the generation mechanism of the uncomfortable feeling when using the power assist device, the authors investigated human lifting motion characteristics when the predicted mass and the perception mass were different [7]. As a result, they found that humans perceive unexpected speed and lifting timing when the predicted mass and the perceived mass are different. Therefore, if the predicted mass and the perceived mass are brought closer, these perceptions can be prevented and the weight perception problem can be solved.

The following methods can be considered to solve the weight perception problem. First, the power assist device estimates the predicted mass from the operator's motion characteristics during the moment from he/she starts lifting the object up to the moment he/she perceives its weight. Next, it assists to realize the estimated predicted mass. We aim to realize this method. In this method, it is necessary that the power assist device performs two tasks: the estimation of human predicted mass and the control of human weight perception. We have already shown that we can control human weight perception by inertial control [8]. This study is based on the idea of controlling the weight perception while suppressing the steady burden on the operator by separating the presumed weight and inertial force realized by the assist device, and increasing the inertial component while reducing the gravity component. On the other hand, the research on estimation of predicted mass has not been done yet. Therefore, this report aims to clarify the quantitative relationship between the predicted masses and the lifting motion characteristics of human. For this purpose, we conducted lifting experiments with multiple mass conditions and motion times.

II. EXPERIMENTAL DEVICE

A. Configuration of Experimental Device

The experiment targets a lifting motion with one degree of freedom in the vertical direction. Fig. 1 shows the appearance of the experimental device, and Fig. 2 shows the system configuration. The experimental device consists of an object intended to be lifted, a desk on which the object is grounded, an eddy current displacement meter, a force sensor which measures human lifting force, VCM (Voice Coil Motor) to support lifting force, a guide to constrain the movement of VCM in the vertical direction, and a control circuit. The object and VCM are connected by the connecting rod. It moves only in the vertical direction due to the constraint of the guide. The force generated by the human when he/she lifts the object is

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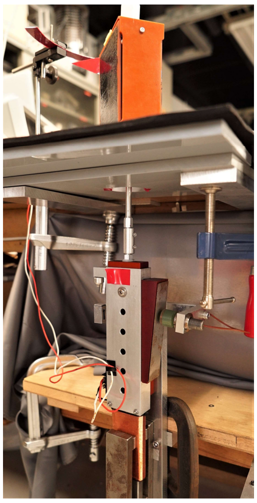

Fig. 1 Picture of the experimental device

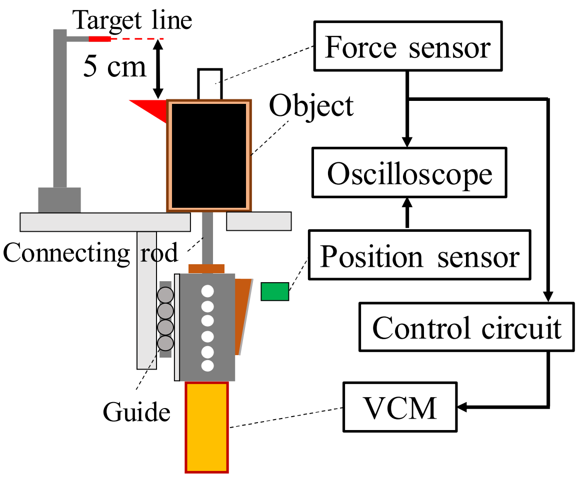

Fig. 2 Configuration of the experimental device

detected by the force sensor attached to the top of the object. However, since the lifting force is transmitted to the force sensor after the side plate of 0.140 kg is lifted, the subsequent lifting force graphs were added with 0.140 kgf as an offset. The lifting force signal is amplified by the control circuit and transmitted to the VCM, which becomes the assist force in the vertical direction. The mass can be virtually changed by switching the gain in the control circuit with the switch. In addition, we prepared the target line and the metronome as devices to indicate the stroke and timing of the lifting motion.

B. VCM Control

When the object is away from the desk and stays in the condition to keep the acceleration; gravity, human lifting force, and assist force by VCM are applied to the object as shown in Fig. 3. In this model, the guide friction of this experimental device was considered small enough, thus it was ignored. At this time, the equation of motion of the object is given by the following equation.

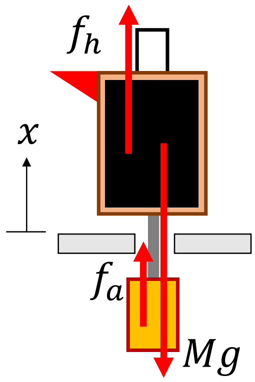

Fig. 3 Forces applied to the object

TABLE I
FREQUENCY OF HIGH SOUND ASSIGNED TO BPM

BPM	Frequency of high sound
80	1 in 3
100	1 in 3
120	1 in 4
140	1 in 5

$$M\ddot{x} = f_h + f_a - Mg \tag{1}$$

In equation (1), M (kg) is the total mass of the moving parts including the object, connecting rod and VCM, x (m) is the vertical displacement with the contact surface of the object and the desk as the origin, f_h (N) is the human lifting force, f_a (N) is the assist force by VCM, and g (m/s^2) is the gravitational acceleration. In this experiment, it is necessary to set the mass arbitrarily. Therefore, the VCM is controlled to realize the following model equation.

$$m_d\ddot{x} = f_h - m_d g \tag{2}$$

Here, m_d (kg) is the mass realized by the control. From equation (1) and equation (2), the assist force f_a is given by the following equation.

$$f_a = \left(\frac{M}{m_d} - 1\right) f_h \tag{3}$$

Using this f_a as the VCM command value, m_d was realized.

III. Outline of Experiment

In order to clarify the quantitative relationship between human predicted mass and lifting motion characteristics, we conducted lifting experiments using the experimental device described in the previous section. We had subjects repeat the lifting motion. By this movement, subjects get used to the weight sensation, so we can manipulate their predicted mass arbitrarily.

A. Lifting Motion

In order to unify the repetition period and the motion time of the lifting motion, we used a metronome to instruct subjects on the timing of their motion. The metronome emits sound with the certain period according to the value of BPM. In addition, it emits two kinds of sound, high sound "H" and low sound "L". The frequency of high sound is set individually for each BPM as shown in Table Ⅰ. For example, in the case of BPM100, H sounds once in every three times like "… H, L, L, H, L, L, H …" in this order. The procedure for the repetitive motion and the assignment of instruction sounds are shown below. The repetitive motion in BPM100 is shown in Fig. 4.

I. The object is lifted up by pinching with the right thumb and other fingers at the timing of H. And, by the timing of L immediately after H, it is stopped so that the mark spotted on the object coincides with the target line set 5 cm above.
II. The object is kept in this position until the next H timing. Fig. 5 shows the state of keeping.
III. The object is lowered to the desk at the next H signal. The grounding of the object has to be completed by the next H timing, and prepares for the next procedure.
IV. Return to step I.

The reason for preparing multiple BPMs in this experiment is to acquire the data for various motion times. If subjects achieve the lifting that roughly follows the stationary position and BPMs, the data of various lifting speeds can be collected.

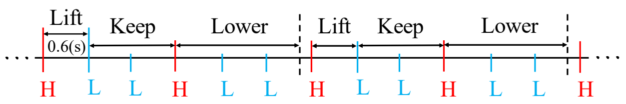

Fig. 4 Repetitive motion in BPM100

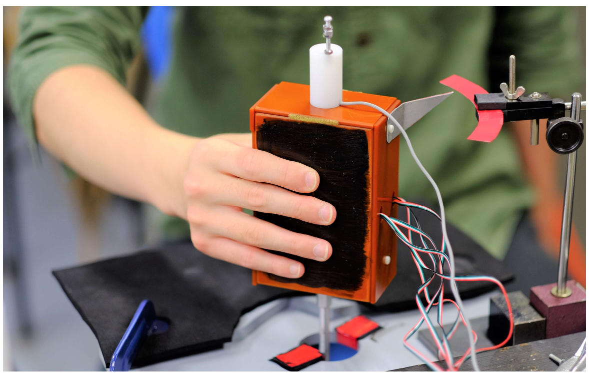

Fig. 5 State of keeping

TABLE II
ASSIGNING EXPERIMENT NUMBERS

m_d / BPM	1.000 kg	0.800 kg	0.600 kg
80	1	2	3
100	4	5	6
120	7	8	9
140	10	11	12

Therefore, the stationary position does not need to be matched to the target line exactly in step I. The reason for setting the frequency of H individually for each BPM is to ensure sufficient time for steps II and III.

B. Experiment Contents

The experiment was conducted on five healthy male college students in their twenties. Table II shows the experiment conditions and the assignment of experiment numbers corresponding to each condition. Two sets of experiments were conducted per subject. In order to eliminate the effect of order, the first set was conducted in the order of No. 1 to No. 12, and the second set was done in the order of No. 12 to No. 1 in reverse to the first set. The flow of the experiment is shown below.

I. The mass and BPM are set according to Table II, and these values are told to the subject.
II. The subject repeats the lifting motion 10 times as practice to get used to the mass and BPM conditions. If the subject claim that they not comfortable enough, continue practicing until they get used to it.
III. The lifting motion is repeated three times under the same conditions, and the third data is acquired for evaluation.
IV. Step III is repeated until five data of this condition are acquired.
V. Return to step I.

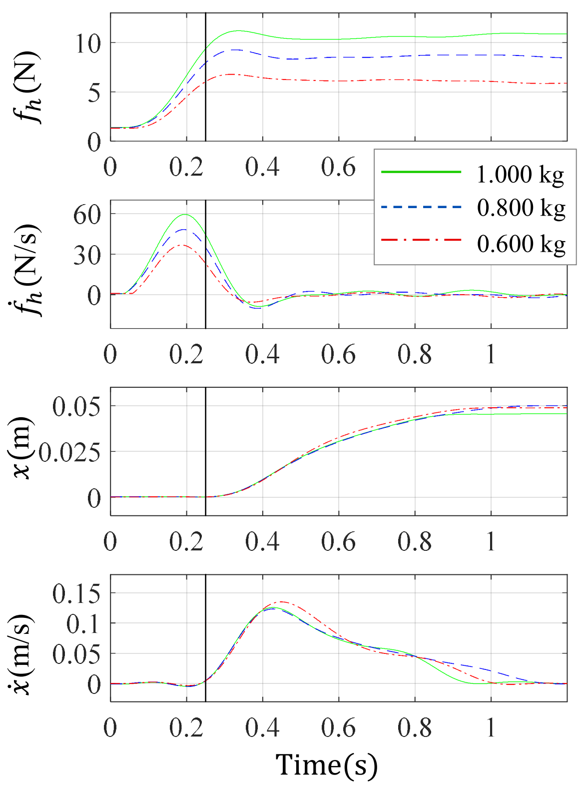

Fig. 6 Waveforms of human lifting motion

The experiment is continued until data for 120 sets of 2 sets of 12 conditions and 5 sets of each condition are acquired. Except for the motion after the experiment condition change, the subject always repeats the lifting motion with the same mass in the same tempo.

IV. RESULTS / DISCUSSION

A. Relationship between Predicted Mass and Lifting Motion Characteristics

Fig. 6 shows an example of waveforms obtained in this experiment. The vertical axis represents the human lifting force, the time differential of the human lifting force, the displacement and the speed in order from the top. All horizontal axes represent time. The vertical line in the figure represents the timing at which the object left the desk. Focusing on $\dot{f}_h$ before and after the lifting of the object in the waveform, it can be seen that it has the bell-shape. Many of the waveforms obtained in this experiment were bell-shaped. Tsuji et al. reported that if humans naturally do a simple work that can be done in the feed-forward manner, the differential waveform of the force becomes bell-shaped [9]. In this experiment as well, it was considered that the subject decided how to apply the force in the feed-forward manner based on the predicted mass and the target motion specified by the metronome. Therefore, there should be the bell-shaped differential waveforms of the force corresponding to the predicted mass and the target motion, and if the relationship between them is clarified, the predicted mass can be estimated from the shape of $\dot{f}_h$.

Fig. 7 shows the differential waveform of the representative subject's force. The vertical axis represents the time differential of the human lifting force and the horizontal axis represents time. This graph is an excerpt of the waveform with the close t_{up} value. This parameter t_{up} represents the time from the moment human applies lifting force to the object until it leaves the desk. In this figure, the larger value is t_{up1}, and the smaller value is t_{up2}. The red vertical line in this figure represents the timing at which the object leaves the desk, and the time axes of all waveforms are aligned at this timing. The graph shows that when the value of t_{up} is close, the peak value of the waveform increases as the predicted mass increases. From this, it is considered that the predicted mass can be classified from the peak value of $\dot{f}_h$ when t_{up} is constant. However, t_{up} is different each time in an actual human lifting motion. Therefore, it is necessary to classify the predicted mass considering the value of t_{up}. Comparing t_{up1} and t_{up2} between each mass, it can be seen that the peak value of $\dot{f}_h$ is larger in t_{up2} than in t_{up1}. From the above, it can be considered that the peak value of $\dot{f}_h$ increases as the predicted mass increases and the value of t_{up} decreases. Therefore, there should exist the quantitative relationship between the peak value of $\dot{f}_h$, t_{up}, and, the predicted masses.

B. Plot on $t_{peak} - \dot{f}_{h\_peak}$ Plane

From the previous section, it can be inferred that the predicted mass of human can be estimated if t_{up} and the peak value of $\dot{f}_h$ can be measured. However, t_{up} cannot be used to estimate the predicted mass. This is because the predicted mass needs to be estimated with parameters that are determined before an object is lifted. Fig. 7 shows that the period of the bell-shaped waveform is close when the value of t_{up} is close. Therefore, by using the parameter related to wave period instead of t_{up}, we investigate the relationship between this parameter and the predicted mass. For this purpose, $\dot{f}_{h\_peak}$ and t_{peak} are defined as shown in Fig. 8. $\dot{f}_{h\_peak}$ is the maximum value of $\dot{f}_h$ before the object is lifted, and t_{peak} is the time from the rise of fh until it reaches $\dot{f}_{h\_peak}$. t_{peak} is the parameter related to the period of the bell-shaped waveform, and determined before the object is lifted.

Fig. 9 shows the results of plotting the lifting motion characteristics of all subjects obtained from the experiment using the $\dot{f}_{h\_peak}$ and t_{peak} to create the $t_{peak} - \dot{f}_{h\_peak}$ plane. Since 120 data were acquired for 5 subject, the total number of plots is 600. In this figure, the plots of each mass were approximated by least squares using the following equation with an offset added to the inverse proportional expression, and results were displayed in a superimposed manner on the plots. Table III shows the calculated values of constants a and b in equation (4).

$$\dot{f}_{h\_peak} = \frac{a}{t_{peak}} + b \tag{4}$$

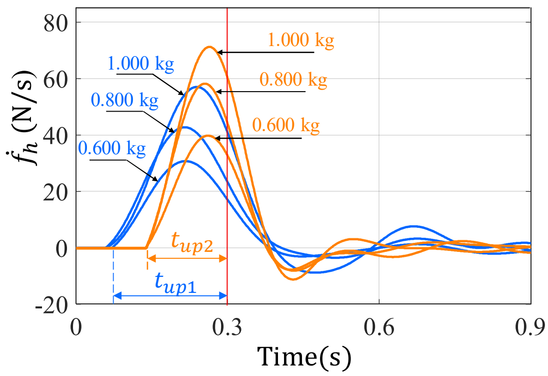

Fig. 7 Waveforms with close values of t_{up}

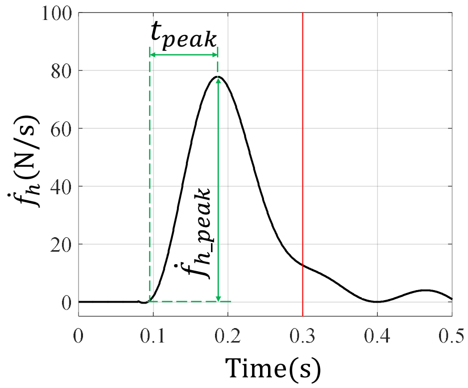

Fig. 8 Define of $\dot{f}_{h\_peak}$ and t_{peak}

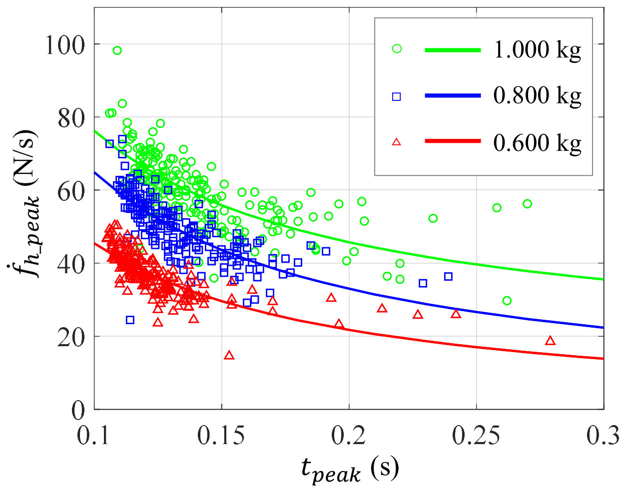

Fig. 9 Plane of $t_{peak} - \dot{f}_{h\_peak}$

TABLE III
CONSTANT VALUES a AND b IN EQUATION (4)

m_d	a	b
1.000 kg	6.1	15.3
0.800 kg	6.0	4.4
0.600 kg	4.7	-1.9

From Fig. 9, the plots were divided by each mass, and a downward-sloping curves were drawn. This confirms the consideration in the previous section that $\dot{f}_{h\_peak}$ increases as the predicted mass increases and the time required for lifting decreases. However, there were some plots deviated from each mass gathering. This corresponds to the data where the peak is off the center of the bell-shape or the data where multiple peaks appear. The reason for the existence of such data is thought that the subjects were not able to respond well to the metronome's instructions. In addition, when the range of t_{peak} was larger, the waveform often collapsed from the bell-shape more. This was because the tempo of the metronome was slow relative to the natural lifting motion of humans, and feedback-like motion characteristics that forcefully match the metronome's instructions had appeared. However, when the range of t_{peak} is large, the human force change is small, so sudden operation of the power assist device is difficult to occur. Therefore, the estimation of the predicted mass is less important in the region where the range of t_{peak} is large.

By the definition of $\dot{f}_{h\_peak}$ and t_{peak}, the relationship between the predicted mass and the lifting motion characteristics could be quantitatively shown. If the force waveform at the time of the object is grounded can be measured, $\dot{f}_{h\_peak}$ and t_{peak} can be obtained. Therefore, the predicted mass of human can be estimated from its position on the plane in Fig. 9. Specifically, the method to set a region for each mass based on the approximate curve of Equation (4) and classify the predicted mass according to the region to which the measured force waveform belongs can be considered. This time, the experiment was conducted under three types of mass conditions. However, more accurate mass prediction is possible by increasing the mass resolution and acquiring experimental data.

V. CONCLUSION

In order to solve the weight perception problem when using the power assist device, it would be effective to estimate the predicted mass of human and assist to realize this estimated mass. Therefore, in this report, in order to achieve the estimation of the predicted mass, we conducted lifting experiments with multiple masses and motion times, and investigated the relationship between the predicted masses and the lifting motion characteristics. As a result, it was found that the size of the predicted mass is reflected in the shape of the differential waveform of the human lifting force before the object was lifted.

In the future, it is necessary to evaluate the effectiveness by incorporating the estimation results of the predicted mass into the control of the actual power assist device. To achieve this, it is necessary to clear the problem that the waveform of $\dot{f}_h$ collapses from the bell shape due to noise and mechanical vibration around the sensor, and the problem that the input signal to the actuator is delayed due to the influence of the noise removal filter.

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