

## Manipulating Objects with a Power Assist Robot in Linear Vertical and Harmonic Motion: Psychophysical-Biomechanical Approach to Analyzing Human Characteristics to Improve the Control\*

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### Abstract

This paper investigates human characteristics in terms of weight perception, load forces, motions etc. for manipulating objects with a power assist robot and proposes a novel control for the robot based on the human characteristics to improve maneuverability, safety etc. We hypothesized that weight perception due to inertia might be different from that due to gravity for manipulating objects with power-assist. A 1-DOF power assist robot was developed and simulated. Subjects manipulated objects with the robot for two types of motions: (i) linear vertical (lifting objects vertically), (ii) harmonic (objects repeatedly lifted up and lowered down). We analyzed weight perception, load forces and motions. We then introduced a novel control strategy, which was such that a virtual mass exponentially declined from a large value to a small one when the subjects manipulated the objects with the robot and the command velocity exceeded a threshold. The novel control reduced excessive load forces and accelerations and improved maneuverability, safety etc. We compared the results for linear motion to that for harmonic motion. We also demonstrated the conditions to further optimize the performances. Finally, we proposed using the findings to develop human-friendly power assist devices to manipulate heavy objects in industries that would improve productivity, worker's health and wellness. We also argued that the weight perceptual and psychophysical criteria used to control the robot would satisfy the biomechanical criteria of robot operator manipulating heavy objects, and thus we attempted to establish a trade-off between psychophysical and biomechanical criteria for manipulating objects with power-assist.

**Key words:** Human-Robot Cooperation, Power Assist Robot, Object Manipulation, Weight Perception, Harmonic, Load Force, Motion, Biomechanics, Psychophysics, Control, Maneuverability, Safety, Health, Welfare

### 1. Introduction

In the ensuing years, uses of robots in fields such as mining, logistics, transport, home automation, industrial and agricultural production, health care, rehabilitation etc. will be

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unavoidable. As a result, robots need to be human-friendly and to execute tasks in cooperation with humans <sup>(1)</sup>. There is increasing demand for human-friendly robot technologies, with which robots should collaborate with humans sharing the same workspace that may expand robot applications as well as may help achieve better productivity and quality, safety etc. The technology has evolved to the point where intuitive human-robot cooperation is no longer a novelty, rather it has become a reality <sup>(2)</sup>.

When a human manipulates an object with a Power Assist Robot (PAR), the human feels a scaled-down effect of the load <sup>(3)</sup>. At present, PARs are designed mostly for aged and disabled people <sup>(4)-(7)</sup>, and hence suitable PARs for manipulating heavy objects are still demanding. Manipulating heavy objects in industries is a very common task. It is thought that the uses of PARs may be appropriate for handling heavy objects because manual manipulation of heavy objects is very cumbersome, causes disabilities and disorders such as back pain, and on the contrary, handling objects by autonomous systems may not provide required flexibility. However, such PARs are not available in practices. Several PARs are available for other purposes such as support for agricultural workers<sup>(8)</sup>, hydraulic power-assist for automobiles<sup>(9)</sup>, doors for automobiles<sup>(10)</sup>, skill-assist in manufacturing<sup>(11)</sup>, assist for cycle <sup>(12)</sup>, assist for sports training <sup>(13)</sup>, assist for lifting baby carriage <sup>(14)</sup> etc. However, design of PARs for manipulating heavy objects has not got much attention yet.

Though several PARs have already been developed for manipulating objects <sup>(15)-(18)</sup>, these are not so suitable, safe, natural and human-friendly for manipulating heavy objects in industries <sup>(19)</sup>. The fact is that the power-assisted weight (weight of an object perceived by the human when the object is manipulated with a PAR, abbreviated as PAW) is always less than the actual weight (weight of an object perceived by the human if the object is manipulated manually). But, the human cannot differentiate between PAW and actual weight and eventually applies load force (load force abbreviated as LF is the manipulative force tangential to grip surfaces) according to the actual weight of the object. This faulty force programming (excessive LF) gives faulty motion to the PAR and jeopardizes its maneuverability, stability, ease of use, safety etc. We argue that the aforementioned limitations with PARs still prevail because the development of human-friendly PARs for manipulating heavy objects in industries based on human features especially weight perception and LFs has not received much attention and importance yet. Hence, this paper attempts to present a model to solve the aforementioned limitations and inconveniences with the PARs. The model adopts a hypothesis that pertains to weight perception.

Again, our previous research <sup>(19)</sup> considered only moving up load in linear vertical motion. However, the results could be different for more general motion such as the harmonic motion (object is manipulated repeatedly). Motions in two directions are very important for object manipulation: (i) vertical lifting, (ii) horizontal translation. Both of these motions are linear. However, these linear motions are not perfectly linear. Workers in practical fields, in order to ensure proper positioning of manipulated objects, frequently need to exercise harmonic motions. Again, it is still unknown whether or not a worker feels better in harmonic manipulation than in linear manipulation. Hence, harmonic manipulation of objects seems to be relevant and necessary for many practical cases in industries and a comprehensive study on this issue may further enhance the effectiveness of the research results and of the control for the PAR. However, such study has not been carried out yet.

As it is presented in this paper, we developed a one-degree-of-freedom (1-DOF) PAR adopting a hypothesis pertaining to weight perception. The hypothesis means that perception of weight due to inertia differs from perceived weight due to gravity when manipulating an object with a PAR. The robot was simulated and subjects manipulated different sizes of light-weight objects with it. We considered (i) linear vertical motion, and (ii) harmonic motion. We then critically analyzed weight perception, LFs and object's motion features for both motions. We then introduced a novel control strategy to reduce the

excessive load forces and thus to produce satisfactory maneuverability, safety, naturalness, ease of use, stability etc. of the robot. We compared the findings derived in linear vertical motion to that derived in harmonic motion. We then demonstrated the conditions to further optimize the system performances.

The main objective of this paper was to just analyze human characteristics for manipulating objects with power-assist under different protocols, identify some control parameters, preliminarily propose some novel control strategies to improve performances etc. so that the results can be used to develop a suitable control method for human-friendly real power assist robot for manipulating heavy objects in near future. Hence, we proposed to use the findings derived with the light-weight objects to develop human-friendly PARs to manipulate heavy objects in industries. We also argued that the weight perceptual and psychophysical criteria used to control the PAR would satisfy the biomechanical criteria of robot operator manipulating heavy objects in industries, and thus this paper attempted to establish a trade-off between psychophysical and biomechanical criteria for manipulating objects with power-assist.

## **2. The Experimental PAR System**

### **2.1 Development of the PAR system**

A one-degree-of-freedom (1-DOF) PAR system was developed using a ball screw assembly activated by an AC servomotor (Type: SGML-01BF12, made by Yaskawa, Japan). The ball screw assembly and the servomotor were fixed coaxially on a metal plate and the plate was vertically attached to a wall as shown in Fig.1 (a). A force sensor (load transducer, Type: 9E01-L44, 1 mV/V, 350 ohm, max. 2KN) was attached to the nut of the ball screw through an acrylic resin block. Three rectangular objects (boxes) were made by bending aluminum sheets (thickness: 0.5 mm) and their dimensions (length x width x height) were 6cm x 5cm x 8.6cm, 6cm x 5cm x 12cm and 6cm x 5cm x 16cm for the small, medium and large size respectively. Top side of each box was covered with a cap made of aluminum sheet (0.5 mm thick). The bottom and back sides were kept open. Self-weight of each box was small. The boxes were separately tied to the force sensor through a wooden block, were manipulated by subjects with the PAR and were named the power-assisted objects (PAOs). A PAO was kept on a soft surface before it was manipulated, as shown in Fig.1 (b). The complete experimental setup of the robot system is shown in Fig.2. The control was to develop in such a way that the actual weight of the PAO is 0.5kg<sup>(19)</sup>.

We made three more 'non power-assisted objects' (NPAOs) (boxes) of three different sizes (large, medium, small), as shown in Fig. 1 (c) and (d). The NPAOs were lifted manually and were not physically connected to the PAR system. The dimensions, shape, material and outlook of a PAO of a particular size were same as that of the NPAO of that particular size. It was possible to change the weight of a NPAO by attaching extra mass to its back side while keeping its front view unchanged. The NPAOs were used as reference weights to estimate the perceived weights of the PAOs (i.e., power-assisted weights, PAWs).

We used small size (the largest one is 6cm x 5cm x 16cm) and low-weight PAO (actual weight is 0.5kg) for two reasons: (i) we, at this stage, wanted to avoid the costs to develop the real system suitable for manipulating heavy objects, and (ii) we wanted to compare the findings of this paper to that of other psychological experiments, and for this reason our object sizes and weights should be small because most of the psychological tests use low weights and small objects. Such comparison with equal basis may produce important information that may help develop the real system in near future adjusting with human perceptions. The use of low weight and small size objects instead of heavy and large objects may also help us reach the objective of this paper.



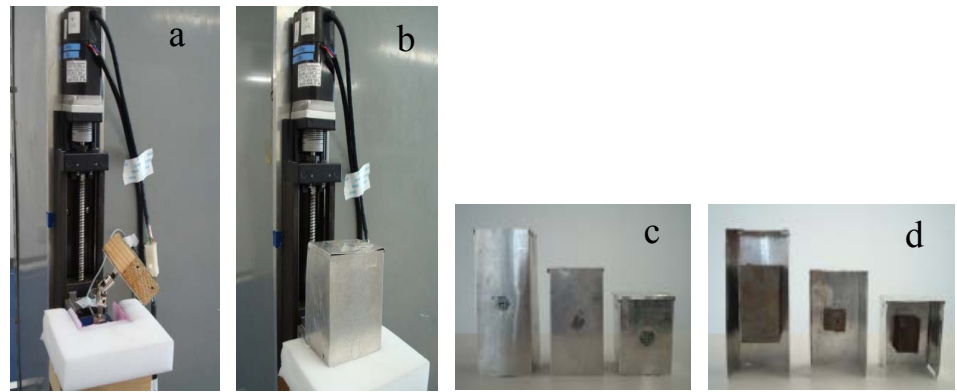


Fig.1: The main power assist device is in (a). One end of a universal joint is tied to the load transducer and the other end is attached to a wooden block. The wooden block helps tie the PAO to the load transducer. The complete device with a PAO (medium size) is shown in (b). The front and back views of the large, medium and small NPAOs are shown in (c) and (d) respectively.

## 2.2 Dynamics and control of the PAR

As shown in Fig.3 (a), the target model of the system for manipulating a PAO is Eq. (1).

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

Where,

$f_h$  = Load force applied by a subject

$m$  = Actual mass of the object visually perceived by a subject

$x_d$  = Desired displacement of the power – assisted object

$g$  = Acceleration of gravity

We hypothesized Eq. (1) as Eq. (2) to include weight perception in control, where  $m_1 \neq m_2 \neq m$ ,  $m_1 \ll m$ ,  $m_2 \ll m$ ,  $m_1\ddot{x}_d \neq m_2g$ . As shown in Fig.3 (b)-(c), the human errs as he/she considers that the actual weight and the PAW are equal. The hypothesis means that the human errs because he/she considers that the two ‘masses’ used in inertial and gravitational forces are equal to the actual mass of the object (i.e.,  $m_1=m_2=m$ ). 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 ( $m$ ). This is why we considered  $m_1$  different from  $m_2$  because human’s perception and reality regarding the weight of the object manipulated with the PAR differ as a PAR reduces the perceived weight of the manipulated object <sup>(3)</sup>.

We then derived Eqs. (3) ~ (5) based on Eq. (2). We diagrammed the control based on Eqs. (3) ~ (5), as shown in Fig.4. If the PAR is simulated using Matlab/Simulink with the servomotor in velocity control mode, the command velocity ( $\dot{x}_c$ ) to the servomotor is derived by Eq. (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.

$$m_1\ddot{x}_d + m_2g = f_h \quad (2)$$

$$\ddot{x}_d = \frac{1}{m_1}(f_h - m_2g). \quad (3)$$

$$\dot{x}_d = \int \ddot{x}_d dt. \quad (4)$$

$$x_d = \int \dot{x}_d dt. \quad (5)$$

$$\dot{x}_c = \dot{x}_d + G(x_d - x). \quad (6)$$

## 3. Experiment 1: Weight Perception, Load Force and Motion Analysis

### 3.1 Subjects

Ten male students of mechanical engineering aged between 24 and 30 years were selected to voluntarily conduct the experiment. All the subjects were physically and mentally healthy. The subjects did not have any prior knowledge of the hypothesis being tested. Instructions regarding the experiment were given to the subjects, but no training was given to them.

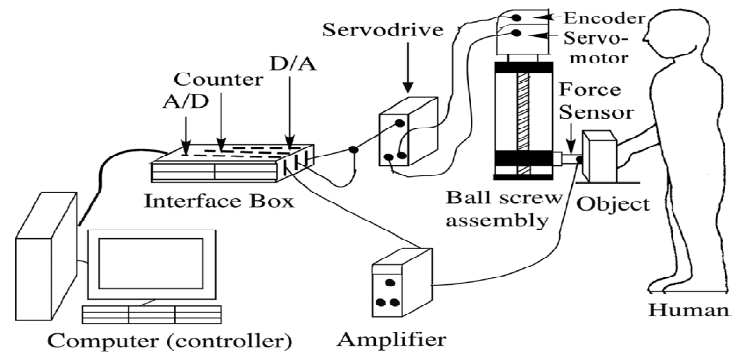


Fig.2: Experimental setup of the 1-DOF PAR system for manipulating objects. The computer gave 16-bit BUS data. A noise filter (type: LF-205A) was also mounted to prevent electrical noises from the power supply line.

### 3.2 Objectives

Objectives of the experiment were (i) to analyze weight perception and manipulative force features, and (ii) to analyze object's motions –displacement, velocity and acceleration features for manipulating objects with the PAR in both linear vertical and harmonic motions.

### 3.3 Experiment procedures

We simulated the PAR shown in Fig.4 using Matlab/Simulink (solver: ode4, Runge-Kutta; type: fixed-step; fundamental sample time: 0.001s) for the PAOs of three different sizes. We set  $m_1=0.5\text{kg}$  and  $m_2=0.5\text{kg}$  during the simulation as we found previously that subjects feel high maneuverability when manipulating objects with the PAR at  $m_1=0.5$  and  $m_2=0.5$  <sup>(19)</sup>.

In each trial of the first phase of the experiment, the subject lifted the PAO using his right hand alone from 'A' to 'B' (as Fig.3(a) shows, the distance between A and B was about 0.12 m) and then lowered it from 'B' to 'A' and repeated the lifting-lowering task for approximately 10 seconds, and then released the object. Then the subject manually lifted a NPAO at about 0.12 m using the right hand alone (and then lowered and released it) for reference weights. The NPAO weight was sequentially changed in a descending order

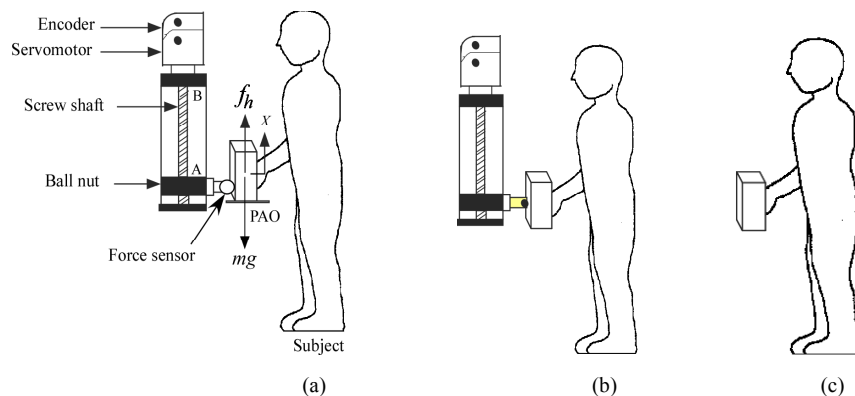


Fig.3: (a) Dynamics of manipulating a PAO with the PAR. Differences in perceived weights between (b) a power-assist-manipulated and (c) a manually manipulated object.

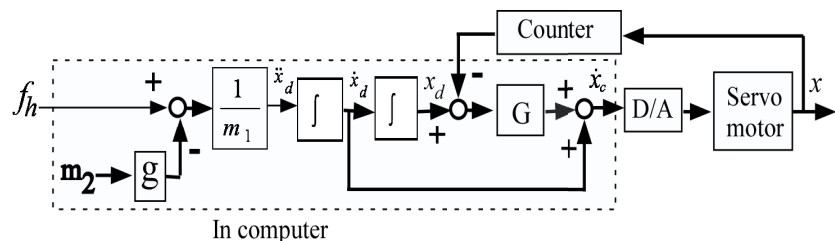


Fig.4: Block diagram of the power-assist control. G, D/A,  $\int$  and  $x$  denote feedback gain, D/A converter, integral and actual displacement respectively. Feedback position control is used with the servomotor in velocity control mode.

starting from 0.5 kg and ending at 0.1 kg while maintaining an equal difference of 0.05 kg (i.e., 0.5, 0.45..., 0.15, 0.1kg). Thus the subject compared the perceived PAO weight (PAW) to that of the NPAO (reference weights) and estimated the magnitude of the PAW following the psychophysical method 'constant stimuli'. Reference weights could be changed in an ascending order and there might have a small difference in estimated weights between the ascending and the descending order. However, we ignored this. If the subject could not estimate the PAW correctly, the trial was repeated. In each trial, the subject subjectively evaluated (scored) motion, maneuverability, stability, safety, naturalness, and ease of use of the PAR system following a 7-point bipolar and equal-interval scale as follows:

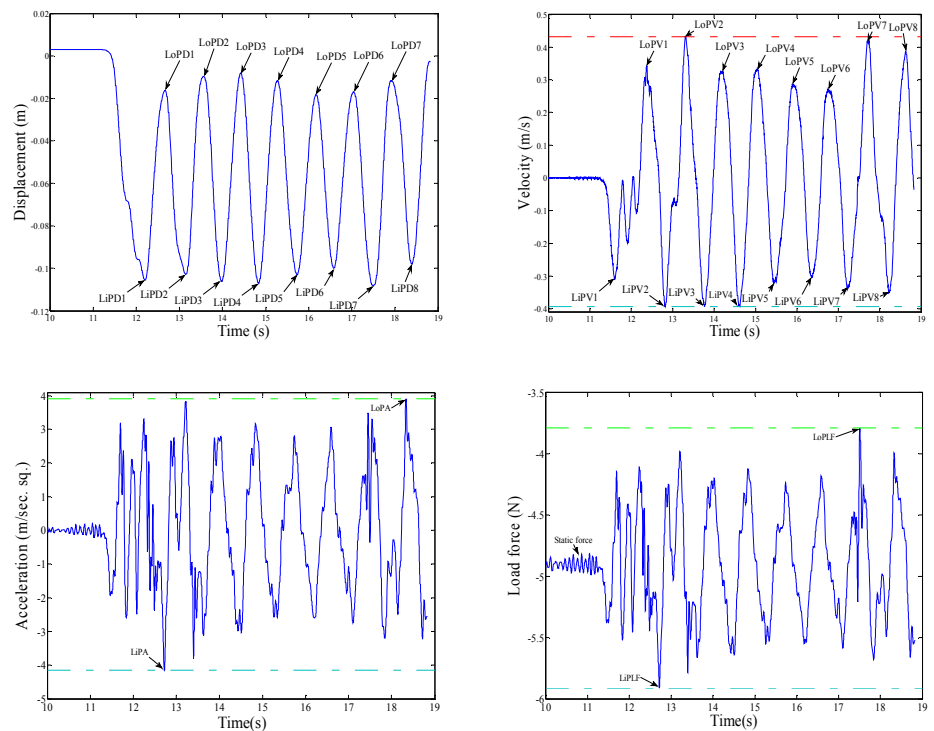
1. Undoubtedly the best (score: +3)
2. Conspicuously better (score: +2)
3. Moderately better (score: +1)
4. Borderline (score: 0)
5. Moderately worse (score: -1)
6. Conspicuously worse (score: -2)
7. Undoubtedly the worst (score: -3)

All subjects conducted the experiment for small, medium, and large objects separately. In each trial, the experimenter recorded the LF, object's displacement, velocity and acceleration data separately. In the second phase of the experiment, the first phase as described above was repeated. However, the object was manipulated in linear vertical motion i.e., in each trial, the object was lifted once from 'A' to 'B' as shown in Fig.3 (a) and then it was lowered and released. In each phase, the subjects took sufficient rest between trials, and hence they were not affected by fatigue.

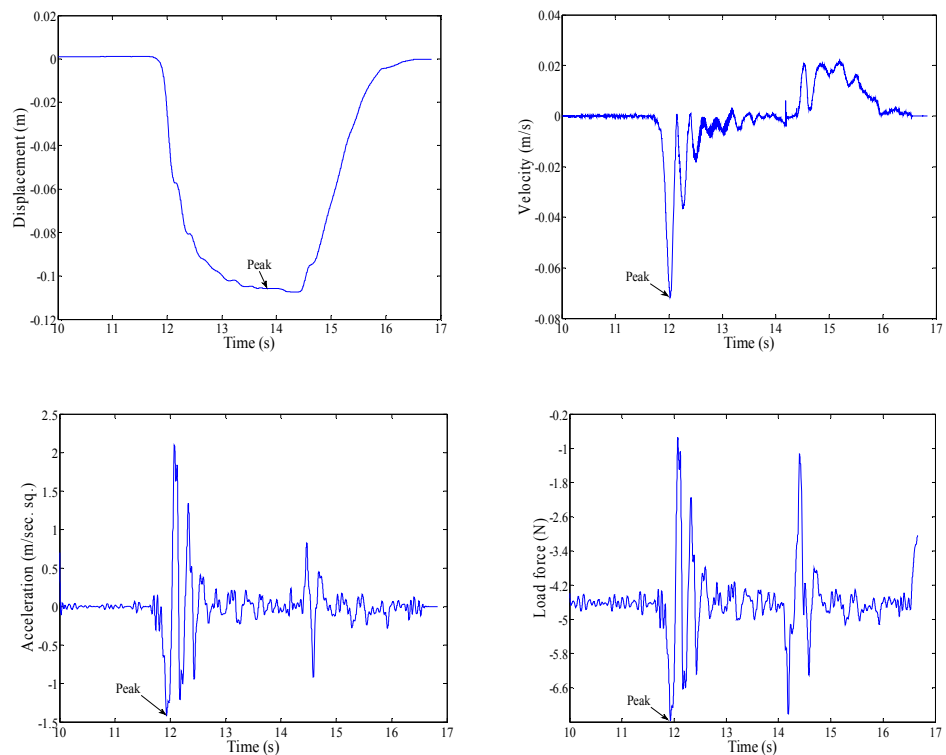
### 3.4 Experiment results and analyses

Typical displacement, velocity, acceleration and LF for harmonic and linear vertical motion are shown in Fig.5 (a) and (b) respectively. For harmonic motion, we derived the magnitudes of all Lifting Peak Velocity (LiPV) and Lowering Peak Velocity (LoPV) for all trials and determined their means for each object size separately. For linear vertical motion, we derived the magnitudes of peak velocity for all trials and determined their means for each object size separately. Table 1 shows the results. Results show that the peak velocity for lowering is less than that for lifting for harmonic motion. The reason may be that the subject tries to prevent the object from falling while lowering it by reducing its velocity. The peak velocity is proportional to object size <sup>(20)</sup>. We similarly calculated and compared the peak acceleration as shown in Table 2. Results show that the peak acceleration for lowering is lower than that for lifting for harmonic motion. The reason may be that the subject tries to prevent the object from falling during the lowering phase. We see that velocity and acceleration for linear vertical motion are less than that for the lifting phase of harmonic motion. Reasons may be that, for linear vertical motion, whole work is done against gravity and the subject possesses a mentality to stop the motion when the object reaches near the target. But, for harmonic case, inertia is felt more and the subject possesses a mentality to continue the motion. Peak acceleration is proportional to object size <sup>(20)</sup>.

We determined mean PAW for each object size separately for harmonic motion and compared them to that for linear vertical motion as shown in Fig.6. If the actual weight is  $m_2=0.5\text{kg}$ , then the PAW for linear vertical and harmonic cases are 0.2kg and 0.1833kg respectively, which are 40% and 36.66% of actual weights. The PAR reduces the perceived weight, but it was not quantified. This research quantifies this fact and presents a difference in weight perception between linear vertical and harmonic manipulation. Results show that PAWs for harmonic motion are lower than that for linear vertical motion. The reason may be that human feels inertia more in harmonic motion than in linear vertical motion. However, weight perception is caused not by inertia, but by gravity <sup>(21)</sup>. We think that the higher effect of inertia in harmonic motion might cause the reduced PAW.



(a)



(b)

Fig.5: Typical displacement, velocity, acceleration and load force are shown in (a) for a trial for the small size object for harmonic motion and in (b) for another trial for the small size object for linear vertical motion. Here, Li and Lo stand for lifting and lowering respectively. P stands for peak. D, V, A and LF stand for displacement, velocity, acceleration and load force respectively. The negative sign indicates upward motion.

For each trial, we derived magnitudes of LiPLF and LoPLF for harmonic motion and that of peak load force (PLF) for linear vertical motion and determined their means for



each object size separately as in Fig.7. Results show that LiPLF is very larger than LoPLF. The reason may be the influence of gravity during lowering phase that dictates the subject to apply smaller LF. LiPLF is proportional to object size <sup>(20)</sup>. However, LoPLF is inversely proportional to object size meaning that the inertial force is proportional to object size. Again, PLF for linear vertical motion is larger than that for the lifting phase of harmonic motion. The reason may be that, for linear vertical motion, work is done against gravity, inertia is felt less and heaviness is perceived more that dictate subjects to apply larger force.

Table 1: Mean peak velocity with standard deviations (in parentheses) for different sizes of objects for harmonic and linear vertical motion

Object Size	Mean peak velocity (m/s)		
	Lifting phase of harmonic motion	Lowering phase of harmonic motion	Linear vertical motion
Large	0.3135(0.1163)	0.2805(0.0845)	0.0949 (0.0158)
Medium	0.2966(0.0933)	0.2733(0.1004)	0.0699(0.0142)
Small	0.2720 (0.0713)	0.2716 (0.0628)	0.0655(0.0135)

Table 2: Mean peak acceleration with standard deviations (in parentheses) for different sizes of objects for harmonic and linear vertical motion

Object Size	Mean peak acceleration (m/s <sup>2</sup> )		
	Lifting phase of harmonic motion	Lowering phase of harmonic motion	Linear vertical motion
Large	6.5 (1.6268)	5.25 (0.9592)	3.1750(0.5627)
Medium	5.0 (0.7746)	4.20 (1.8166)	1.70 (0.7031)
Small	4.25 (1.1292)	4.05 (1.2749)	0.9929(0.3493)

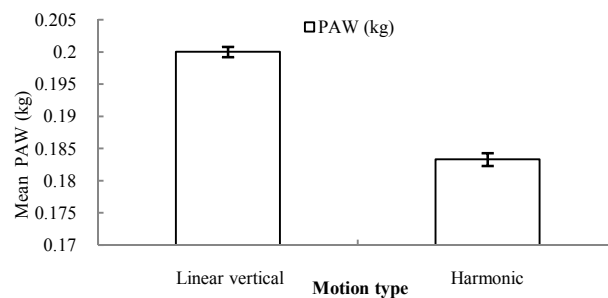


Fig.6: Mean PAWs for harmonic and linear vertical motion for the medium size object.

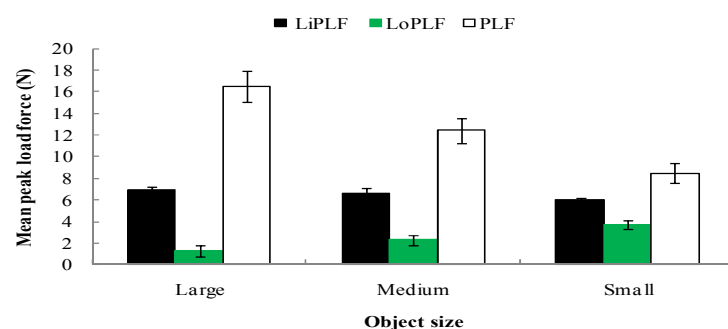


Fig.7: Mean LiPLF and LoPLF for the harmonic motion and the mean peak load force (PLF) for the linear vertical motion for different object sizes.

## 4. Experiment 2: Performances Improvement by a Novel Control

### 4.1 Experiment

Fig.7 shows that subjects apply very excessive load forces for both harmonic (LiPLF) and linear vertical (PLF) motion as the actually required load force for lifting an object with the PAR is slightly larger than the PAW, which is 0.1833kg or 1.80N for the harmonic motion and 0.2kg or 1.962N for linear vertical motion as shown in Fig.6 <sup>(20)</sup>. LoPLFs are also excessive. Excessive load forces cause problems that we explained in section 1.



The objective of experiment 2 was to reduce the excessive load forces by applying a novel control strategy, which is shown in Fig.8 as a flowchart. The novel control is such that the value of  $m_1$  exponentially declines from a large value to 0.5 when the subject manipulates the PAO with the PAR and the command velocity of Eq.(6) exceeds a threshold. We previously found that load force magnitude is linearly proportional to  $m_1$  and subjects do not feel the change of  $m_1$ <sup>(21)</sup>. Hence, reduction in  $m_1$  would also reduce the load force proportionally. Reduction in load force would not adversely affect the relationships of Eq. (2) because the subjects would not feel the change of  $m_1$ . It means that the following equations for  $m_1$  and  $m_2$  were used to modify the control of Fig.4. The digit 6 in Eq. (7) was determined by trial and error. The procedures for experiment 2 were same as that for experiment 1, but  $m_1$  and  $m_2$  were set as  $m_1=6*e^{-6t} + 0.5$ ,  $m_2=0.5$  for the simulation.

$$m_1=6 * e^{-6t} + 0.5 \quad (7)$$

$$m_2=0.5 \quad (8)$$

#### 4.2 Experiment results and analyses

Typical displacement, velocity, acceleration and load force trajectories for a trial for the small size object for harmonic manipulation for experiment 2 (after control modification) are shown in Fig.9. Appearances of displacement, velocity, acceleration and load force trajectories for linear vertical motion for experiment 2 were almost same as that for experiment 1, however, their magnitudes changed. We determined mean LiPV1 (lifting peak velocity for the first cycle), LiPVs (lifting peak velocities other than the first cycle such as LiPV2, LiPV3, LiPV4...), LoPV1 (lowering peak velocity for the first cycle) and LoPVs (lowering peak velocities other than the first cycle such as LoPV2, LoPV3, LoPV4...) for each object size separately for the harmonic motion and compared them to the mean peak velocity for the linear vertical motion as shown in Table 3. We compared the results shown in Table 3 to that shown in Table 1. Results indicate that LiPV1, LiPVs, LoPV1 and LoPVs reduced significantly due to control modification; however, the reduction in LiPV1 and LoPV1 was greater than that in LiPVs and LoPVs. Again, the peak velocity for the linear vertical motion reduced due to control modification, however, the amount of reduction was smaller than that for the harmonic motion. It means that the control modification makes the system slightly slow. Peak velocity is proportional to visual object size<sup>(20)</sup>.

We determined the mean LiPLF1, LiPLFs, LoPLF1 and LoPLFs for each object size separately for the harmonic motion after the control modification as shown in Fig.10 (a). The mean peak load forces for different object sizes for the linear vertical motion after the control modification are shown in Fig.10(b). We then compared the results to that shown in Fig.7. The figures reveal that, for the harmonic motion, the LiPLF reduced significantly due to control modification. However, the reduction in LiPLF1 was greater than that in LiPLFs. It means that the novel control strategy was more effective for the lifting phase of the first cycle than that for other cycles. In order to further reduce the LiPLF for other cycles, the control strategy may need to be modified in such a way that the  $m_1$  exponentially declines repeatedly for the lifting phase of each harmonic cycle. The figures also show that the LoPLF1 and LoPLFs increase, which means that the inertial forces also reduced due to the control modification. LiPLF was found proportional to visual object size<sup>(20)</sup>. The figure also shows that, for the linear vertical motion, peak load force reduced significantly<sup>(21)</sup>.

We determined the mean PAWs before and after the control modification for harmonic and linear vertical motion separately and compared them as shown in Fig.11. The results show that the PAW remains unchanged due to the control modification for the linear vertical motion, but it slightly increases for the harmonic motion. The reason may be that the control modification makes the PAR slightly slower that in turn increases the PAW.

We determined the mean LiPA and LoPA for the harmonic motion and the mean peak acceleration for the linear vertical motion for each object size separately as shown in Table 4, and we compared the findings to that determined in Table 2. The results show that peak

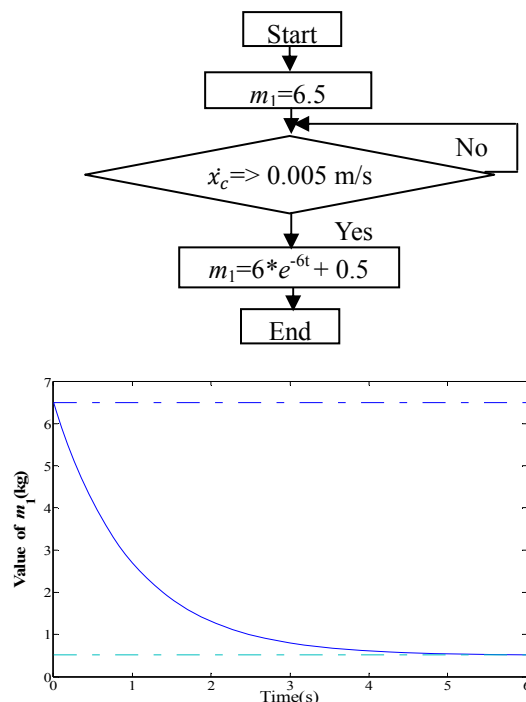


Fig.8: The upper figure shows the flowchart of the novel control strategy. The lower graph shows the hypothetical time trajectory of  $m_1$  during the experiment.

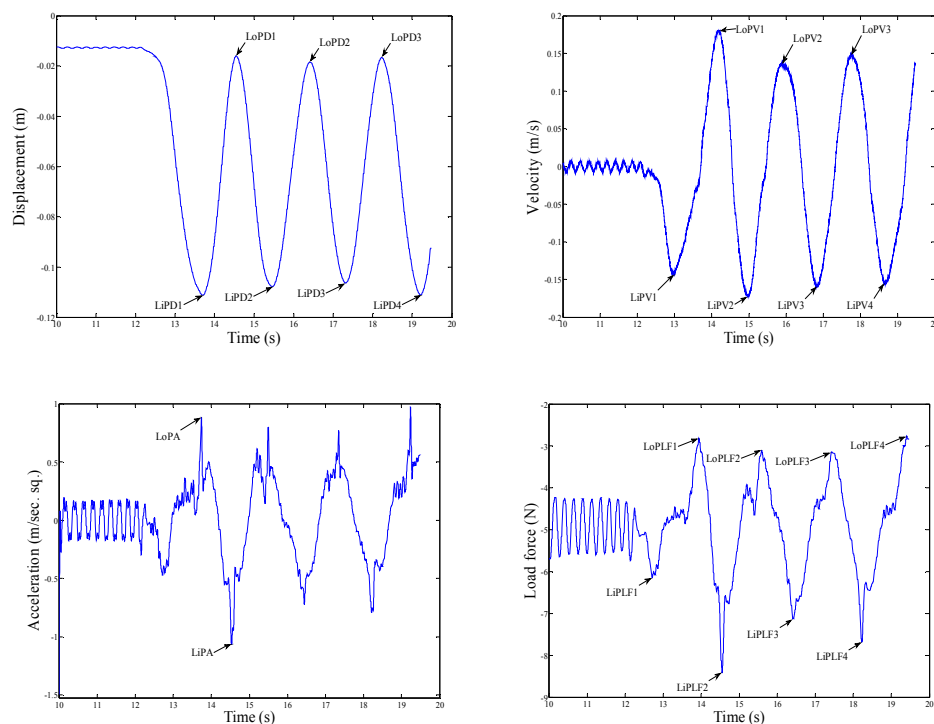


Fig.9: Typical displacement, velocity, acceleration and load force for a trial for the small size object for harmonic motion after the control modification (after applying the novel control strategy).

acceleration for harmonic and linear vertical motions reduced due to the control modification. The reason may be that the reduction in load forces due to control modification reduced the peak acceleration.

For harmonic motion, we determined mean evaluation score for each criterion for each object size separately before the control modification and compared them to that after the control modification as in Fig.12 (a). The mean evaluation scores for linear vertical motion

after the control modification only are shown in Fig.12 (b). The results show that, for harmonic motion, motion, stability and safety improved due to control modification. These are also better than that for linear vertical motion. However, maneuverability, naturalness and ease of use slightly reduced due to control modification for harmonic motion though these are still quite satisfactory. The reason may be that the control modification slightly increases the PAW that increases the fatigue in human's hand and reduces the maneuverability, naturalness and ease of use. The performances for the linear vertical motion are satisfactory. We think that the maneuverability, naturalness and ease of use can be further optimized by optimizing the value of  $m_2^{(22)}$ , which will further augment the effectiveness of the control. Visual object size was found not affecting evaluation scores<sup>(19)</sup>.

Table 3: Mean peak velocity with standard deviations (in parentheses) for different sizes of objects for harmonic and linear vertical motion after control modification

Object Size	Mean peak velocity (m/s)				
	LiPV1 for harmonic	LiPVs for harmonic	LoPV1 for harmonic	LoPVs for harmonic	Linear peak velocity
Large	0.168 (0.0206)	0.19 (0.01)	0.1567 (0.0163)	0.1767 (0.0273)	0.08102 (0.0263)
Medium	0.1500 (0.0224)	0.1867 (0.0121)	0.1454 (0.0205)	0.1563 (0.0200)	0.0632 (0.013)
Small	0.1367 (0.0351)	0.1567 (0.0306)	0.1331 (0.0197)	0.1340 (0.0255)	0.0597 (0.0284)

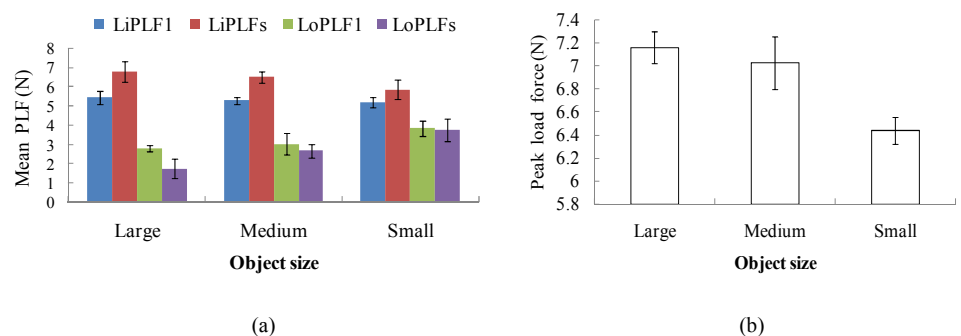


Fig.10: (a) Mean LiPLF and LoPLF for different object sizes for harmonic motion after the control modification. LiPLF1 and LoPLF1 indicate the PLF for lifting and lowering respectively for the first cycle of the harmonic motion. LiPLFs and LoPLFs indicate the PLF for lifting and lowering respectively for other cycles of the harmonic motion. (b) Mean peak load forces for different object sizes for linear vertical motion after control modification.

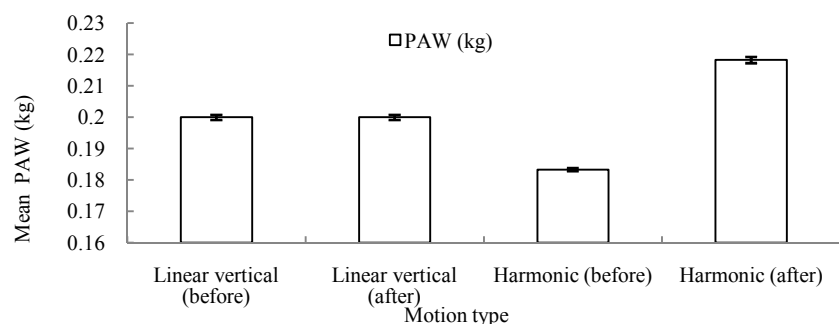


Fig.11: Mean PAWs for harmonic and linear vertical motion before and after the control modification for the medium size object.

Table 4: Mean peak acceleration with standard deviations (in parentheses) for different sizes of objects for harmonic and linear vertical motion after control modification

Object Size	Mean peak acceleration (m/s <sup>2</sup> )		
	Lifting phase of harmonic motion	Lowering phase of harmonic motion	Linear vertical motion
Large	1.926 (0.102)	1.612 (0.106)	1.33(0.3441)
Medium	1.521 (0.068)	1.293 (0.039)	0.9632(0.1962)
Small	1.12(0.017)	0.913 (0.023)	0.5238(0.2452)

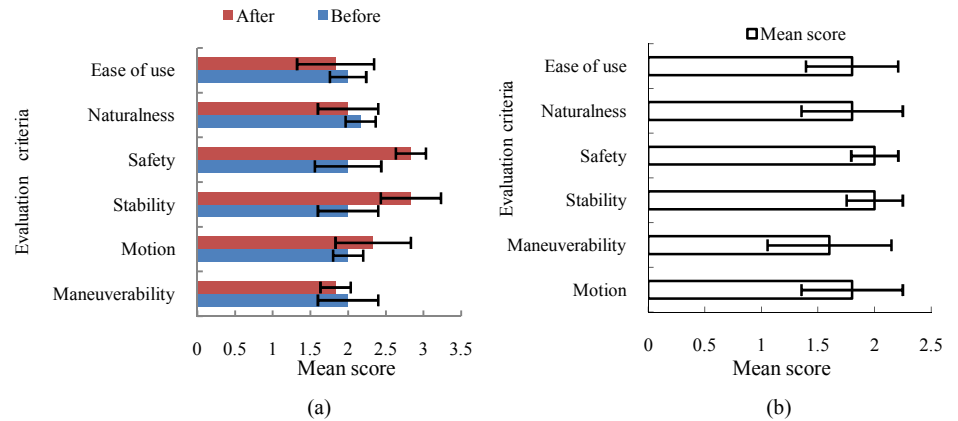


Fig.12: Mean evaluation scores with standard deviations for the system for the medium size object for (a) harmonic motion (before and after control modification), (b) linear vertical motion (after control modification).

We conducted Analyses of Variances, ANOVAs (object size, subject) on maneuverability scores, PAW, PLF, peak velocity, peak acceleration, performance evaluation scores etc. for experiments 1 and 2 separately. Results show that variations between object sizes were significant ( $p < 0.01$  at each case) for PLF, peak velocity and peak acceleration. However, variations between object sizes were not significant for maneuverability scores, PAWs and evaluation scores ( $p > 0.05$  at each case). On the other hand, variations between subjects were not significant in all cases ( $p > 0.05$  at each case).

### 5. Experiment 3: Further Optimization of the System Performances

#### 5.1 Experiment

Experiment 2 successfully improved the system performances. The objective of experiment 3 was to further optimize the performances. In the first phase of this experiment, experiment 2 was repeated for different values of  $m_2$  for linear vertical and harmonic motion separately. It means that Eq. (7) was unchanged, but Eq. (8) was changed to modify the control. We changed  $m_2$  because we wanted to measure its effects on performances and to identify the optimum  $m_2$ . For linear vertical motion,  $m_2$  were 0.5, 0.45, 0.4...0.1, 0.05, 0 kg.

For each motion, for each trial, the subject subjectively evaluated maneuverability, naturalness and ease of use of the system for each value of  $m_2$ <sup>(22)</sup>. Maneuverability was further divided into three sub criteria-mobility, positioning and fatigue. Mobility of the object (abbreviated as mobility) means ease of moving the object and it is related to perceived heaviness, required LF and forces acting on musculoskeletal system etc. Ease of positioning and maintainability (abbreviated as positioning) is related to perceived heaviness, required LF, stability, haptic sensations etc. It also covers the awareness and control over the direction of object motion and it is related to haptic sensations (tactile, proprioceptive and kinesthetic) regarding the object. It also affects human's authority, communication and roles in the human-robot interaction. As the human grips the PAO while manipulating it with the PAR, object's motion also affects hand motion and may transmit vibrations, jerks etc. to human body. 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. Ease of use is human's ease and comfort while manipulating objects. Naturalness is related to human's likeness, absence of clumsiness, psychological adjustment, mental acceptance, normalcy etc.

#### 5.2 Experiment results and analyses

Mean scores for the evaluation criteria for different  $m_2$  for different sizes of objects for harmonic and linear vertical motion were determined separately. The results for the linear vertical motion for the medium size object are shown in Fig.13. The figure shows that human enjoys the highest level of object mobility, ease of positioning and maintainability



and naturalness as well as least probability of fatigue in hand muscle at  $m_2=0.05$ . Ease of use at  $m_2=0.05$  is also good. We see that the performances of the system at zero-gravity ( $m_2=0$ ) are much lower than that at  $m_2=0.05$  and  $m_2=0.1$ . Fatigue and less mobility may be experienced at zero-gravity due to numbness in hand muscle. This is because the human loses some haptic information or senses at zero-gravity that reduces human's haptic weight perception ability<sup>(22)-(24)</sup>. Hence, we decided 0.05kg as the best (optimum) value of  $m_2$  for the dynamics of the PAR for manipulating objects in linear vertical motion. The optimality was decided heuristically using subjective evaluation. The optimum value of  $m_2$  for harmonic motion was also similarly estimated as 0.04kg.

ANOVAs (object size, subject) were conducted on evaluation scores for each criterion separately for each  $m_2$ . Results show that effects of object size on maneuverability were not significant ( $F_{2,18}<1$  for each case). However, variations in haptic sizes might affect maneuverability. Variations in maneuverability between subjects were not significant ( $F_{9,18}<1$  for each case). It means that the findings may be used in general.

We derived the PLF for each trial and determined the means of the PLF for each value of  $m_2$  for small, medium and large objects separately. Mean PLFs with standard deviations for different  $m_2$  for different object sizes for the linear vertical motion are shown in Fig.14. The figure shows that PLF decreases with the decreases in  $m_2$ , and the minimum PLF is obtained at  $m_2=0.05$ . The PLF is proportional to object sizes<sup>(20)</sup>. ANOVAs (object size, subject) were conducted on PLF for  $m_2=0$  and  $m_2=0.05$  separately. Results show that the effects of object size on PLF were highly significant ( $F_{2,18}=119.11$ ,  $p<0.01$  for  $m_2=0$ ;  $F_{2,18}=112.23$ ,  $p<0.01$  for  $m_2=0.05$ ). However, variations in PLF between subjects were not significant ( $F_{9,18}=0.32$  for  $m_2=0$ ;  $F_{9,18}=1.02$ ,  $p>0.1$  for  $m_2=0.05$ ).

Fig.14 shows that PLF suddenly increases at  $m_2=0$ . We assume that reduction in haptic senses at zero-gravity may result in higher and irregular PLF, which is not good for safety and maneuverability. However, irregular, multi-peaked and impulsive nature of the PLF were experienced at  $m_2=0$ . The results indicate that advantages in static properties (e.g., zero weight) may not always produce advantages in dynamic properties (e.g., mobility, positioning, motion, LF etc.), especially for the systems that integrate humans (e.g., PAR).

In the second phase of experiment 3, we fixed the value of  $m_2$  as 0.05kg for the linear vertical motion and gradually reduced the value of  $m_1$  in Eq. (7). The system was evaluated for each trial and it was found that the system performed the best at  $m_1=6 * e^{-6t} + 0.3$ ,  $m_2=0.05$  for the linear vertical motion. Similarly, the system performed the best at  $m_1=6 * e^{-6t} + 0.25$ ,  $m_2=0.04$  for harmonic motion. These were proposed as the optimum conditions. Zero-inertia ( $m_1=0$ ) was not possible.

We think that most of the topics that we have so far discussed (e.g., motivation, problem identification, ideas, assumptions, hypotheses, modeling, dynamics, control design etc.) and the results we have derived in the above three experiments (e.g., experiment methods, determination of psychophysical relationships between actual and perceived weights, analysis of force and motion features, development and testing of the human-interactive novel control, system evaluation techniques and results, determination of optimum performances etc.) seem to remain true, valid and effective (but magnitudes may change) for developing PARs for manipulating heavy and large size objects, which will be addressed in near future. The introduced experimental system is valid to derive the above findings and its validity may be further justified when the findings will be reinvestigated using heavy objects and real robotic system. The non-linearity of human actions is also included in the derived results because the experiments were conducted by several humans at several times for objects of different sizes and weights. Effects of non-linearity may be reduced by increasing the number of subjects, object weights and sizes, object shapes etc.

For a power assist system, the human does not carry the load-the load is carried by the system and human's load force adds motions to the object and controls its motion. The mass

parameter used in the control is used to produce an optimum feeling of heaviness in human hand. We think that the nature of the human characteristics derived using light objects will be similar to the nature of the human characteristics derived using heavy objects. If there is slight difference in the magnitude of the characteristics as well as non-linearity between light and heavy objects, it may be adjusted by further modification of the novel control and of the real system configuration and its structure. However, there will be no effects on human's feelings because the system will give the human the feelings that are optimum for the human.

## 6. Biomechanical significance of the results

There are different opinions among the researchers regarding whether or not psychophysical ratings correlate with biomechanical criteria in manipulation tasks<sup>(25)-(27)</sup>. Garrison *et al.*<sup>(25)</sup> found that psychophysical and biomechanical approaches produce similar results. The main factor affecting biomechanical properties is the magnitude of the load felt by human when manipulating heavy objects. In our case, the human will feel only 0.05kg (0.49N) and 0.04kg (0.39N) even when manipulating a very heavy load with the PAR in linear vertical and harmonic motion respectively, which is far below the biomechanical tolerance limits (strength - compressive, tensile, torsional; fatigue) at different locations of human body<sup>(28)</sup>. We think that the dynamic psychophysical ratings for  $m_1$  and  $m_2$  in this paper will not only produce appropriate maneuverability, stability, naturalness etc., but also satisfy operator's biomechanical criteria such as motions, hand movement and posture, joint torque, joint shear, joint stress, joint compression, joint work distribution, total mechanical work, muscular moments at joints, torque equilibrium, muscle force, forces acting on musculoskeletal system, low back stress etc. that will help avoid injuries, risks, vibrations and jerks on human body when manipulating heavy objects with PARs in industries.

## 7. Discussion

We think that the requirements for humans or the necessary factors for power-assist system in the viewpoint of human perception for manipulating heavy objects are as the following: (i) optimization of perceived heaviness, load forces, motions, maneuverability, safety, naturalness, ease of use, comfort (absence of fatigue), situational awareness of user, efficiency, manipulating speed etc., (ii) system stability, (iii) system flexibility to adjust with objects of different shapes, sizes, weights etc., (iv) DOFs such as vertical, horizontal and rotational manipulation of objects, (v) adjustment with worst-cases, uncertainty, rapid changes, disturbances etc., (vi) fulfilling operator's biomechanical requirements etc.

We think that the above requirements are influenced by the control parameters as follows: (i) the values of  $m_1$  and  $m_2$ , (ii) relationships between actual and perceived weights, (iii) relationship between  $m_1$  and PLF, and the fact that  $m_1$  does not affect perceived weight, but  $m_2$  does affect, (iv) magnitudes of PLF and accelerations, (v) the value of  $G$ , (vi) time constant of the servomotor, (vii) controller type of the servomotor such as PD, PID etc., (viii) control method such as position/force control etc., (ix) mode of the servomotor such as velocity/torque control mode, (x) solver type, sampling time etc. for the simulation etc. These parameters are to be handled/examined to optimize the requirements.

All of the above control parameters (except time constant of the servomotor) have already been addressed in this paper that optimized/fulfilled most of the requirements as it is evident through the evaluation results. However, further modification/optimization of the control parameters may further improve the performances of the system.

The results are somewhat dependent on experiment system, but the same approaches are applicable to any type of system with various configurations and capacity. The study approaches, methodologies etc. of this paper are to be universal. The results of this paper along with our previous works related to the development of power assist devices and investigations of human characteristics as well as our future extension works are to satisfy all of the requirements/factors for the proposed industrial power assist system<sup>(1),(21)-(22)</sup>.

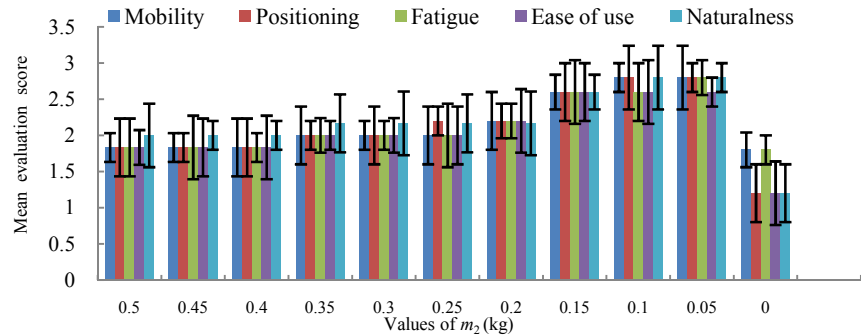


Fig.13: Mean evaluation scores with standard deviations for the system for the medium size object for linear vertical motion.

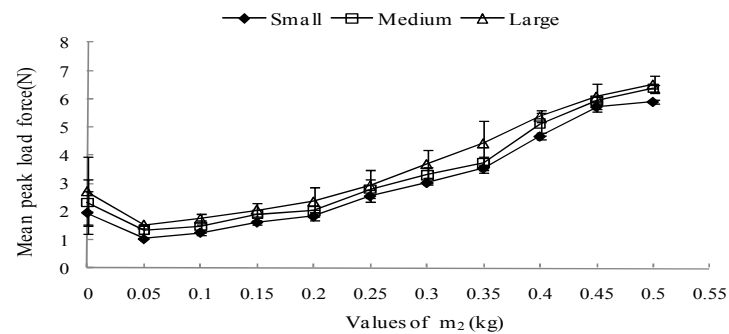


Fig.14: Mean PLFs with standard deviations for different  $m_2$  for different object sizes for the linear vertical motion.

## 8. Conclusions and Further Works

This paper emphasizes a new area of application of power assist devices i.e., emphasizes to use these devices for manipulating heavy objects in industries that would positively affect productivity and operators' health and safety. This paper shows how to design a power assist robot and its control for object manipulation based on weight perception, load forces and motion features that indicate its superiority over the conventional devices. This paper considers linear vertical and harmonic motions and compares human features for these two motions so that the findings are usable with broader scope. Conditions of optimum system performances are also demonstrated. The findings may be used to develop power assist robots for manipulating heavy industrial objects.

Advanced control methods and strategies for the robot will be searched. The system will be upgraded to a multi-DOF system (horizontal, rotational etc.). Experimental verifications of the findings with heavy objects and real system will be conducted. Generality of the system will be confirmed. Psychophysical and biomechanical approaches will be applied to assistive devices for rehabilitation, healthcare etc.

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