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Controlling a Power Assist Robot for Lifting Objects Considering Human's Unimanual, Bimanual and Cooperative Weight Perception

S.M.Mizanoor Rahman, *Member, IEEE*, Ryojun Ikeura, *Member, IEEE*, Masaya Nobe, Hideki Sawai

Abstract—**We developed a 1 DOF power assist robot for lifting objects. We hypothesized that human's perception of weight due to inertial force might be different from the perceived weight due to gravitational force for lifting an object with a power assist robot. We established psychophysical relationships between the actual weights and the power-assisted weights for the objects lifted with the robot, and also determined the excess in load forces that the subjects applied for three independent lifting schemes or grasp configurations: (i) unimanual lift, (ii) bimanual lift, and (iii) cooperative lift. We also compared the weight perceptual and load force features for the unimanual lifts to that for the bimanual and cooperative lifts. We then modified the power-assist control using a novel control strategy based on the weight perceptual and load force features. The control modification reduced the excessive load forces applied by the subjects in each lifting scheme and thus enhanced maneuverability, naturalness, ease of use, stability, safety etc. of the robot system significantly. Finally, we proposed using the findings to design human-friendly power assist robots for carrying heavy objects in various industries.**

I. INTRODUCTION

A. Background and Motivation

It is assumed that in the near future many aspects of our lives and activities will be encompassed by tasks done in cooperation with robots because the barriers between humans and robots have already started to decline with the turn of the twenty first century. Uses of robots in industrial production, logistics, transport, agricultural production, mining, medical operations, welfare and rehabilitation, military and rescue operations etc. will be indispensable. Hence, robots should be developed as human-friendly so that they can perform tasks in cooperation with humans. There is increasing demand for human-friendly robotic technologies, with which robots could collaborate with humans sharing the same workspaces that might expand robot applications as well as could help achieve better work quality, productivity, work adjustment, work environment, safety, stability etc. The technology has been evolved to the point where intuitive human-robot interaction, coordination, cooperation and communication are no longer the novelty, rather it has become the reality.

Power assist robot (PAR) is one of the latest types of human-robot cooperation. When a human manipulates any object in cooperation with a PAR, the human feels a scaled-down effect of the weight and the required forces applied by the human to manipulate the object also reduce [1]. Though the breakthrough in power-assist technology was conceived in early 1960s with "Man-amplifier" and "Hardiman" [1], the progress of research on this important field is still unsatisfactory. Currently, PARs are being designed mainly for the aged and disabled people and for rehabilitation [2]-[6]. Some power-assist devices are available for other purposes such as physical support systems for agricultural workers [7], hydraulic power assist for automobiles [8], slide doors for automobiles[9], skill-assist systems in manufacturing [10], power-assist control for cycle [11], assist for sports training [12], assist for lifting baby carriage [13] etc. However, designs of suitable PARs for carrying heavy objects in various industries have not received so much attention yet.

Manipulating heavy objects in industries is a very common and familiar task. However, manual manipulation is very cumbersome. On the contrary, automatic devices may not provide required level of flexibility in manipulation of objects in many practical cases. Hence, it is thought that suitable power-assist devices may be appropriate for this purpose. However, such devices are usually not available in practices.

B. Related Works, Problem Statement, Research Objective

A few PARs have already been designed for carrying objects [14]-[17], but these are not so safe, natural and human-friendly for lifting heavy objects in industries. Limitations with the conventional PARs are that the operator applies excessive load force (LF-vertical lifting force) as the operator cannot correctly perceive the weight of the object before lifting it with the robot. The excessive LF results in sudden increase in acceleration, fearfulness of the operator, lack of maneuverability and stability, accident etc. [18].

We argue that the aforementioned limitations and inconveniences with the PARs still prevail because special types of industrial PARs for lifting heavy objects have not been designed yet based on weight perceptual and load force features. This paper presents a model of the PAR for lifting heavy objects based on a hypothesis that pertains to human's weight perception.Fig.1 exemplifies the hypothesis.

C. The Paper Summary

In this article, we developed a 1 DOF (vertical up-down) PAR system using a ball screw assembly for lifting objects. Then, we established psychophysical relationships between the actual weights (weight of an object perceived by the human if the object is lifted manually) and the power - assisted weights (PAWs-weight of an object perceived by the

This work was supported in part by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). S.M.Mizanoor Rahman, Ryojun Ikeura, Masaya Nobe and Hideki Sawai are with the Department of Mechanical Engineering, Faculty of Engineering, Mie University, Tsu, 514-8507, Japan. Tel/Fax: +81-59-231-9668. E-mails: {mizan, ikeura, nobe, sawai}@ss.mach.mie-u.ac.jp

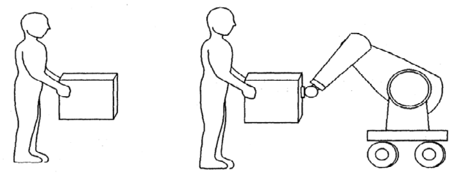

Fig.1. The human at the left side lifts an object manually and the same human at the right side lifts the same object with a PAR. When the human lifts the object manually, he/she feels the actual weight of the object. On the contrary, when the human lifts the object with the PAR, he/she feels a scaled-down portion of the weight. The desired dynamics for lifting the object is the LF that consists of inertial and gravitational forces. We hypothesize that, when lifting an object with a PAR, human's perception of weight due to inertia may be different from the perceived weight due to gravity. The hypothesis means that the human must consider the mass parameter for the inertial force different from the mass parameter for the gravitational force when lifting an object with a PAR because the perception and the reality regarding the object weight are different in this case. The mass parameters for the inertial force and the gravitational force should also be less than the actual mass of the object.

human (operator) when the object is lifted with the PAR) for the objects lifted with the robot system. We also determined the excess in the LFs that the subjects applied when lifting objects with the robot system.

In industrial practices, workers decide to employ one or two hands to transport objects on the basis of object's physical features such as shape, size, mass etc. Hence, we established the psychophysical relationships and determined the excess in LFs for three protocols separately: (i) unimanual lift, (ii) bimanual lift, and (iii) cooperative lift. We also compared the weight perceptual and LF features for the unimanual lifts to that for the bimanual and cooperative lifts.

Then, we modified the control using a novel control strategy based on the weight perceptual and LF features. The modified control reduced the excessive LFs in each lifting protocol and thus enhanced maneuverability, operability, naturalness, ease of use, stability, safety etc. of the robot system significantly. Finally, we proposed using the findings to develop PARs for carrying heavy objects in industries.

II. THE EXPERIMENTAL ROBOT SYSTEM

A. *Configuration of the Power Assist Robot System*

A 1DOF PAR was developed using a ball screw assembly actuated by an AC servomotor (Type: SGML-01BF12, made by Yaskawa, Japan). The ball screw assembly and the servomotor were coaxially fixed on a metal board and the board was vertically attached to a wall. Three rectangular objects (boxes) were made by bending aluminum sheets (thickness: 0.5 mm).These objects were lifted with the PAR and were named as the power-assisted objects (PAOs). The dimensions (length x width x height) of the boxes were 6cm x 5cm x 16cm, 6cm x 5cm x 12cm and 6cm x 5cm x 8.6cm for the large, medium and small size respectively. Top side of each box was covered with a cap made of aluminum sheet (thickness: 0.5 mm).The bottom and the back of each box were open. An object (box), at a time, could be tied to the ball nut (linear slider) of the ball screw assembly through a force sensor (foil strain gauge type, NEC Ltd.) and be lifted by a subject. The PAO tied to the force sensor was kept on the soft surface of a table before it was lifted.

We made three more 'non power-assisted objects' (boxes) (NPAOs) of three different sizes (small, medium, large).The NPAOs were lifted manually and were not physically connected to the PAR system. The shape, dimensions, material and outlook of a NPAO of a particular size were same to that of the PAO of that particular size. The NPAOs were used as reference weights for estimating the perceived weights of the PAOs i.e., the PAWs.

The PAOs and the NPAOs are shown in Fig.2. The main power assist device is shown in Fig.3. The complete experimental setup of the PAR system is depicted in Fig.4.

B. *Dynamic Modeling of the Robot System*

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

$$m\ddot{x}_d + mg = f_h. \qquad (1)$$

Where,

f_h = Load force (vertical lifting force) applied by human

m = Actual mass of PAO visually perceived by human

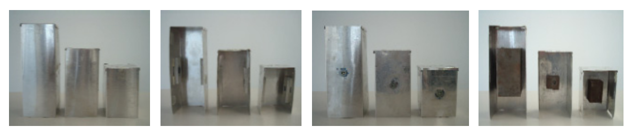

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Fig.2. The first photo (i), from left to right, shows the front sides of the large, medium and small PAOs respectively, and the second photo (ii), from left to right, shows their backs. The third photo (iii), from left to right, shows the front sides of the large, medium and small NPAOs respectively, and the fourth photo (iv), from left to right, shows their backs. The extra mass attached to the back of each NPAO is shown as examples. The extra mass helped change the weight of the object while keeping the outlook (front view) same. Self-weight of each PAO and NPAO was negligible.

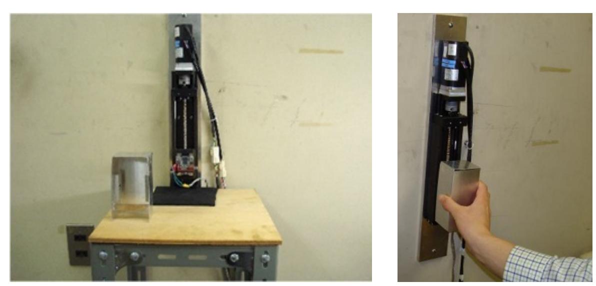


Fig.3. The left photo shows various components of the main power assist device. The back view of a PAO is also shown. Two rectangular metal pieces with holes in the center of each are attached to the interior of the left and right sides of the box. The holes help the box be tied to the force sensor through the object holder. The complete device is shown right.

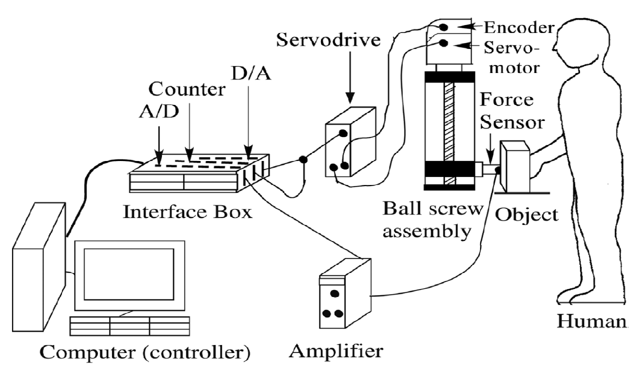


Fig.4. Experimental setup of the 1 DOF PAR system for lifting objects.

x_d = Desired displacement of the PAO
g = Acceleration of gravity

As an attempt to introduce the weight perceptual consideration in the dynamic modeling of the PAR, we hypothesized (1) as (2), where $m_1 \neq m_2 \neq m, m_1 \ll m$, $m_2 \ll m$, and hence $m_1\ddot{x}_d \neq m_2 g$. Both m_1 and m_2 stand for mass. In our hypothesis, m_1 forms inertial force and m_2 forms gravitational force. A difference between m_1 and m_2 arises due to the difference between human's perception and reality regarding the weight of the object lifted with the PAR.

Usually, $m_1 = m_2 = m$ is considered for all psychological experiments, but we hypothesized that $m_1 \neq m_2 \neq m, m_1 \ll m$, $m_2 \ll m$, and hence $m_1\ddot{x}_d \neq m_2 g$ would be considered by the human while lifting an object with the PAR. The human errs when lifting an object with the PAR as the human considers that the actual weight and the PAW are equal. The hypothesis means that the human errs because the human considers that the two 'masses' used in inertial and gravitational forces are equal to the actual mass of the object ($m_1 = m_2 = m$). In order to realize a difference between actual weight and PAW, the human needs to think that the two 'masses' used in inertial and gravitational forces are different and less than the actual mass ($m_1 \neq m_2 \neq m, m_1 \ll m$, $m_2 \ll m$) .We then derived (3)~ (5) from (2).

$$m_1\ddot{x}_d + m_2 g = f_{h.} \tag{2}$$
$$\ddot{x}_d = \frac{1}{m_1}(f_h - m_2 g). \tag{3}$$
$$\dot{x}_d = \int \ddot{x}_d \; dt. \tag{4}$$
$$x_d = \int \dot{x}_d \; dt. \tag{5}$$
$$\dot{x}_c = \dot{x}_d + G(x_d - x). \tag{6}$$

C. Control Architecture

We diagrammed the power-assist control based on (3)~(5), as shown in Fig.6. If the system is simulated using Matlab/Simulink in the velocity control mode of the servomotor, the commanded velocity ($\dot{x}_c$) to the servomotor is calculated by (6), which is provided to the servomotor through a D/A converter. The servodrive generates the control law based on the error displacement (x_d-x) following the velocity control with position feedback. The control law serves as the actuating force of the servomotor.

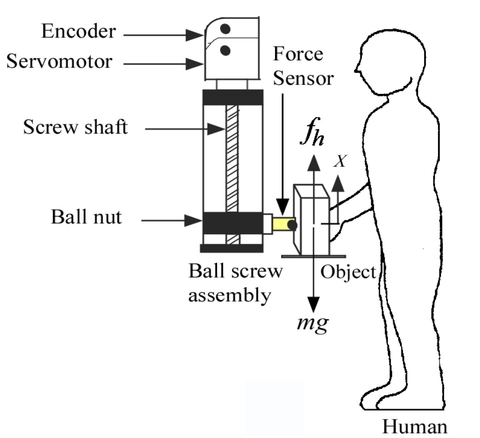


Fig.5. Dynamics of lifting a PAO with the PAR system

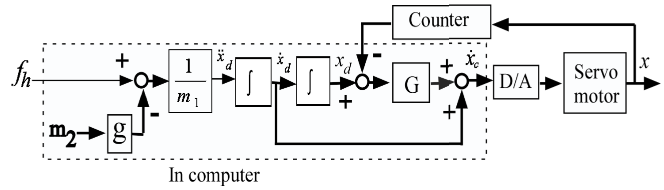


Fig.6. Block diagram of the control system of the PAR system. G denotes feedback gain, D/A indicates D/A converter, ∫ refers to integral and x denotes the actual displacement. Feedback position control method is used for this system. The servomotor is in velocity control mode.

III. Experiment 1:Determining Psychophysical Relationships Between Actual Weights and Power-Assisted Weights, Excess in the Load Forces

A. Subjects

Five mechanical engineering male students, aged between 22 and 28 years (Mean=23.40 years, S.D. =2.6077), were selected as the subjects and they voluntarily participated in the experiments. All the subjects were right-handed, physically and mentally healthy. 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.

B. Design of the Experiments

In each lifting scheme, the independent variables were m_1 and m_2, and visual size of object. The dependent variables were PAWs, peak load forces (PLFs).

C. Experiments

1) Protocol 1: For the unimanual protocol, the system shown in Fig.6 was simulated using Matlab/Simulink (solver: ode4, Runge-Kutta; type: fixed-step; fundamental sample time: 0.001s) for 12 m_1 and m_2 sets separately. Table I contains 12 m_1 and m_2 sets. The experimenter randomly chose the m_1 and m_2 set (e.g., $m_1 = 2, m_2 = 1$) and maintained its confidentiality. For each m_1 and m_2 set, the subject unimanually (right hand, power grip) lifted a PAO with the PAR following a demonstration of the experimenter, maintained the lift for 1-2 seconds at a height of 0.1 meter and then released the object. Then, the subject manually lifted a NPAO using unimanual right handed power grip several times for reference weights. The NPAO weight was sequentially changed in a descending order starting from 1.5 kg and ending at 0.1 kg while maintaining an equal difference of 0.1kg (1.5, 1.4,…..0.2, 0.1kg).Thus, the subject compared the perceived weight of the PAO (PAW) to that of the NPAO (reference weights) and estimated the magnitude of the PAW.

Five subjects performed this experiment for small, medium and large objects independently. We also recorded the LF data for each trial separately. We covered the PAR system with a cloth except the PAO in order to eliminate any visual difference between the PAO and the NPAO. Fig.7 (a) shows the experimental procedures.

2) Protocol 2: The same procedures described in protocol 1 were followed for the bimanual protocol. However, two handles were perpendicularly attached to the left and right sides of the PAO. For each m_1 and m_2 set, the subject gripped two handles with two hands using power grips and then synchronously lifted the PAO. Then, the subject manually lifted the NAPO using unimanual right handed power grip several times for reference weights, compared the PAW to the reference weights and estimated the PAW. Fig.7 (b) shows the experimental procedures.

3) Protocol 3: The same procedures described in protocol 1 were followed for the cooperative protocol. However, two handles were perpendicularly attached to the left and right sides of the PAO. For each m_1 and m_2 set, two subjects gripped two handles with their right hands using power grips and then synchronously lifted the PAO. Then, each subject independently lifted a NPAO using unimanual right handed power grip several times for reference weights, compared the PAW to the reference weights and estimated the PAW. Fig.7(c) shows the experimental procedures.

D. Results of Experiment 1

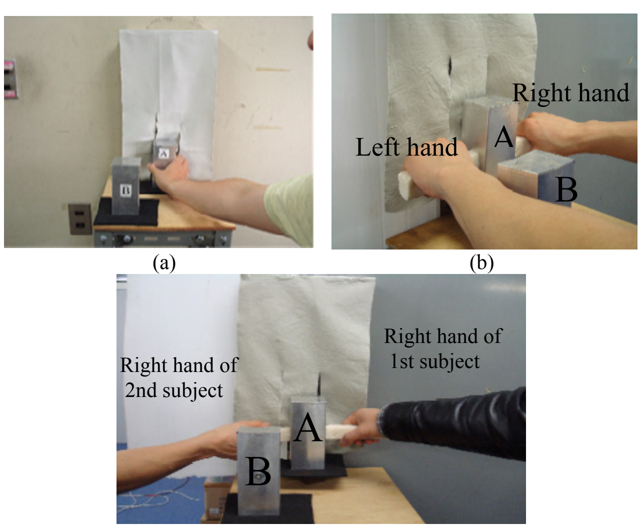
1) Relationships between Actual Weights and PAWs

For each protocol, we calculated the means (*n*=5) of the PAWs for each m_1 and m_2 set for the small, medium and large object separately. Then, we drew graph for each size of object separately taking the simulated gravitational weights (m_2) of the 12 m_1 and m_2 sets as the abscissa and the mean PAWs for the 12 m_1 and m_2 sets as the ordinate. Here, m_2 was assumed as the actual weight of the PAO.The relationships between the actual weights and the PAWs for the large size object for the unimanual, bimanual and

TABLE I

INERTIAL AND GRAVITATIONAL MASS VALUES FOR SIMULATION

Inertial mass (m_1)	Gravitational mass (m_2)		
2	0.5	1	1.5
1.5	0.5	1	1.5
1	0.5	1	1.5
0.5	0.5	1	1.5



(a) (b) (c)

Fig.7. Above at (a), a subject unimanually lifts the PAO (A) and compares its weight to that of the NPAO (B) in a trial. Above at (b), a subject lifts the PAO (A) by gripping the handles with two hands and then compares its weight to that of the NPAO (B) in a trial. Above at (c),two subjects synchronously lift the PAO (A) by gripping the handles with their right hands and then independently compare its weights to that of the NPAO (B) in a trial.

cooperative protocols are shown together in Fig.8.The relationships for the medium and small size objects were almost same to that for the large size object.

2) Determination of Excess in the Load Forces

For each protocol, we derived the magnitude of the PLF for each trial for each size PAO separately. Fig.9 gives an illustration of the time trajectories of the LF and displacement for a typical trial. We then determined the means (*n*=5) of the PLFs for each m_1 and m_2 set for each size PAO separately for each protocol. Table II shows the mean PLFs for 12 m_1 and m_2 sets for different sizes of objects for the unimanual protocol. PLFs were proportional to visual object sizes [19]. Analyses of Variances (ANOVAs) showed that variations in PLFs due to object sizes were highly significant, but variations in PLFs due to subjects were not significant.

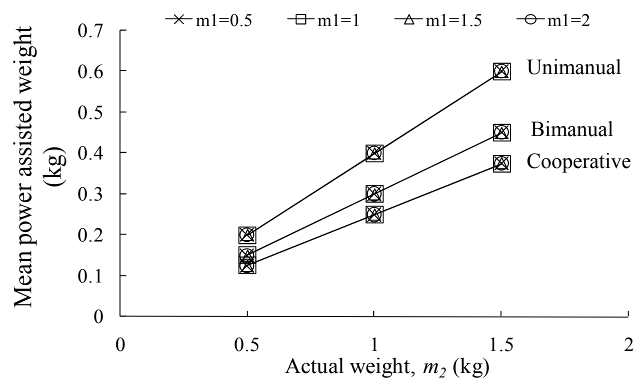


Fig.8. The linear psychophysical relationships between the actual weights and the PAWs for unimanual, bimanual and cooperative lifting of the large size object. The figure shows that humans do not feel the change of inertial mass (m_1) i.e., m_1 does not affect weight perception. The figure also shows that the PAWs are 40%, 30% and 25% of the actual weights for the unimanual, bimanual and the cooperative protocol respectively.

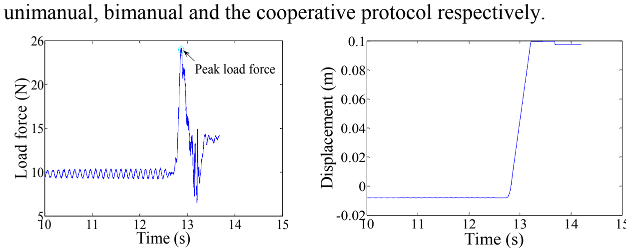


Fig.9. Time trajectories of the load force and the displacement for a typical trial in the unimanual protocol. During this trial, a subject lifted the large PAO with the PAR at $m_1 = 1.5, m_2 = 1.0$ condition.

TABLE II

MEAN PEAK LOAD FORCES FOR THE UNIMANUAL PROTOCOL

m_1, m_2 sets	Mean PLFs(*N*) with standard deviations (in parentheses) for different object sizes		
	Large	Medium	Small
1,0.5	16.66 (1.1954)	13.7617(1.3347)	9.83(0.2961)
2,0.5	21.225(0.9857)	18.065(1.9986)	13.46(0.5377)
2,1.5	29.864 (0.1851)	25.85(1.2384)	22.2025(1.106)
1.5,1.5	28.7467(1.4258)	24.176(0.8327)	20.524(1.244)
2,1	27.588(1.7348)	22.23(1.3023)	19.152(1.2787)
1.5,1	25.7383(1.7121)	20.87(0.529)	17.0817(1.7438)
0.5,1.5	24.668(1.0244)	19.55(0.9833)	18.35(1.2425)
1,1.5	26.0067(0.4594)	20.87(1.5486)	19.554(0.8365)
0.5,1	21.855(0.9682)	15.2633(0.9952)	14.145(0.5723)
1.5,0.5	19.2283(1.8561)	15.704(1.0796)	11.746(1.1006)
1,1	23.3767(1.1465)	16.824(1.5309)	15.394(1.6208)
0.5,0.5	**16.56(1.147)**	**12.09(0.7393)**	**8.88(0.8505)**

We determined the relationships between the inertial mass (m_1) and the PLFs for different values of m_2 for different sizes of objects for each protocol. The relationships for the unimanual protocol are shown in Fig.10. The figure shows that there are linear relationships between m_1 and PLFs. Linear relationships between m_1 and PLFs were also derived for the bimanual and the cooperative protocol.

We see in Table II that the PLFs are proportional to m_2.We also see in Fig.10 that the PLFs are proportional to m_1. As our objective is to reduce the PLFs, we assume that the PLFs would be the lowest for the smallest values of m_1 and m_2 i.e., m_1=0.5, m_2=0.5.Hence, we compared the PLFs for the unimanual protocol (from Table II) to that for the bimanual and the cooperative protocol for $m_1 = 0.5, m_2 = 0.5$. We also compared the PLFs to the PAWs (from Fig.8) for each size PAO for the unimanual, bimanual and cooperative protocols for $m_1 = 0.5, m_2 = 0.5$. The comparisons are shown in Fig.11.

We see in Fig.11 that, for the unimanual protocol, PLF is 16.56 N and PAW is 1.962 N (0.2kg as of Fig.8) for the large size object. Hence, the PLF is 8.44 times larger than the PAW for the large object. Similarly, we can show that the PLF is 6.16 times and 4.53 times larger than the PAW for the medium and the small size object respectively. Hence, on average, the PLF is 6.38 times larger than the PAW for the unimanual protocol. Similarly, we find that the PLF is on average 7.55 times and 7.32 times larger than the PAW for the bimanual and the cooperative protocol respectively. However, the actually required (optimum) PLF should always be slightly larger than the PAW [19].

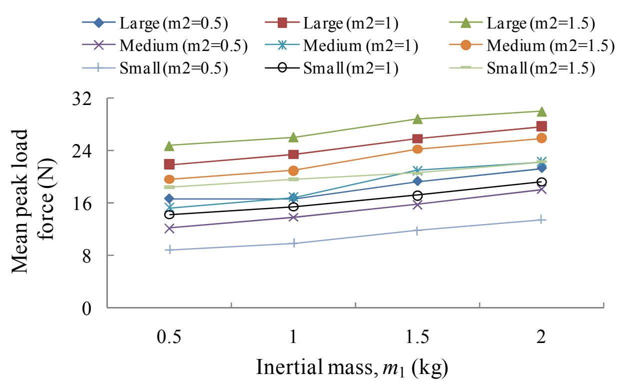


Fig.10. Linear relationships between inertial mass and PLFs for different values of m_2 for different sizes of objects for the unimanual protocol.

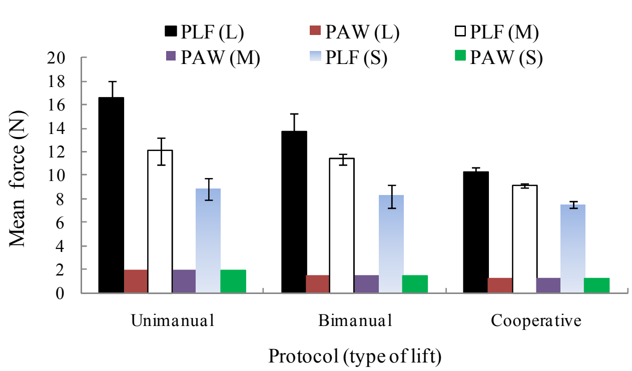


Fig.11. Mean PLFs and PAWs with standard deviations for large (L), medium (M) and small(S) size objects for the unimanual, bimanual and cooperative protocols for $m_1 = 0.5, m_2 = 0.5$ condition.

These excessive PLFs cause problems that we discussed in section I. If the excessive PLFs are reduced to the optimum, the optimum PLFs would optimize the motions of the objects lifted with the PAR and the optimized motions would enhance the maneuverability, operability, stability, ease of use, naturalness, safety etc. of the robot system.

IV. Experiment 2: Modifying the Control to Reduce the Excessive Peak Load Forces

A. *Experiment 2*

The objective of this experiment was to modify the control based on the weight perceptual and LF features derived in experiment 1. The modified control would reduce the excessive PLFs and thus would enhance maneuverability, naturalness, ease of use, stability, safety etc. of the system. There were two constraints to modify the control. The first constraint was that the PLFs must be greater than the PAWs at m_1=0.5, m_2=0.5 in each protocol. The second was that the modification would not hamper the relationships of (2).

In order to modify the control, the system shown in Fig.6 was simulated using Matlab/Simulink for only one set of values of m_1 and m_2 (m_1= e^{-6t} +0.5, m_2=0.5). The control strategy based on the exponential reduction of m_1 is shown in Fig.12 as a flowchart. The experiment was done for each size object for each protocol separately. The procedures were similar to that of experiment 1, but the system was simulated for only one set of values of m_1 and m_2 (m_1= e^{-6t}+0.5, m_2=0.5).

In each trial in each protocol, each subject also subjectively evaluated (scored) the motion, maneuverability, naturalness, stability, safety and ease of use of the system following the 7 rating alternatives of a 7-point bipolar & equal-interval subjective rating scale [20]:

1. Undoubtedly best (score: +3)
2. Conspicuously better (score: +2)
3. Moderately better (score: +1)
4. Alike (score: 0)
5. Moderately worse (score:-1)
6. Conspicuously worse (score:-2)
7. Undoubtedly worst (score:-3)

B. *Results of Experiment 2*

1) *Reduction in Peak Load Forces*

We derived the PLF for each trial in each protocol. We then determined the means of the PLFs for each size object for each protocol separately. We then compared the mean PLFs for different sizes of objects determined in experiment 2 at m_1= e^{-6t} +0.5 and m_2=0.5 with that determined in experiment 1 at m_1= 0.5 and m_2=0.5. The results are shown in Fig.13.The results show that the PLFs significantly reduced due to the control modification.

We determined the means of the PAWs for each size object separately for each protocol for experiment 2 and compared them to the PAWs derived in experiment 1 at m_1= 0.5 and m_2=0.5. The results are shown in Fig.14. The figure shows that mean PAWs were unchanged even though m_1 reduced exponentially. It means that the control modification did not adversely affect the relationships of (2).

2) Improvement in Power-Assist Performances

We calculated the means (n=5) of the evaluation scores for each of the evaluation criterion (motion, maneuverability, naturalness, stability, safety, ease of use) for each size object for each protocol separately. The results for the medium size object are shown in Fig.15. Similar results were also derived for the large and small size objects. The results show that reduction in PLFs produced satisfactory motions, maneuverability, safety, stability, naturalness etc.

V. DISCUSSION

Estimation of weight perception used in this article is subjective instead of objective. Nevertheless, the subjective evaluation is to be reliable because subjective evaluations in technical domains have already been proven efficacious in various researches [21]. However, accuracy of the experiments may be further increased by adding more reference weights, subjects and trials. In this paper, the servomotor was kept in velocity control mode. Another mode, torque control mode, may be tested to further prove the accuracy and effectiveness of the findings. The hypothesis introduced in this paper produced satisfactory findings. However, it may be further validated by a comparative experiment of vision vs. non vision condition.

It may be beneficial to estimate the subjective force of PAW and to objectify more the subjective force of human. Time series of m_1, motor torque, and LF may be analyzed. The effectiveness of the system may be enhanced by reflecting back-drivability, mechanical inertia, compliance, friction and gear effect in ball screw and servo motor control response delay to the proposed dynamic modeling of the system. Use of a linear motor in place of the ball screw may enhance the effectiveness and accuracy of the system.

We see in Fig.8 that the PAR reduces the weight of the PAO. Again, m_1 does not affect weight perception, but m_2 does in each protocol. Derivation of mathematical reasoning behind these empirical findings may further enhance the effectiveness of the control.

This paper effectively measures moving up load, but the results may be different for more general motion, such as harmonic motion (i.e., moving up and down). In such cases, the inertial load will be felt more by the operator. This may be relevant to many practical cases.

We designed a controller common to two hands for bimanual and cooperative tasks. In both protocols, each trial

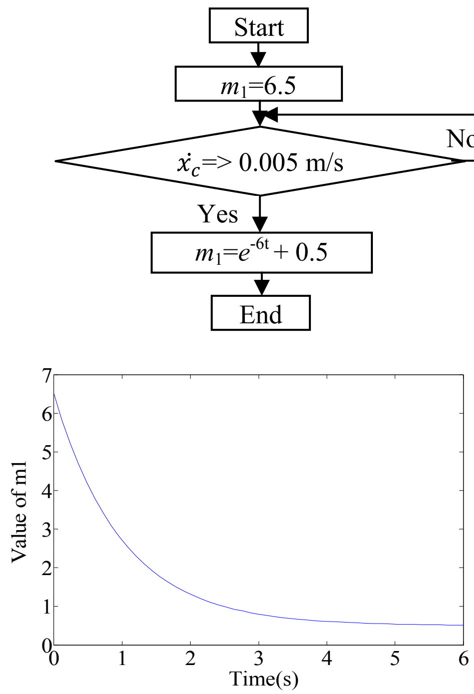


Fig.12. The upper figure shows that m_1 exponentially declines from a large value to 0.5 when the subject lifts the object with the robot and the commanded velocity ($\dot{x}_c$) of (6) exceeds a threshold. As m_1 is proportional to PLF (Fig.10), reduction in m_1 would reduce the PLF proportionally. Reduction in PLF would not hamper the relationships of (2) because the subject would not feel the change of m_1 (Fig.8). The lower figure shows the hypothetical time trajectory of m_1 during the experiment.

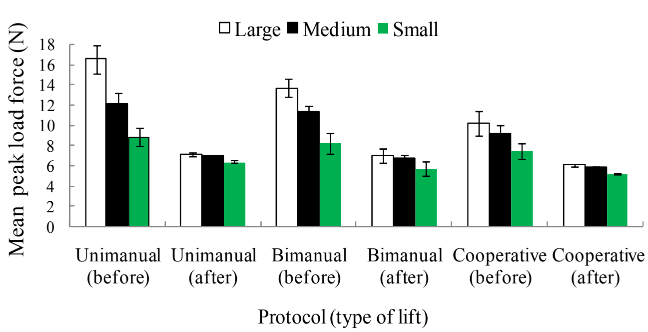


Fig.13. Mean PLFs with standard deviations for large, medium and small objects at (a) m_1= 0.5, m_2=0.5 (before modification) and (b) m_1= e^{-6t} +0.5, m_2=0.5(after modification) for unimanual, bimanual and cooperative protocols.

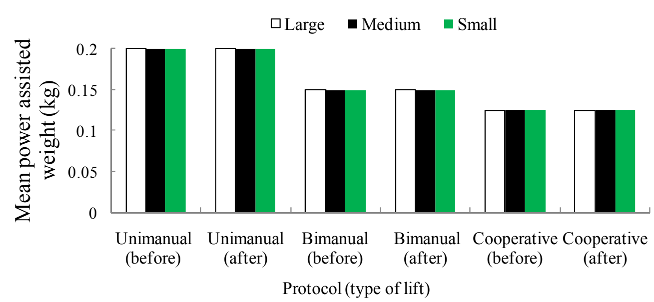


Fig.14. Mean PAWs with standard deviations for large, medium and small objects at (a) m_1= 0.5, m_2=0.5 (before modification) and (b) m_1= e^{-6t} +0.5, m_2=0.5 (after modification) for unimanual, bimanual and cooperative protocols.

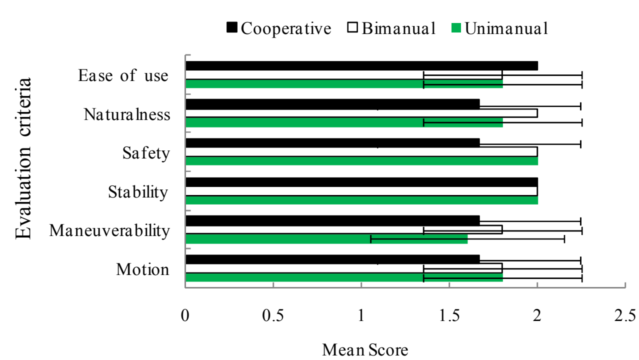


Fig.15. Mean scores with standard deviations for the evaluation criteria for the system simulated at m_1= e^{-6t} +0.5, m_2=0.5 (after modification) for the medium size object for unimanual, bimanual and cooperative protocols.

was in-phase, symmetric and synchronized. The resultant of the LFs of two hands and their cross-talk represented a common command [22]. However, it is also possible to design separate, but interacting controllers for each hand.

In this paper, we used position feedback control method. However, impedance control may be useful and adaptive control may be suitable for industrial environments with uncertainties and changes [17], [23].

The findings may be used to develop PARs for lifting heavy objects in industries such as manufacturing and assembly, mining, transport and logistics, construction, military and rescue operations etc. However, the operator would feel as if he were lifting an object of only 0.2 kg, 0.15 kg and 0.125 kg for unimanual, bimanual and cooperative task respectively. The proposed system would provide optimum maneuverability, safety, stability, naturalness etc. when lifting heavy objects with the system. We addressed all possible schemes of lifting tasks (unimanual, bimanual, cooperative) so that the systems are effective in all cases [24].

We considered low simulated weights (m_2 =0.5 kg) in order to adjust with human requirements (naturalness, best feeling, safety etc.) and to compare to other psychological experiments. A worker does not bear the weight of an object while carrying it with a PAR. The load is carried by robot/system and the LF controls the motions. Hence, the value of m_2 used in this paper does not mean the actual mass of objects to be lifted in industrial applications, rather it means the value that would be put into the control program for the best/satisfactory feeling and perception. Experimental verification with heavy loads may further justify the results.

VI. Conclusions and Future Works

We successfully addressed the control of a 1DOF PAR for lifting objects based on human's weight perceptual and LF features in various grasping schemes. The findings would help develop human-friendly PARs for manipulating heavy objects in industries. We will conduct verifications of the findings with heavy objects using real robots. Practicality, commercialization and business issues of the proposed PARs will be elucidated. Other approaches that may further optimize the perceived heaviness as well as the PLFs will be investigated. New and advanced control methods (e.g., adaptive, impedance, robust etc.) for the PAR will also be searched. The system will be upgraded to multi-DOF system (horizontal, rotational etc.).

References

[1] H. Kazerooni, "Extender: a case study for human-robot interaction via transfer of power and information signals," *Proc. 1993 IEEE Int. Workshop on Robot and Human Communication*, pp.10-20.

[2] K. Kong, H. Moon, B. Hwang, D. Jeon, M. Tomizuka, "Impedance compensation of SUBAR for back-drivable force-mode actuation," *IEEE Trans. on Robotics*, vol. 25, issue: 3, pp.512 – 521, June 2009.

[3] S.Inagaki, T. Suzuki, T. Ito, "Design of man-machine cooperative nonholonomic two-wheeled vehicle based on impedance control and time-state control," *in Proc. of 2009 IEEE International Conference on Robotics and Automation*,pp. 3768-3773.

[4] S. Tashiro and T. Murakami, "Step passage control of a power-assisted wheelchair for a caregiver," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 4, pp. 1715-1721, April 2008.

[5] H. Seki, K. Ishihara and S. Tadakuma, "Novel regenerative braking control of electric power-assisted wheelchair for safety downhill road driving," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 5, pp. 1393-1400, May 2009.

[6] S. Oh, N. Hata, Y. Hori, "Integrated motion control of a wheelchair in the longitudinal, lateral, and pitch directions," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 4, pp. 1855-1862, Apr. 2008.

[7] T. Tanaka , Y. Satoh, S. Kaneko, Y. Suzuki , N. Sakamoto and S. Seki, "Smart suit: soft power suit with semi-active assist mechanism – prototype for supporting waist and knee joint," *in Proc. of 2008 International Conference on Control, Automation and Systems*, Oct. 14-17, 2008 in COEX, Seoul, Korea, pp. 2002-2005.

[8] G.Liu, Y. Yan, J. Chen, T. Na, "Simulation and experimental validation study on the drive performance of a new hydraulic power assist system," *in Proc. of 2009 IEEE Intelligent Vehicles Symposium*, June 3-5, 2009, pp.966-970.

[9] K. Osamura, S. Kobayashi, M. Hirata, H. Okamoto, "Power assist control for slide doors using an ideal door model," *in Proc. of 2008 IEEE International Symposium on Industrial Electronics*, June 30 2008-July 2 2008, pp. 1293 – 1299.

[10] S. Lee, S. Hara, Y. Yamada, "Safety-preservation oriented reaching monitoring for smooth control mode switching of skill-assist," *in Proc. of 2008 IEEE International Conference on Systems, Man and Cybernetics*, 12-15 Oct. 2008, pp. 780 – 785.

[11] K.Kosuge, H. Yabushita, Y. Hirata, "Load-free control of power-assisted cycle," *in Proc. First IEEE Technical Exhibition Based Conference on Robotics and Automation*, 18-19 Nov. 2004,pp.111-112.

[12] M. Ding, J. Ueda, T. Ogasawara, "Pinpointed muscle force control using a power-assisting device: system configuration and experiment," *in Proc. of 2008 IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, pp. 181 – 186.

[13] T. Kawashima, "Study on intelligent baby carriage with power assist system and comfortable basket," *Journal of Mechanical Science and Technology* 23 (2009) 974~979.

[14] T.Takubo,H. Arai,Y.Hayashibara,K. Tanie,"Human-robot cooperative manipulation using a virtual nonholonomic constraint," *International Journal of Robotics Research*,vol.21, no.5,pp.541 – 553, 2002.

[15] A. Niinuma,T.Miyoshi, K. Terashima,Y. Miyashita, "Evaluation of effectiveness of a power-assisted wire suspension system compared to conventional machine," *in Proc. 2009 IEEE International Conference on Mechatronics and Automation*, Aug. 9-12, 2009, pp.369-374.

[16] T.Doi, H. Yamada, T. Ikemoto, and H. Naratani, "Simulation of a pneumatic hand crane power-assist system," *Journal of Robotics and Mechatronics*, vol.20, no.6, pp. 896-902, 2008.

[17] S. Hara, "A smooth switching from power-assist control to automatic transfer control and its application to a transfer machine," *IEEE Trans. on Industrial Electronics*, vol. 54, no. 1, pp.638-650, 2007.

[18] S.M.M.Rahman, R. Ikeura, M. Nobe, H. Sawai, "Human operator's weight perception of an object vertically lifted with a power assist system," *in Proc. of 2008 IEEE/SICE International Symposium on System Integration*, December 2008, Japan, pp.24-29.

[19] A.M.Gordon, H. Forssberg, R.S. Johansson, and G. Westling, "Visual size cues in the programming of manipulative forces during precision grip," *Experimental Brain Research*, vol. 83, no.3, pp. 477–482, 1991.

[20] S.G. Charlton and T.G. O'Brien, "Handbook of Human Factors Testing and Evaluation," Lawrence Erlbaum Associates Inc., New Jersey, ch. 5, pp.81-99, 1996.

[21] H.Kobayashi, R. Ikeura, H.Inooka, "Evaluating the maneuverability of a control stick using electromyography," *Biological Cybernetics*, vol. 75, no.1, pp.11-18, 1996.

[22] R.M. Bracewell, A.M.Wing, H.M. Scoper, K.G. Clark,"Predictive and reactive co-ordination of grip and load forces in bimanual lifting in man,"*European Journal of Neuroscience*, vol.18, no.8, pp.2396-2402, 2003.

[23] H. Kato, R. Ikeura,S. Noguchi, K. Mizutani, H. Nakamura, T. Honda, "Impedance control for an industrial power assist device considering contact operations," *Transactions of the Japan Society of Mechanical Engineers,* Series C,vol.72,no.714,pp.214-221,2006-2.[In Japanese]

[24] S.M.M.Rahman, R. Ikeura, M. Nobe, S. Hayakawa, H. Sawai, "Weight-perception-based model of power assist system for lifting objects," *International Journal of Automation Technology*, vol.3, no.6, pp. 681-691, 2009.