A Psychophysical Model of the Power Assist System for Lifting Objects

S.M.Mizanoor Rahman, Ryojun Ikeura, Masaya Nobe, Hideki Sawai
Dept. of Mechanical Engineering, Faculty of Engineering, Mie University, Tsu, 514-8507, Japan
{mizan,ikeura,nobe,sawai}@ss.mach.mie-u.ac.jp

Abstract— In this paper, we designed a 1DOF power assist system for lifting objects. Human’s vertical lifting force, comprises of inertial force and gravitational force, was considered as the desired dynamics of the system. We hypothesized that human’s perception of object weight due to inertial force might be different from the perceived weight due to gravitational force for lifting object with the power assist system. The hypothesis meant that the mass parameter of the inertial force might be different from the mass parameter of the gravitational force. We then designed the control system of the power assist system on the basis of the desired dynamics and simulated the system using MATLAB. We then psychophysically determined the optimum mass parameters for the inertial and the gravitational force components of the desired dynamics of the power assist system on the basis of human’s perception of object weight. The results showed that human’s weight perceptual consideration with the dynamics (control system) of the power assist system enhanced maneuverability, stability, naturalness, ease of use, safety etc. when lifting objects with the system. Finally, we suggested using the findings to design human-friendly power assist systems for manipulating heavy objects in various industries.

Keywords—power assist system, lifting task, maneuverability, stability, psychophysics, haptic weight perception.

I. INTRODUCTION

In the ensuing years, the uses of robots in various fields such as home automation, industrial production, mining, agricultural production, logistics and transportation, medical operations, rehabilitation etc. will be unavoidable. As a result, robots need to be made human-friendly and to execute tasks in cooperation with humans. There is increasing demand for human-friendly robot technologies, with which robots could collaborate with humans sharing the same workspace that might expand robot applications as well as could help achieve better work quality, work adjustment, productivity, safety etc. The technology has evolved to the point where intuitive human-robot cooperation is no longer a novelty, rather it has become the reality [1].

Power assist system is one of the very latest types of human-robot cooperation. When a human manipulates any object in cooperation with a power assist system, the human feels a scaled-down effect of the load and the required forces applied by the human to manipulate the object also reduce [2]. Though the breakthrough in power assist system was incepted in early1960s with “Man-amplifier” and “Hardiman” [2], the progress of research on this potential field is still unsatisfactory. At present, power assist systems are being designed mostly for the aged and disabled people and for rehabilitation purposes (e.g.,[3]-[5]). Hence, suitable power assist systems for manipulating heavy objects in various industries are still demanding.

Though several power assist systems have already been developed for manipulating objects (e.g.,[6]-[8]), these are not so suitable, safe, natural and human-friendly for manipulating heavy objects in various industries. We discussed the limitations and inconveniences of these conventional power assist systems in our previous research [9]. The fact is that, the perceived weight of an object lifted with the power assist system is always very much less than the actual weight of the object. But, the human operator cannot differentiate between the perceived weight and the actual weight and eventually applies load force (vertical lifting force) according to the actual weight of the object. This faulty force programming (excessive load force) gives faulty motion (excessive acceleration) to the power assist system and jeopardizes its maneuverability, operability, stability, naturalness, ease of use, human-friendliness, safety etc.

We argue that the aforementioned limitations and inconveniences with the power assist systems still prevail because human characteristics especially human’s weight perception are not included in the design of the conventional power assist systems. This paper attempts to present a model to solve the aforementioned limitations and inconveniences of the conventional power assist systems. The model adopts a hypothesis that pertains to human’s weight perception. Fig.1 exemplifies the hypothesis. The objectives of this research are to determine the optimum perceived heaviness of object lifted with the power assist system and to optimize (reduce) the peak load forces applied by humans that would result in optimum maneuverability, operability, naturalness, ease of use, human-friendliness, stability and safety when lifting objects with the power assist system.

In this paper, we designed a 1DOF power assist system for lifting objects. We then psychophysically determined the optimum values of inertial mass ($m_1$) and gravitational mass ($m_2$) for the desired dynamics (control system) of the power assist system. We also studied the feasibility of zero-gravity ($m_1=0$) and zero-inertia ($m_2=0$) conditions for lifting objects with the power assist system. We then outlined how the psychophysical findings of this research would be used to design power assist systems for manipulating heavy objects in various industries.

II. THE EXPERIMENTAL POWER ASSIST SYSTEM

A. Construction of the Power Assist System

A 1DOF power assist system (vertical up-down) was developed using ball screw assembly actuated by an AC
servomotor (Type: SGML-01BF12, manufactured by Yaskawa, Japan) at velocity control mode. The ball screw assembly and the servomotor were coaxially fixed on a metal board and the board was vertically attached with the wall. We made three rectangular boxes by bending aluminum sheet (thickness: 0.5 mm) in order to lift them with the power assist system. These boxes were termed as the power assisted objects. The dimensions (length \times width \times height) of the boxes were 6cm \times 5cm \times 16cm, 6cm \times 5cm \times 12cm and 6cm \times 5cm \times 8.6cm for the large, medium and small size respectively. Top side of each box was covered with a cap made of the same material (aluminum, thickness: 0.5 mm). The bottom side and the back side of each box were open. An object (box), at a time, could be tied with the ball nut (linear slider) of the ball screw assembly through a force sensor (foil strain gage type, NEC Ltd.) and be lifted by a human. The power assisted objects are shown in Fig.2.

Construction of the main power assist device is shown in Fig.3. Experimental set-up of the complete power assist system is depicted in Fig.4.

According to Fig.5, the power assisted object is controlled by the equation of motion derived as (1).

\[ m\ddot{x}_d + mg = f_h \]

Where,

- \( f_h \) = Vertical lifting force (load force) applied by the human
- \( m \) = Actual mass of the object visually perceived by the human
- \( x_d \) = Desired displacement of the object
- \( g \) = Acceleration of gravity

According to basic physics, the local effects induced by gravity and acceleration on load force are identical and cannot be separated by any physical experiment, but Zatsiorsky et al.
forces are different and less than the actual mass of the object.

The human considers that the two 'masses' used in inertial and gravitational forces are equal to the actual mass of the object (m₁ = m₂ = m). In order to realize a difference between the actual weight and the perceived weight, the human needs to think that the two 'masses' used in inertial and gravitational forces are different and less than the actual mass of the object (m₁ ≠ m₂ ≠ m, m₁ ≪ m₂). In our hypothesis, the human makes the mistake because the two 'masses' used in inertial and gravitational forces are equal to the actual mass of the object (m₁ = m₂ = m).

We derived (3), (4) and (5) from (2).

\[ \ddot{x}_d = \frac{1}{m_1}(f_h - m_2 g) \]  

\[ \dot{x}_d = \int \ddot{x}_d \, dt \]  

\[ \dot{x}_e = \dot{x}_d + G(x_d - x) \]  

We developed the block diagram of the control system of the power assist system based on (3), (4) and (5). The block diagram is shown in Fig.6. Equation (3) gives the desired acceleration that is shown in the block diagram. Then, (3) is integrated and the integration gives the desired velocity (\( \dot{x}_d \)). Then, the velocity is integrated and the integration gives the desired displacement (\( x_d \)). If the system is simulated using MATLAB (The MathWorks Inc.) in the velocity control mode of the servomotor, the commanded velocity (\( \dot{x}_e \)) to the servomotor is calculated by (6). The commanded velocity is provided to the servomotor through the D/A converter.

![Block diagram of the control system of the power assist system.](image)

Fig.6. Block diagram of the control system of the power assist system. G denotes feedback gain, D/A indicates D/A converter, I refers to integral and \( x \) denotes the actual displacement. Feedback position control method is used for this system. The servomotor is in velocity control mode.

III. EXPERIMENTS

A. Experiment 1: Determination of Optimum Gravitational Mass (m₂)

1) Objectives

The first objective of this experiment was to psychophysically determine the optimum gravitational mass (m₂) for the dynamics of the power assist system based on operator’s weight perception that would provide optimum maneuverability, safety, naturalness etc. of the system. The second objective was to study the feasibility of zero-gravity (m₂=0) condition for lifting objects with the system.

2) Subjects

Five mechanical engineering students, aged between 22 and 28 years (Mean=23.40 years, S.D. = 2.6077), were selected as subjects and they voluntarily participated in the experiments. All the subjects were right-handed, physically & mentally healthy, naive in attitude and male in sex. The subjects did not report any sensory, neurological, visual, muscular or cutaneous problems or impairments. The subjects had neither prior experience with this system nor familiarity with the hypothesis being tested. No training was given to the subjects, but instructions about the experiments were given to them. The subjects gave informed consent.

3) Design of Experiment

The independent variables of this experiment were m₂ and visual size of object. The dependent variables were maneuverability and peak load force.

4) Method

In this experiment, we simulated the system shown in Fig.6 using MATLAB. We fixed the value of m₁ at 0.5. The value of m₁ was fixed because m₁ does not affect weight perception and maneuverability. However, we changed the values of m₂. The values of m₂ were 0.5, 0.45, 0.4, 0.35, 0.3, 0.25, 0.2, 0.15, 0.1, 0.05 and 0. The values of m₂ higher than 0.5 were not considered because those values would not produce optimum maneuverability. During this experiment, following a demonstration by the experimenter, the subject lifted the object with the power assist system only one time for each value of m₂ separately. The experimenter randomly set the value of m₂, and strictly maintained its confidentiality. While lifting the object for a particular value of m₂, the subject subjectively evaluated how he felt to lift the object for that particular value of m₂ and then rated (scored) his feelings of maneuverability as any one of the following rating alternatives of a 7-point bipolar & equal-interval subjective rating scale [11]: (i) Undoubtedly best (score: +3), (ii) Conspicuously better (score: +2), (iii) Moderately better (score: +1), (iv) Alike (score: 0), (v) Moderately worse (score: -1), (vi) Conspicuously worse (score: -2), and (vii) Undoubtedly worst (score: -3).

The subject evaluated the maneuverability based on 5 criteria. The subject rated (scored) the maneuverability of the system for each of the 5 criteria separately after a trial of lifting. In the case when the subject could not rate any criterion of maneuverability properly, the trial was repeated. The maneuverability criteria were: (i) mobility of object, (ii) ease of positioning and maintainability, (iii) awareness and
control over the direction of object motion, (iv) probability of
fatigue in hand muscle, and (v) naturalness. Mobility of the
object (abbreviated as mobility) means ease of moving or
lifting the object and is related to perceived heaviness,
required load force etc. Ease of positioning and maintainability
(abbreviated as positioning) is related to perceived heaviness,
required manipulative force, system stability, haptic sensations
etc. Awareness and control over the direction of object motion
(abbreviated as motion control) is related to haptic sensations
tactile, proprioceptive and kinesthetic). Motion control also
affects human’s authority, communication and roles in the
human-system interaction. Probability of fatigue in hand
muscle (abbreviated as fatigue) is related to the probability of
fatigue and stress in hand muscle if the trials are repeated for
long time. Least probability of fatigue is to be the best.
Naturalness is related to human’s likeness, absence of
clumsiness, psychological and biomechanical adjustment,
mental acceptance, normalcy etc.

All five subjects rated their feelings regarding the
maneuverability of the system for objects of three different
sizes (small, medium, large) independently for each value of
m1. Force data for each trial were also saved separately.

B. Experiment 2: Determination of Optimum Inertial Mass(m2)

The objective of this experiment was to understand the
effects of m1 on system stability and to determine the optimum
value of m1 from the stability point of view. This experiment
was conducted by only one subject using only one object
(medium size). The independent variable of this experiment
was m2 and the dependent variable was stability of the system.

In this experiment, we simulated the system shown in Fig.6
using MATLAB. The value of m2 was fixed at 0.05. The
experimenter sequentially changed the value of m1 in a
descending order staring from 0.5 and ending to 0 while
always maintaining an equal difference of 0.05 between two
adjacent values of m1. During each trial of lifting, the
experimenter set the value of m1 and then the subject lifted the
object approximately 0.1 meter, maintained the lift for 1-2
seconds and then released the object. During each trial of
lifting, the subject subjectively checked whether or not there
were any oscillations. In this experiment, absence of
oscillations was considered as the criterion of system stability.
The subject also examined the severity of the oscillations.

IV. RESULTS AND ANALYSES

A. Results of Experiment 1

We calculated the means of the scores of the 5 subjects
for each maneuverability criterion for each value of m2 for each
size of object separately. Means (n=5) of the scores for the
maneuverability criteria with standard deviations for different
values of m2 for the medium size object are shown in Fig.7.
The figure shows that, humans enjoy the highest level of
mobility, positioning and naturalness as well as the least
fatigue in hand muscle for m2=0.05 condition. Motion control
for m2=0.05 condition is also satisfactory. We also see that for
zero-gravity condition (m2=0), positioning, motion control
and naturalness are lower than that for m2=0.05 and m2=0.1

conditions. Hence, we decided 0.05 as the best value of m2 for
the dynamics of the power assist system for lifting objects.

Two-way (visual size of object, subject) analyses of
variance (ANOVAs) were performed on the evaluation scores
for each maneuverability criterion separately for each value of
m2. Total number of ANOVAs was 5 x 11=55. The results show
that the effects of visual sizes of objects on maneuverability
were not significant (F_{2,8}<1 for each case). However, variations
in haptic size cues might affect the maneuverability. Again,
varying in maneuverability scores between the subjects were
at all not significant (F_{4,8}<1 for each case). It means that the
findings may be used as a general model.

The results in Fig.7 show that positioning, motion control
and naturalness are lower for zero-gravity condition (m2=0).
Again, fatigue and reduction in mobility may be caused for
zero gravity condition due to numbness in hand muscle. These
problems occur for the zero-gravity condition because the
humans lose some haptic information for the zero-gravity
condition that reduces humans’ weight perception ability [12],
[13]. On the other hand, the larger values of m2 do not produce
expected mobility, positioning, motion control and naturalness
because the objects always show a tendency to go downward
for comparatively larger values of m2. Again, the larger values
of m2 may produce fatigue in hand muscle.

We derived the peak load force for each trial and
determined the means of the peak load forces of the 5 subjects
for each value of m2 for different sizes of objects separately.
Mean peak load forces with standard deviations for different
values of m2 for different sizes of objects are shown in
Fig.8. The figure shows that peak load forces decrease with the
decreases in the values of m2. The peak load forces are the least
for m2=0.05 condition. The reduced peak load forces for
m2=0.05 condition optimize the motions and maneuverability
and ensure human’s safety when lifting objects with the
system. Peak load forces are proportional to object sizes [14].

Two-way (visual size of object, subject) ANOVAs were
performed on the peak load forces for m2=0 and m2=0.05
conditions separately. The results show that the effects of
visual sizes of objects on peak load forces were highly significant ($F_2,3=122.19, p<0.01$ for $m_2=0$; $F_2,3=117.85, p<0.01$ for $m_2=0.05$). However, variations in peak load forces between subjects were not significant ($F_4,9=0.36$ for $m_2=0$; $F_4,9=1.10, p>0.1$ for $m_2=0.05$).

Fig.8 shows that, the peak load forces suddenly increase at $m_2=0$. We assume that reduction in haptic senses at zero-gravity condition ($m_2=0$) may result in larger and irregular peak load forces, which is not good for safety and maneuverability. Fig.9 shows, as an example, the irregular, multi-peaked and impulsive nature of the load force at $m_2=0$.

The results as a whole indicate that advantages in static properties (e.g., least or zero weight) may not always produce advantages in dynamic properties (e.g., mobility, positioning, motion, load force etc.) especially for the systems that integrate human elements (e.g., power assist system).

### B. Results of Experiment 2

Table 1 shows the state of the oscillations for each value of $m_1$. The results show that oscillations started at $m_1=0.25$ and the severity of oscillations gradually increased with the decreases in the values of $m_1$. Oscillations were so severe at $m_1=0.1$ that it was not possible to conduct the experiment for the values of $m_1$ lower than 0.1. Hence, zero-inertia ($m_1=0$) condition was not feasible. The results show that $m_1$ affects system stability. Hence, we may accept all the values of $m_1$ where there are no oscillations. But, we have already proved in [9] that, $m_1$ also proportionally affects the peak load forces. Hence, we need to accept the minimum value of $m_1$ where there are no oscillations because the objective of our hypothesis is to minimize the peak load forces. Hence, we suggested $m_1=0.3$ as the optimum value of $m_1$ for the desired dynamics of the system from the stability point of view.

#### C. The Combined Results of Experiment 1 and 2

From the results of experiment 1 and 2 we see that the optimum values of $m_1$ and $m_2$ for the dynamics of the power assist system for lifting objects are $m_1=0.3$ and $m_2=0.05$. At $m_1=0.3$ and $m_2=0.05$, the system offers the best maneuverability, naturalness, safety and stability. The results also suggest that system stability significantly affects maneuverability, naturalness and safety of the system. Hence, $m_1=0.3$ and $m_2=0.05$ should be used together.

In another experiment, we simulated the system shown in Fig.6 using MATLAB for three sets of values of $m_1$ and $m_2$ separately for objects of different sizes. The three sets of values of $m_1$ and $m_2$ were: a) $m_1=0.5$, $m_2=0.5$ b) $m_1=0.5$, $m_2=0.05$ and c) $m_1=0.3$, $m_2=0.05$. The objective of this experiment was to compare the peak load forces for the optimum set ($m_1=0.3$, $m_2=0.05$) with some other alternatives.

During this experiment, the subject lifted the object with the system only one time for each set of values of $m_1$ and $m_2$ separately. The experimenter randomly chose the set of values of $m_1$ and $m_2$ and strictly maintained its confidentiality. All five subjects performed this experiment for objects of three different sizes independently for each set of values of $m_1$ and $m_2$. Force data for each trial were also saved separately.

We derived the peak load force for each trial and determined the means of the peak load forces of the 5 subjects for each set of values of $m_1$ and $m_2$ for small, medium and large object separately. Mean $(n=5)$ peak load forces with standard deviations for three sets of values of $m_1$ and $m_2$ for different sizes of objects are shown in Fig.10. The results show that the optimum set ($m_1=0.3$, $m_2=0.05$) produces the least peak

### Table 1. Oscillations at Different Inertial Mass

<table>
<thead>
<tr>
<th>Value of $m_1$</th>
<th>Results</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>No oscillations</td>
<td>Acceptable value of $m_1$</td>
</tr>
<tr>
<td>0.45</td>
<td>No oscillations</td>
<td>Acceptable value of $m_1$</td>
</tr>
<tr>
<td>0.4</td>
<td>No oscillations</td>
<td>Acceptable value of $m_1$</td>
</tr>
<tr>
<td>0.35</td>
<td>No oscillations</td>
<td>Acceptable value of $m_1$</td>
</tr>
<tr>
<td>0.3</td>
<td>No oscillations</td>
<td>The optimum value of $m_1$</td>
</tr>
<tr>
<td>0.25</td>
<td>Oscillations start</td>
<td>Unacceptable value of $m_1$</td>
</tr>
<tr>
<td>0.2</td>
<td>Oscillations</td>
<td>Unacceptable value of $m_1$</td>
</tr>
<tr>
<td>0.15</td>
<td>Strong oscillations</td>
<td>Unacceptable value of $m_1$</td>
</tr>
<tr>
<td>0.1</td>
<td>Severe oscillations</td>
<td>Unacceptable value of $m_1$</td>
</tr>
<tr>
<td>0.05</td>
<td>Not examined</td>
<td>Unacceptable value of $m_1$</td>
</tr>
<tr>
<td>0</td>
<td>Not examined</td>
<td>Unacceptable value of $m_1$</td>
</tr>
</tbody>
</table>

**Fig.8** Mean ($n=5$) peak load forces with standard deviations for different values of $m_1$ for different sizes of objects.

**Fig.9.** Time trajectories of the load forces for $m_1=0.1$, 0.05 and 0 conditions for a representative subject for the large object. The impulsive and irregular nature of the peak load force at zero-gravity ($m_2=0$) is also shown (encircled).
also satisfy the biomechanical criteria for the operators. Hence, the psychophysical criteria of this paper may even when lifting a very heavy load with the power assist objects. In our case, the human will feel only 0.05kg (0.49N) when lifting objects with the system and thus may ensure help avoid injuries, risks, vibrations and jerks on human body. The findings may be used to design power assist systems for carrying heavy objects in industrial applications. The number of subjects will be increased to generalize the results in future. We will conduct experimental verifications of the findings with heavy objects. Other approaches that may further optimize the perceived heaviness and the peak load forces will be investigated. New and advanced control methods for the system will also be searched. The system will be upgraded and generalized to multi-DOF system (horizontal, rotational etc.). Bimanual and cooperative weight lifting will also be studied.

V. GENERAL DISCUSSION

In this paper, we have psychophysically determined the conditions \(m_1=0.3, m_2=0.05\) for optimum maneuverability, safety, operability, ease of use, human-friendliness etc. for lifting objects with the power assist system. The research also proves that, zero-gravity \((m_2=0)\) and zero-inertia \((m_1=0)\) conditions are not feasible for lifting objects with the power assist system.

The findings of experiment 1 \((i.e., m_1=0.05\) as the optimum\) provide optimum perceived heaviness, maneuverability, ease of use etc. while lifting objects with the system. This experiment also reduces the peak load forces that optimize the motions of the objects lifted with the system. The experiment 2 ensures the stability of the system. The combined results of the two experiments further reduce the peak load forces that may further optimize the motions. The optimized motions may help avoid injuries, risks, vibrations and jerks on human body when lifting objects with the system and thus may ensure human’s safety while working with the system. Here, the optimality has been determined heuristically and subjectively based on human’s feelings and experiences. Hence, the findings associate with the objectives of the research.

The findings may be used to design power assist systems for carrying heavy objects in various industries. The optimum value of \(m_1\) of this paper does not mean the actual mass of object to be lifted in industrial applications, rather the value of \(m_2\) means the value that would be put into the control systems for getting optimum maneuverability, safety, stability etc. when lifting heavy objects with the power assist systems.

The main factor affecting biomechanical properties is the magnitude of the load felt by the lifter when lifting heavy objects. In our case, the human will feel only 0.05kg (0.49N) even when lifting a very heavy load with the power assist system. Hence, the psychophysical criteria of this paper may also satisfy the biomechanical criteria for the operators.

VI. CONCLUSION

This paper successfully presents the psychophysical model of the power assist system for lifting objects. The findings may be used to design power assist systems for carrying heavy objects in industrial applications. The number of subjects will be increased to generalize the results in future. We will conduct experimental verifications of the findings with heavy objects. Other approaches that may further optimize the perceived heaviness and the peak load forces will be investigated. New and advanced control methods for the system will also be searched. The system will be upgraded and generalized to multi-DOF system (horizontal, rotational etc.). Bimanual and cooperative weight lifting will also be studied.

REFERENCES