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OPTIMIZING PERCEIVED HEAVINESS AND MOTION FOR LIFTING OBJECTS WITH A POWER ASSIST ROBOT SYSTEM CONSIDERING CHANGE IN TIME CONSTANT

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Abstract-Power assist robots are usually used for disabled and elderly people to augment their abilities and skills. This paper proposes to use these robots to handle heavy objects in industries, and thus brings a novelty in the applications of power assist robots. However, it is difficult to optimize perceived heaviness and motion either independently or simultaneously for lifting objects with power-assist. Hence, this paper investigates the techniques to optimize perceived heaviness and motion following bionic and psychophysical approaches. We developed two systems-one was used to lift objects manually, and another was a power assist system to lift objects with it. Several

hypotheses and strategies related to weight perception and time constant were adopted. Humans lifted objects manually and with power-assist independently. Analyses showed that load force rate for power-assisted lifting were lower than that for manual lifting. We hypothesized that time constant of the assist system might be responsible for this. We changed time constant and found that increase in time constant reduced perceived heaviness and load force. Then, objects were lifted with power-assist in some selected conditions pertaining to time constant. Analyses showed that perceived heaviness was related to load force rate while object motion (acceleration) was related to load force magnitude. It was then demonstrated how to independently optimize perceived heaviness and motion by optimizing load force rate and its magnitude respectively. Techniques for simultaneous optimization of motion and perceived heaviness were also presented. Finally, we proposed to use the findings to develop power assist robots for manipulating heavy objects in industries that may enhance interactions with humans in terms of maneuverability, safety etc.

Index terms- Power assist robot system, lifting objects, weight perception, psychophysics, time constant, motion, human-robot interaction, bionics/biomimetics

I. INTRODUCTION

Power assist robot system (PARS) is a human-robot interaction/cooperation system that extends human's abilities and skills in performing various tasks. Breakthrough in power assist robot was conceived in early 1960s with "Man-amplifier" and "Hardiman" [1], however, its applications are still limited to a few areas. As we find in literature, PARSs are currently developed mainly for sick, physically disabled and old people as rehabilitation and medical aids [2]-[3]. Few PARSs are available for other applications such as support for lifting baby carriage[4],physical support for workers in agricultural jobs [5], hydraulic assist systems for automobiles[6], skill-assist in manufacturing [7], assist-control for bicycle [8], assist for sports training [9], assisted slide doors for automobiles [10] etc.

We think that handling heavy objects, which is common and necessary in many industries, is another potential application of PARSs [11]. Manual handling of heavy objects is very tedious, affects human musculoskeletal system negatively[12], and on the contrary, autonomous systems for object handling usually do not provide required flexibility [13]-[14].Hence, we assume that suitable PARSs may be appropriate for handling heavy objects in industries such as agriculture, construction, mining, manufacturing and assembly (e.g., rail line and rail car, ship building and breaking, automobile, timber etc.), forestry, transport and logistics, military activities, disaster and rescue operations, meat processing etc. However, such PARSs are not available in practices because their design and development have not received so much attention, importance and priority yet. A few PARSs are available for handling objects [15]-[17]. However, we think that these robotic systems are not suitable for lifting heavy objects in industries because they are not sufficiently safe, natural, stable, easy and user-friendly. A PARS reduces the perceived weight of an object lifted with it [1], and hence the manipulative forces required to lift the object with the PARS should be lower than that required to lift the object manually. However, limitations with the conventional PARSs are that the user cannot correctly perceive the weight of the object before lifting it with the PARS and eventually applies excessive load force (vertical lifting force).The excessive load force results in sudden increase in acceleration, fearfulness of the user, lack of stability and maneuverability, fatal accidents, injuries etc. Fig.1 shows interactions between a human and a power assist robot when manipulating an object.

We assume that appropriate PARSs in industries for handling heavy objects are not available and their interactions with users are not satisfactory because (i) specialized PARSs for handling heavy objects have not been developed yet, and (ii) the conventional power-assist controls do not consider human features especially weight perception, load forces and motion characteristics. On the other hand, the root cause of reduced heaviness of objects handled with PARSs is unknown and the factors affecting the reduced heaviness are still unclear [18]. We think that the knowledge on the root cause(s) and on the factors affecting the reduced heaviness could be used to improve the interactions between humans and robots in many ways. For example, perceived heaviness and user's feelings when handling objects with a power assist robot could be adjusted if we could know the reasons and factors behind the reduced heaviness of objects handled with the PARS. However, the published literatures on PARSs do not show such reasoning.

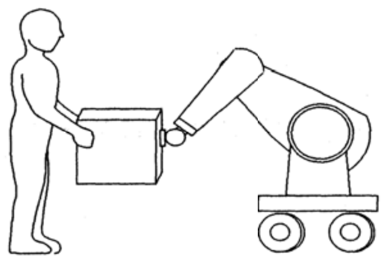

Figure. 1 Interactions between a human and a PARS. The human feels reduced heaviness when manipulating an object with a power assist robot.

Again, the power-assist performances for object manipulation, as a whole, largely depend on maneuverability (perceived heaviness), applied manipulative force, object motion (acceleration) etc. [19]. Because, inappropriate perceived heaviness causes fatigue, lack of mobility etc., and inappropriate object motion reduces safety, stability, mobility, and may transmit jerks, vibrations etc. to human body that may affect human musculoskeletal system and/or may cause injuries/losses to human, devices etc.[11]-[12].However, perceived heaviness and motion are usually considered as distinct aspects, and the currently available research does not take any initiative to optimize these aspects either independently or simultaneously following human requirements that results in unsatisfactory interactions with human users.

We are the first to include weight perceptual, load force characteristics and motion features in power-assist control [20]-[22].This paper investigates the techniques to optimize perceived heaviness and motion independently and simultaneously following bionic and psychophysical approaches. Few hypotheses and strategies related to weight perception, time constant etc. were adopted to reach the target. We analyzed weight perception, load force, motion etc. for lifting objects manually and with power-assist. We also studied the effects of time constant on these. We identified the factors and root cause for reduced heaviness of objects lifted with power-assist. We identified what influenced perceived heaviness and object motion, and demonstrated how to independently optimize the perceived heaviness and the motion. We also presented the techniques for simultaneous optimization of motion and perceived heaviness. We then proposed to use the findings to develop power assist robots for manipulating heavy objects in industries that may enhance interactions with humans in terms of maneuverability, safety etc.

II. CONSTRUCTING THE EXPERIMENTAL DEVICES

The experimental devices consist of two independent systems. The first system was developed to lift objects with the system by human subjects manually, which was called the 'manual system'. The second one was a power assist robot system developed for lifting objects with the system by the same human subjects, which was called the 'PARS'. Detailed configurations of the two systems are described below.

a. Manual System

We made three manually lifted objects (MLOs) of three different sizes (small, medium, large) to lift manually by human subjects. These objects were rectangular boxes made by bending aluminum sheets (thickness: 0.0005 m). Dimensions (length x width x height) of the boxes were 0.06 x 0.05 x 0.16m, 0.06 x 0.05 x 0.12m and 0.06 x 0.05 x 0.09m for the large, medium and small size respectively. Top side of each box was covered with a cap made of aluminum sheet (thickness: 0.0005 m).The bottom and back sides were kept open. Self-weight of each box was 0.013, 0.015 and 0.017kg for small, medium and large size respectively. It was possible to change the weight of the MLO by attaching extra masses to the back side of the object, as shown in Fig.2. One use of these MLOs was that these objects could be used as references weights to estimate the perceived weights of the objects lifted with the power assist robot system.

Again, another use of the MLOs was that the MLOs could be instrumented with a load transducer type force sensor and be lifted by human subjects as shown in Fig.3. The specifications of the load transducer type force sensor were as the following: type 9E01-L44, max. 2KN, 1 mV/V, 350 ohm. The weight of the MLO could be changed by attaching extra masses inside it. The mass was kept on a platform (foam) before the object was lifted by the subject. The complete experimental setup for the system for lifting the MLO instrumented with the force sensor is shown in Fig.4. As shown in the figure, a laser position sensor was set over the object. Specifications of the laser sensor are given in Table 1.When the object was lifted by the subject, the load force (vertical lifting force) was measured by the force sensor and object's position (displacement and its derivatives) was measured by the laser position sensor separately. Then the force signal was amplified by the amplifier as shown in the figure, and the force and position signals were sent to the computer through the analog to digital converter (A/D converter). The computer as shown in the figure gave 16-bit BUS data. A noise filter (type: LF-205A) was also mounted to prevent electrical noises from the power supply line. Matlab/Simulink was installed in the computer [18],[20]-[22].

Figure. 2 Fronts and backs of different sizes of MLOs. The left photo, from left to right, shows the front sides of the large, medium and small MLOs respectively. The right photo, from left to right, shows their backs. The extra mass attached to the back of each object is also shown as examples. Extra mass helps change the weight keeping the front view unchanged.

Table1: Specifications of the laser position sensor

Item	Specifications
Manufacturer	Keyence, Japan
Type	Long range
Sensor Head	LB-300
Amp. Unit	LB-1200
Standard Distance	300mm
Calculation Range	±100mm
Wave Length	780nm (invisible)
Output	15mW (max)
Other	Infrared semiconductor laser

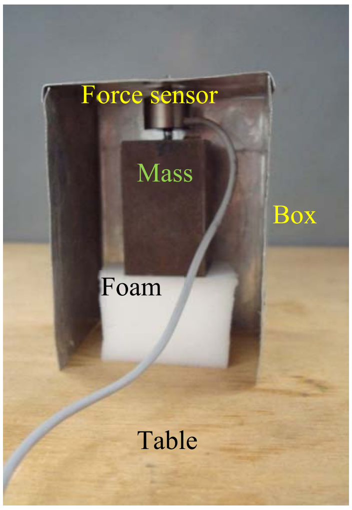

Figure.3 A MLO instrumented with a force sensor. The figure shows the backside of the MLO (box) enriched with a force sensor, a mass and foam. The object is placed on a table.

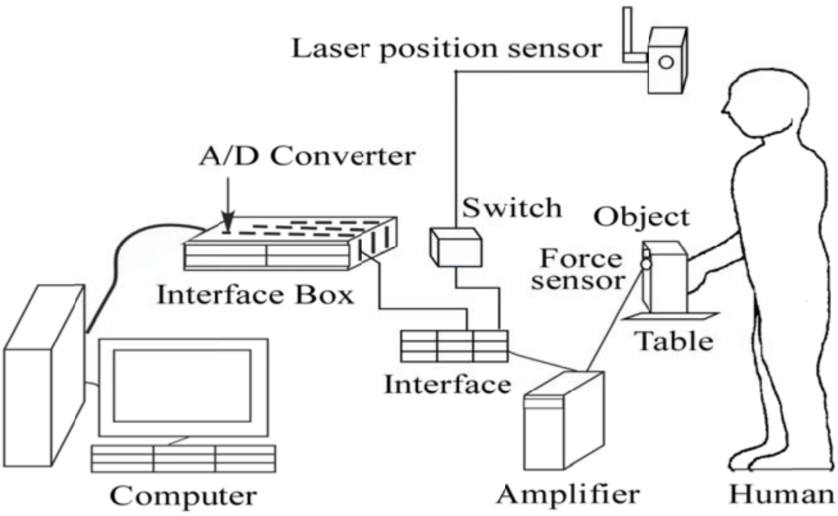

Figure.4 Experimental setup for the manual system for lifting objects (MLOs) manually.

b. Power Assist Robot System

b.i Configuration

We constructed a 1DOF (vertical up-down motion) power assist robot system (PARS) for lifting objects using a ball screw actuated by an AC servomotor (manufactured by Yaskawa, Japan, type: SGML-01BF12). The ball screw assembly and the servomotor were coaxially fixed on a metal plate and the plate was vertically attached to a wall. We made three more rectangular objects (boxes) by bending aluminum sheets (thickness: 0.0005 m) in order to lift them with the PARS and they were called the 'power assisted objects' (PAOs). The shape, dimensions, material and outlook of a PAO of a particular size were same as that of the MLO of that particular size. A PAO, at a time, could be tied to the ball nut (linear slider) of the ball screw through a force sensor (foil strain gauge type, NEC Ltd.) and be lifted by the human subject. The PAO tied to the force sensor was kept on the soft surface of a table before it was lifted. Detailed configuration of the main power assist device along with a PAO is illustrated in Fig.5. The experimental setup of the PARS is depicted in Fig.6.

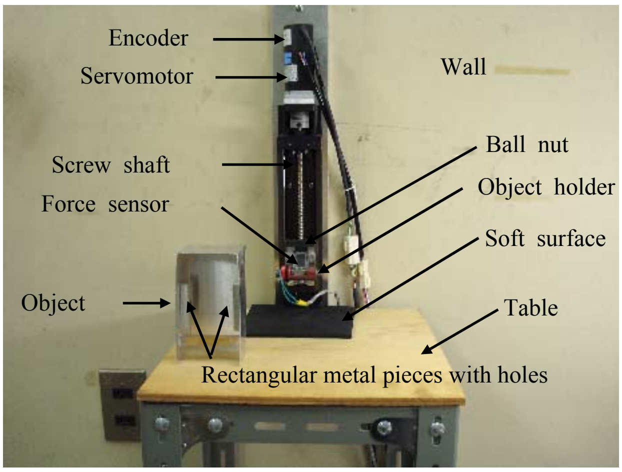

Figure.5 Components of the main power assist device. Back view of a PAO (medium size) is also shown as an example. Two rectangular metal pieces with holes in the center of each are attached to the interior of the left and right sides of the PAO. The holes help the PAO (box) be tied to the force sensor through the object holder.

b.ii Dynamics of the PARS Based on Weight Perception

According to Fig.7, the PAO is to be controlled by the equation of motion derived as Eq. (1).

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

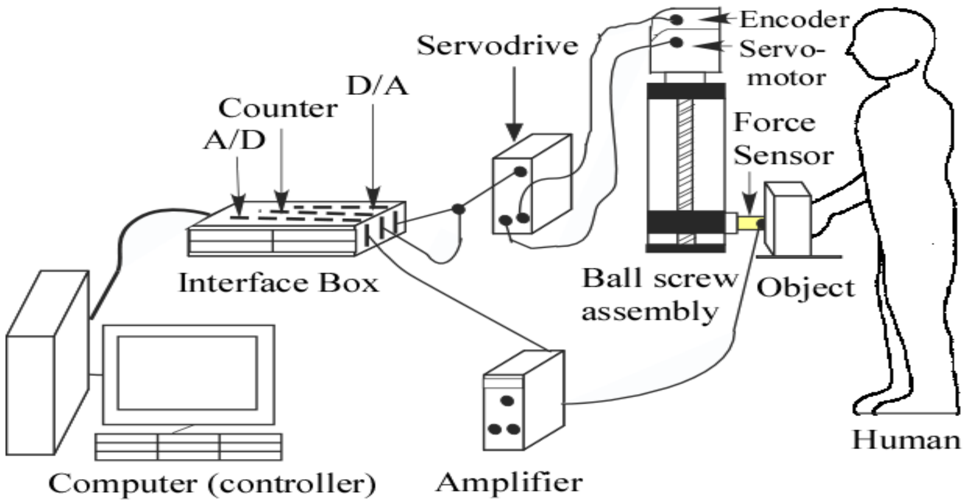

Figure.6 Experimental setup of the PARS for lifting objects.

Where,

f_h = Load force applied by the human

m = Actual mass of object visually perceived by human

x_d = Desired displacement of the object

g = Acceleration of gravity

As an attempt to introduce weight perception in modeling the dynamics of the PARS, we hypothesized Eq. (1) as Eq. (2), where $m_1\ddot{x}_d$ refers to inertial force and $m_2 g$ refers to gravitational force.

$$m_1\ddot{x}_d + m_2 g = f_{h.} \qquad (2)$$

In Eq. (2), both m_1 and m_2 stand for mass, where m_1 forms inertial force and m_2 forms gravitational force. A difference between m_1 and m_2 is considered because of the difference between human's perception and reality regarding the weight of the object lifted with the PARS [1]. Usually, $m_1 = m_2 = m$ is considered for all psychological experiments [26], but we hypothesized that $m_1 \neq m_2 \neq m$, $m_1 \ll m, m_2 \ll m$,and $|m_1\ddot{x}_d| \neq |m_2 g|$ should be considered by the human while lifting an object with the PARS. The human errs when lifting an object with the PARS because he/she considers that the actual weight and the perceived weight (named power-assisted weight, PAW) are equal. The hypothesis means that the human errs because the human considers that the two 'masses' used in inertia and gravity forces are equal to the actual mass of the object (i.e.,$m_1 = m_2 = m$). In order to realize a difference

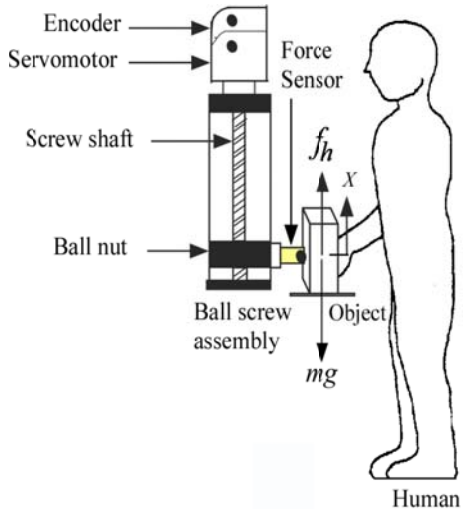

Figure.7 The dynamics when a human lifts a PAO with the PARS.

between actual weight and PAW, the human needs to think that the two 'masses' used in inertia and gravity forces are different and are less than the actual mass (i.e.,$m_1 \neq m_2 \neq m$,$m_1 \ll m, m_2 \ll m$) .Then, we derived Eqs. (3) ~ (5) from Eq. (2).

$$\ddot{x}_d = \frac{1}{m_1}(f_h - m_2 g). \quad (3)$$

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

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

b.iii Design of the Power Assist Control

Block diagram of the control system of the PARS based on Eqs. (3) ~ (5) was developed, which is shown in Fig.8. If the PARS is simulated using Matlab/Simulink in the velocity control mode of the servomotor, the command velocity ($\dot{x}_c$) to the servomotor is calculated by Eq. (6), which is fed to the servomotor through a D/A converter. The servodrive generates the velocity control for the command velocity. An extra term, G_1(s), as given in Eq. (7) is added to the block diagram. G_1(s) helps change the mechanical time constant of the PARS.

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

$$G_1(s) = \frac{1}{Ts+1} \quad (7)$$

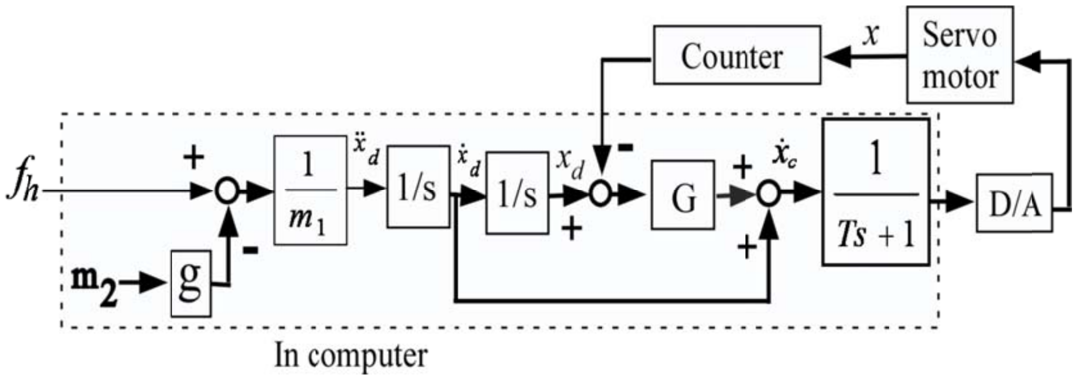

Figure.8 Block diagram of the control system of the PARS. Here, G denotes feedback gain, D/A indicates D/A converter, T refers to software time constant and x denotes actual displacement. Feedback position control is used with the servomotor in velocity control mode.

III. EXPERIMENT 1: DETERMINING RELATIONSHIP BETWEEN MECHANICAL TIME CONSTANT AND PAW, LOAD FORCE MAGNITUDE AND LOAD FORCE RATE

a. Hypothesis

The hypothesis of this experiment was to know whether or not the mechanical time constant of the servomotor was related to PAW, load force magnitude and load force rate.

b. Design of the Experiment

The independent variables were mechanical time constant and visual object size. The dependent variables were PAW, load force magnitude and load force rate.

c. Subjects

Ten mechanical engineering male students aged between 23 and 30 years were selected to voluntarily participate in the experiment. All the subjects were believed to be physically and mentally healthy. The subjects did not have any prior knowledge and experience of the hypothesis being tested. Instructions regarding the experiment procedures were given to them, but no formal training.

d. Experiment Procedures

The whole experiment procedures are divided into four phases or steps as the following:

d.i Step 1

In this step, the subject lifted the MLO shown in Fig.3. The task required the subject to lift the MLO approximately 0.1 meter, maintain the lift for 1-2 seconds and then release the object as shown in Fig.9. A wooden stick was kept beside the object. The wooden stick served as the height scale and helped the subject guess the lifting height. The mass of the MLO was changed as 1.5kg, 1.0kg and 0.5kg. The subject lifted the object only one time at each mass condition.

d.ii Step 2

In this step, the system shown in Fig.8 was simulated using Matlab/Simulink (solver: ode4, Runge-Kutta; type: fixed-step; fundamental sample time: 0.001s) for three sets of values of m_1 and m_2 (i.e., m_1=1.5, m_2=1.5; m_1=1, m_2=1; m_1=0.5, m_2=0.5) separately, m_1 and m_2 were in kg. T was set zero (0). Following a demonstration by the experimenter, the subject lifted a PAO of a particular size with the PARS only one time for each set of values of m_1 and m_2.The experimenter randomly chose m_1 and m_2 set and strictly maintained its confidentiality. For each m_1 and m_2 set, the task required the subject to lift the object approximately 0.1 meter, maintain the lift for 1-2 seconds and then release the object.

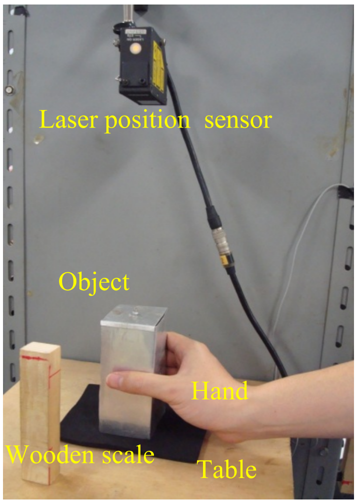

Figure.9 Experimental method of lifting a MLO.

d.iii Step 3

The mechanical time constant of the servomotor of the PARS shown in Fig.8 was measured. The mechanical time constant was the time required for the servomotor to reach 63.2% of its final velocity when a step voltage was applied. T was set zero (0).This time constant was named the 'hardware time constant' of the system for better understanding in contrast with the software time constant, T. The measured hardware time constant was 0.0053s (when T=0). Then, the value of T was gradually increased starting from T=0 and a difference of 0.005s between two adjacent values of T was maintained. At each value of T, the PARS shown in Fig.8 was simulated using Matlab/Simulink, a representative subject lifted a PAO with the system and subjectively checked the stability (presence or absence of oscillations) of the system. The hardware time constant was also measured using a step voltage at each value of T. The system for T>0 was found stable (no oscillations) up to T=0.1. Hence, the limit of stability of the system was determined as $0 \le T \le 0.1$. T was in second (s).

d.iv Step 4

In this step, the system shown in Fig.8 was simulated using Matlab/Simulink for T=0.005, 0.035, 0.065, 0.095 separately. The four values of T were whimsically selected that fell within the limit of stability ($0 \le T \le 0.1$).The experimenter randomly changed the value of T and strictly maintained its confidentiality. For a particular value of T, the subject lifted the PAO of a particular size with the PARS one time only, maintained the lift for 1-2 seconds at a height of 0.1 meter and then released the object. Then the subject lifted a MLO several times for reference weights. The weight of the MLO was sequentially changed in a descending order starting from 0.5kg and ending at 0.1 kg while maintaining an equal difference of 0.025kg (i.e., 0.5kg, 0.475kg...0.125kg, 0.1kg). Thus, the subject compared the perceived weight of the PAO (PAW) to that of the MLO (reference weights) and thus estimated the magnitude of the PAW. In the case when the subject could not estimate the PAW properly, the trial was repeated.Fig.10 shows the experimental procedures.

The experiment in steps 1, 2 & 4 was conducted by all subjects for small, medium and large size object separately. The load force and position data in each trial in steps 1, 2 & 4 were recorded separately. Values of m_1 and m_2 were fixed at m_1=0.5, m_2=0.5 in steps 3 & 4 because these values resulted in high maneuverability [22].

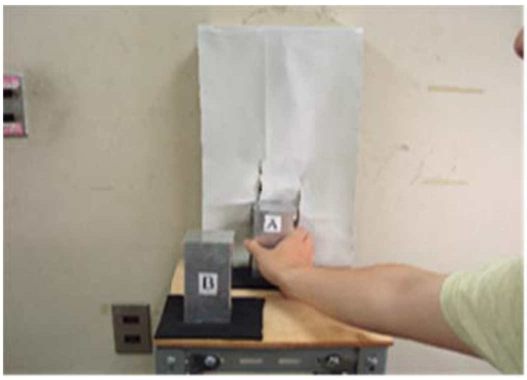

Figure.10 Experimental method for lifting a PAO. The human lifts the PAO (A) and compares its weight to that of the MLO (B).The main PARS is hidden behind the PAO in order to eliminate any visual differences between the MLO and the PAO.

IV. RESULTS OF EXPERIMENT 1

We derived the initial and peak load force (PLF) for each trial for both MLO (step 1) and PAO (step 2). Fig.11 shows the typical time trajectories of the load forces for MLO and PAO. We calculated the load force rate (LFR) for each trial in each step following Eq.(8), where

MPLF stands for magnitude of peak load force, MILF stands for magnitude of initial load force, TPLF stands for time corresponding to peak load force and TILF stands for time corresponding to initial load force.

$$\mathrm{LFR} = \frac{\mathrm{MPLF} - \mathrm{MILF}}{\mathrm{TPLF} - \mathrm{TILF}} \qquad (8)$$

Then, we calculated the mean LFRs for small, medium and large objects for each mass condition for MLOs and PAOs separately. Fig.12 shows the comparison between the load force rates for MLOs (step 1) and PAOs (step 2) in similar mass conditions (e.g.,m=1 kg for MLO, and m_1=1kg, m_2=1kg for PAO) for different sizes of objects. The results show that load force rates for lifting objects with the PARS are much lower than that for lifting objects manually. The results also show that the load force rate decreases with the decrease in visual object size and object mass [26].

We conducted analyses of variances, ANOVAs (object size, subject) on load force rates at each mass condition for MLOs and PAOs separately. Results show that variations between object visual sizes were highly significant. However, variations between subjects were not statistically significant. We also conducted ANOVAs (type of lift, subject) on the load force rates at each similar mass condition (e.g., m_1=1.5,m_2=1.5 and m=1.5 kg) for each size object separately. The results show that variations between lift types (power assisted vs. manual) were highly significant ($p<0.01$ at each case). We also conducted ANOVAs (mass, subject) on the load force rates for each size object for simulated and actual mass separately. The results showed highly significant variations between masses ($p<0.01$ at each case) [26].

Fig.13 shows the typical step voltage responses at two distinct values of T for step 3. We determined the relationship between the hardware time constant (mechanical time constant) and the software time constant (T) and found a linear (approximately) relationship between them as shown in Fig.14.

For step 4, we determined mean PAWs for each of the four distinct values of T for the small, medium and large objects separately as shown in Fig.15. The figure shows that PAW decreases with the increase in software time constant. We see in Fig.14 that hardware time constant (mechanical time constant) is linearly proportional to software time constant. Hence, PAW decreases with the increase in mechanical time constant. The results also show that PAW is not affected by visual object size for equal mass. The reason may be that the human subject perceives the PAW using haptic senses where object's visual size cue has no influence. However, variations in haptic cues might affect the PAW [26].

We conducted ANOVAs (object size, subject) on PAWs at T=0.005 and T=0.035 only separately as the individual differences were the highest for these two cases. The results show that variations between object sizes were at all not statistically significant ($F_{2,18}$<1 at both values of T). Variations between subjects were also statistically insignificant ($F_{9,18}$<1 at both values of T) [26].

We may explain the probable reason behind the aforementioned relationship between the mechanical time constant and PAWs as the following. As we know, according to basic physics, mass (weight) is solely dependent upon the inertia of an object. We assume that increase in the mechanical time constant increases the inertia of the servomotor rotor and thus reduces the load inertia to rotor inertia ratio. Reduction in this ratio results in a lower relative contribution of the load inertia to the total inertia of the PARS and the reduced inertia contribution of the load under the dynamic touch may cause the perceptual attenuation i.e., the feeling of reduced heaviness [23]-[25].

We derived the magnitude of PLF for each trial and calculated their means separately for each of the four values of T for the small, medium and large objects as shown in Fig.16. The results show that PLFs decrease with the increase in software time constant. The results also show that PLFs are proportional to visual object sizes [26].We also calculated the load force rate for each trial following Eq. (8) and determined their means as shown in Fig.17. The results show that load force rates decrease with the increase in T. The load force rates were also proportional to visual object sizes.

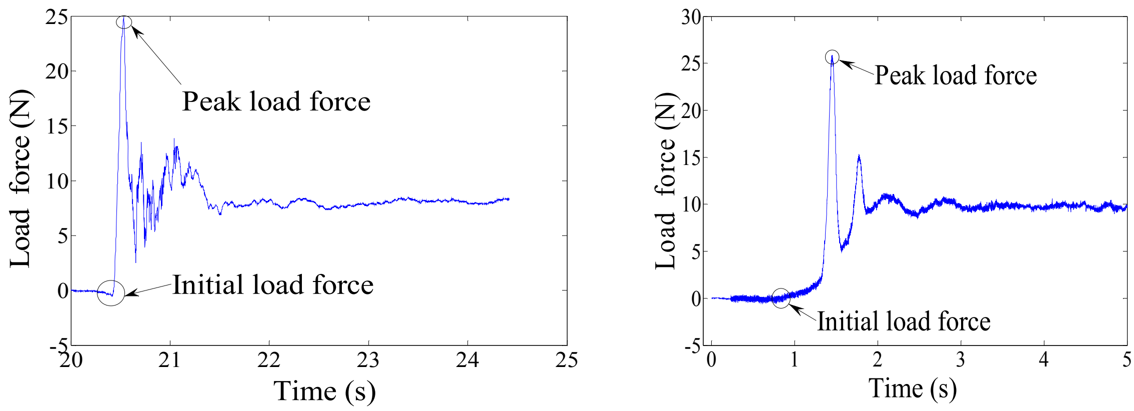

Figure.11 Typical load force time trajectories for MLO and PAO (after properly filtered). Left graph shows the load force time trajectory when a subject lifted a MLO (large size, m =1 kg). Right graph shows the load force time trajectory when the same subject lifted a large size PAO with the PARS at m_1=1kg, m_2=1kg.

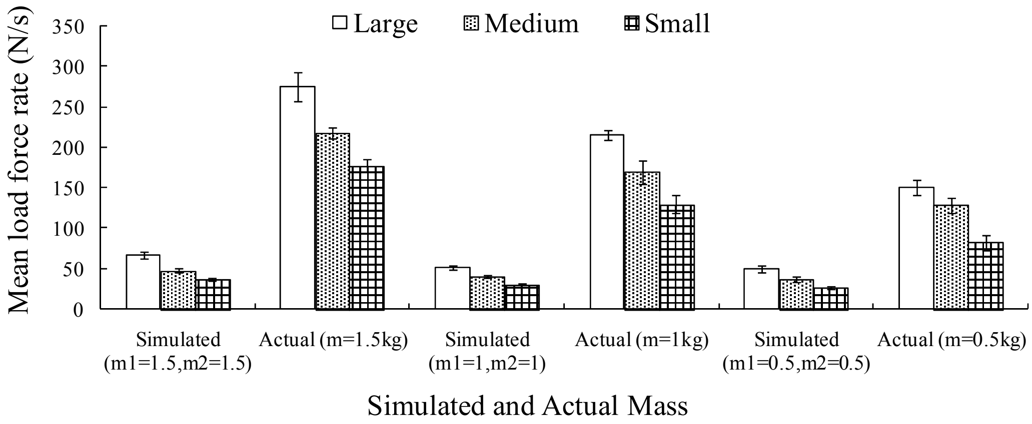

Figure.12 Mean load force rates with standard deviations for simulated (PAO, step 2) and actual (MLO, step1) objects for various mass conditions for different sizes of objects.

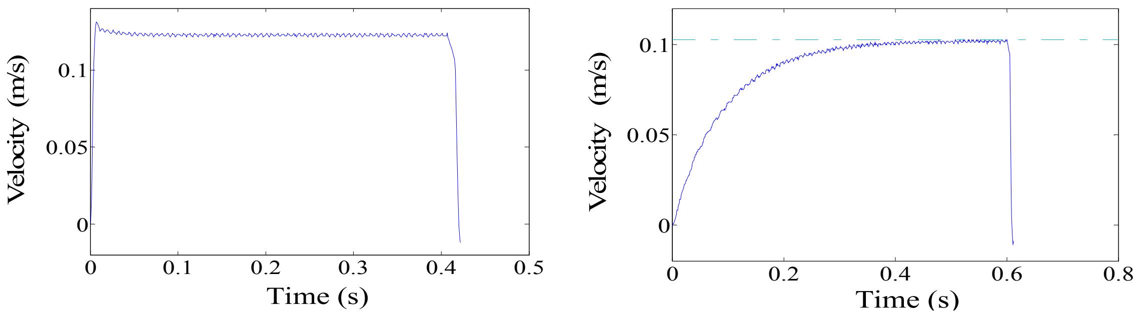

Figure.13 Step voltage responses for different values of T. The left and right graphs show the step voltage responses at T=0 and T=0.095s respectively. The mechanical time constant (hardware time constant) is defined as the time required to reach 63.2% of the final velocity.

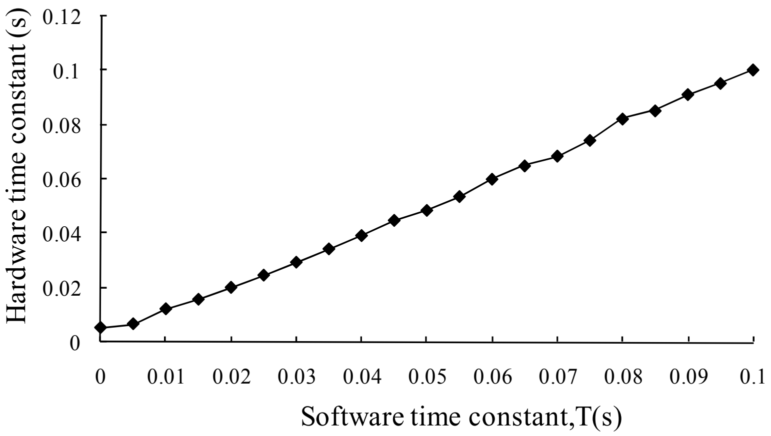

Figure.14 Linear relationship between software and hardware time constant.

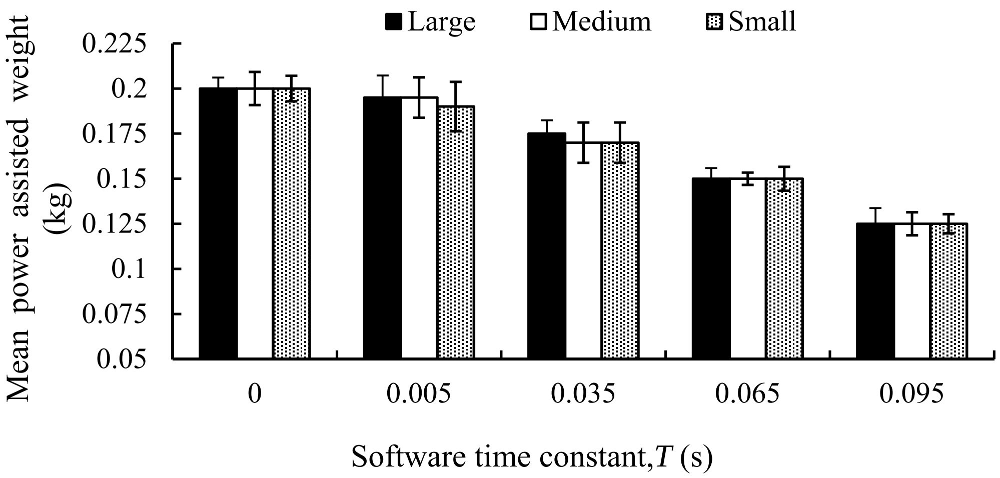

Figure.15 Mean PAWs along with standard deviations for small, medium and large PAOs for different values of *T*.

We may summarize the findings derived in this experiment and then may draw the conclusions. We find that the load force rates decrease with the decrease in object weights (Fig.12). We also find that the PAWs decrease with the increase in *T* (Fig.15). We also see that the load force rates decrease with the increase in *T* (Fig.17). If we consider these together, we can find that the heaviness of objects lifted with the PARS is related to the load force rates. It means that the higher mechanical time constant lowers the load force rates and the lower load force rates produce the feeling of reduced heaviness of the objects. Hence, the mechanical time constant is a cause that affects the perceived heaviness of objects lifted with the PARS. Again, it was found that the PLFs reduce due to the increase in *T* (Fig.16). We think that the reduced PLF is not the cause of the reduced heaviness of an object lifted with the PARS; rather it is the effect of the reduced heaviness due to higher mechanical time constant. Hence, we may conclude that the higher mechanical time constant lowers the load force rates, the lower load force rates produce the feelings of reduced heaviness and the reduced heaviness results in the reduced PLFs when lifting objects with the PARS.

V. EXPERIMENT 2: OPTIMIZATION OF MOTION AND PERCEIVED HEAVINESS

a. Hypothesis

We found in experiment 1 that PAW is related to load force rate. The hypothesis of experiment 2 was to know whether or not the load force magnitude and load force rate affected the system characteristics and human-robot interactions differently.

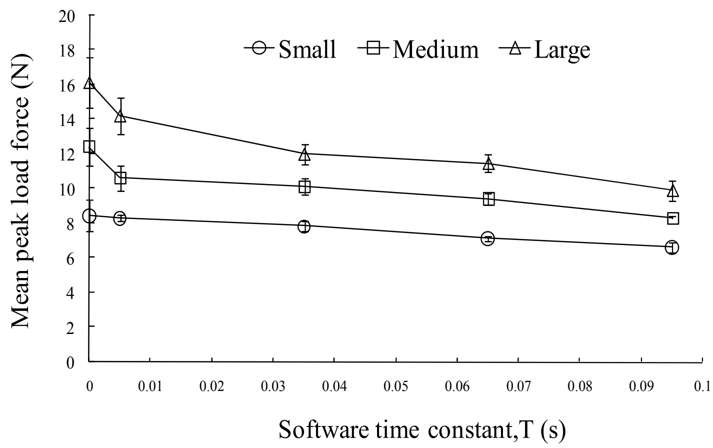

Figure.16 Mean PLFs along with standard deviations for small, medium and large PAOs for different values of *T*.

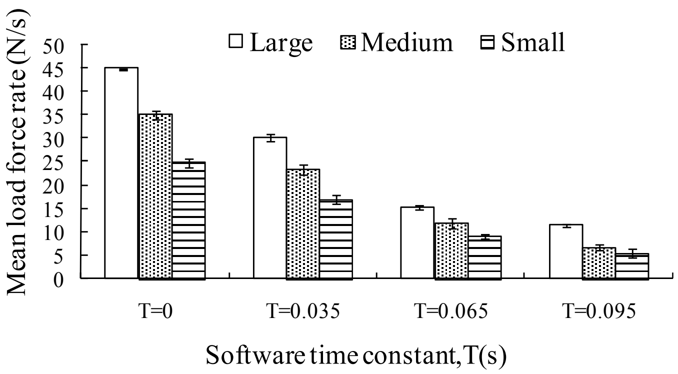

Figure.17 Relationship between software time constant and load force rates for different sizes of objects.

b. Experiment Procedures

Experiment 2 was divided into 4 steps based on 4 distinct conditions. We simulated the system shown in Fig.8 for the following conditions.

Condition 1: m_1=0.5, m_2=0.5, $T=0$

Condition 2: m_1=0.5, m_2=0.5, T=0.095

Condition 3: $m_1=6 * e^{-6t}+0.5$, m_2=0.5, T=0

Condition 4: $m_1=6 * e^{-6t}+0.5$, m_2=0.5, T=0.095

In each condition, all the subjects independently lifted three different sizes of PAOs with the PARS. The subjects subjectively estimated the PAWs for each trial in each condition by comparing the PAWs to the reference weights. The experimenter recorded the load force and position data for each trial in each condition.

$m_1=6 * e^{-6t}+0.5$ was determined in our previous research [27], where we found a linear relationship between m_1 and PLFs and we introduced a novel control strategy based on this relationship. The novel control was such that the value of m_1 exponentially declined from a large value to 0.5 when the subject lifted the PAO and the magnitude of the command velocity ($\dot{x}_c$) exceeded a threshold. As m_1 was proportional to PLF, reduction in m_1 also reduced the PLF proportionally. However, reduction in m_1 did not affect the PAWs [27].

The reasons/background for choosing the 4 conditions are as the following. The 4 conditions were selected to compare the system characteristics and human features among 4 best possible conditions derived in 4 distinct experimental protocols. The comparisons were done in terms of perceived weights, load forces and object's motions. Condition 1 produced very high maneuverability, very low load forces and perceived heaviness in our previous experiment [22]. Condition 2 produced the lowest perceived weights, load forces and load force rates in experiment 1 of this paper. Condition 3 reduced the peak load forces and thus improved the system performances by applying a novel control strategy in our previous research [27].However, the effects of time constant were not considered. Experiment in condition 4 was conducted to reduce the peak load forces by applying the novel control strategy as well as to see the combined effects of the novel control and of the time constant.

VI. RESULTS OF EXPERIMENT 2

We determined the mean peak load forces, PAWs and mean load force rates with standard deviations for different sizes of objects for different conditions as shown in Fig.18, Fig.19 and Fig.20 respectively. Fig.18 and Fig.19 jointly show that the pattern of the PLF characteristics for the 4 conditions (Fig.18) does not match with that of the PAWs (Fig.19). Hence, it may be concluded that the PAW is not related to the PLF magnitude when lifting objects with the PARS. It means that the magnitude of the PLF does not affect the perceived weight (heaviness) of the object lifted with the PARS i.e., reduced PLF does not reduce perceived weight; rather the reduced heaviness may reduce the PLFs. However, the magnitude of the PLF may affect the motion (acceleration) of the object lifted with the system that we discussed in section I. We determined the mean peak accelerations based on the acceleration time trajectories for each size object in each condition and found as shown in Fig.21 that the reduction in the PLFs in four experiment conditions in Fig.18 also reduced the peak accelerations as well [27]-[28].The results show that the patterns of PLF (Fig.18) and peak acceleration (Fig.21) match with each other. On the other hand, Fig.19 and Fig.20 jointly show that the pattern of the load force rates for the four conditions (Fig.20) matches with that of the PAWs (Fig.19). Hence, it may be concluded that the PAW is related to the load force rate when lifting objects with the PARS. It means that it is the load force rate that affects the perceived weight (heaviness) of object lifted with the PARS.

This experiment proves that the effects of magnitude of PLF and its rate on the performances and characteristics of the PARS for lifting objects are different. The magnitude of PLF affects the motion (acceleration), but the load force rate affects perceived heaviness. Hence, the magnitude of PLF is to be optimized to optimize the motion of the PARS and load force rate is to be optimized to optimize the feeling of heaviness of object lifted with the PARS. As we studied in past, the magnitude of the PLF can be optimized (reduced) by applying a novel control strategy (values of m_1 in conditions 3 & 4) [27].On the other hand, load force rate is related to the mechanical time constant of the robot system as we found in experiment 1. Hence, perceived heaviness can be optimized by optimizing the mechanical time constant. The results of condition 4 show that the exponential reduction of m_1 cancels the effect of higher value of T. It indicates that it may be difficult to optimize both the magnitude of PLF and its rate simultaneously. It means that simultaneous optimization of motion and perceived heaviness may be difficult in practical applications. In that case, modification of condition 4 may help achieve simultaneous optimization of motion and perceived heaviness. The modification may be done by (i) further optimizing the value of m_2, and (ii) using the actuator with higher mechanical time constant. Here, the optimization is proposed to be determined subjectively based on human's feelings [29].

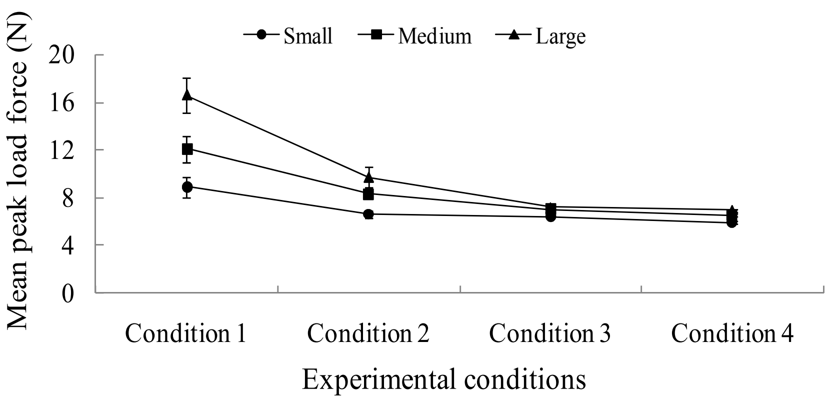

Figure.18 Mean peak load forces with standard deviations for different sizes of objects for different conditions.

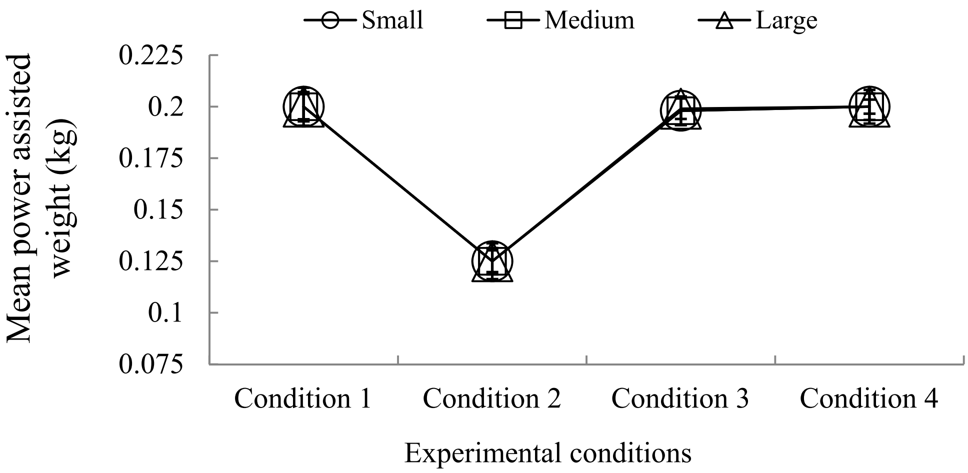

Figure.19 Mean PAWs with standard deviations for different sizes of objects for different conditions.

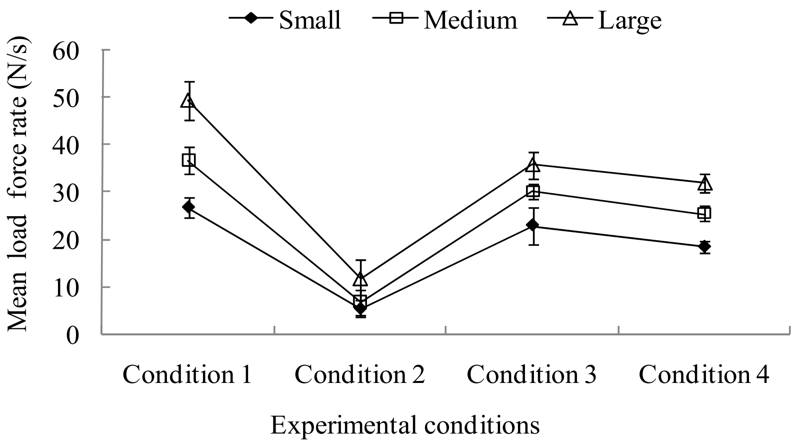

Figure.20 Mean load force rates with standard deviations for different sizes of objects for different conditions.

We also compared the displacement time trajectories between MLOs (experiment 1, step 1, m=0.5kg) and PAOs (experiment 2, condition 1) and found that there was a time delay in position sensing for the PAOs [20].However, the time delay in position sensing was absent or very low for the MLOs. Again, mean peak velocity and peak acceleration for the PAOs were lower than that for the MLOs. We assume that the time delay in position sensing in the PARS may be another cause of reduced heaviness, which will need to be addressed in near future.

VII. DISCUSSION

We kept the servomotor in velocity control mode. Another mode, torque control mode, may be tested to further justify the results. The effectiveness and accuracy of the results may be

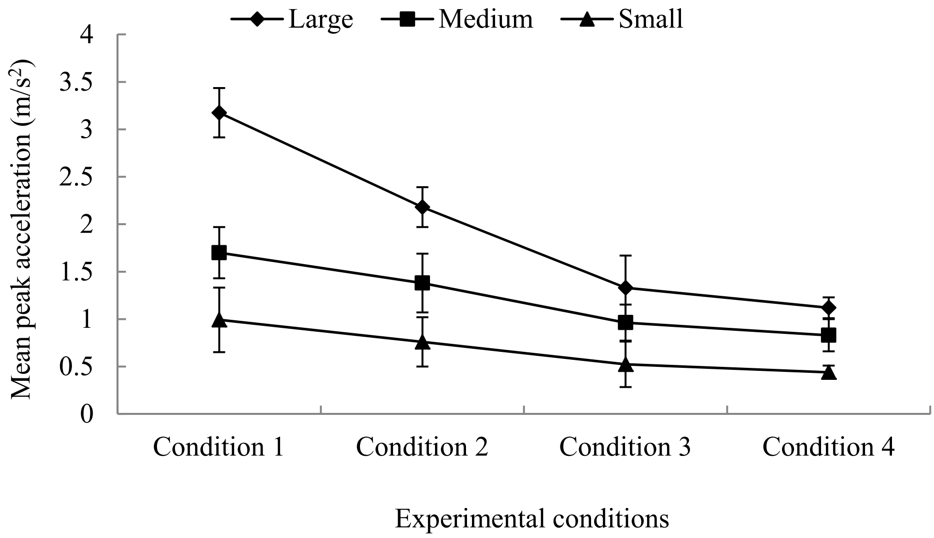

Figure.21 Mean peak accelerations with standard deviations for different sizes of objects for different conditions.

increased by replacing the ball screw by a linear or a direct-drive motor. As the results may depend on back-drivability, mechanical inertia, compliance, friction and servo motor control response delay of the system, these parameters may need to be reflected in the proposed dynamic modeling. In Eq. (1), f_h is the load force applied by the human. Actually, in this system the PARS also provides the force on the object i.e., the actuator force (fa). There may have disturbance (s). However, we did not consider disturbances, fa, friction, viscosity etc. in Eq. (1) because (i) we considered Eq. (1) as the targeted dynamics of the system, (ii) the position control compensates some of these effects, (iii) we wanted to keep the system simple for the time being etc. Consideration of all of these may enhance the accuracy and effectiveness of the results though the present findings are also reliable and useful. Accuracy may be further increased by adding more reference weights, subjects, trials etc.

The findings do not violate the well-established size-weight illusion concepts because the objects of different sizes were lifted independently [30]. Most of the results are based on subjective evaluations instead of objective data. However, we argue that the subjective results are acceptable because (i) it is difficult to collect objective data in a human-robot interaction system, and (ii) this type of subjective results have already been proven reliable in many cases [31]-[36].Again, subject's memory is not transient, rather more stable for estimating perceived weight. Research shows that the sensorimotor memory is fully maintained for a period of 15 minutes and largely retained for 24 hours, even in presence of misleading visual size cues. Hence, the subjects did not forget the perceived weights of the power-assisted object while comparing them with the reference weights, which made the subjective estimation reliable [40].

Though the control is simple the findings are totally novel. The novelties are: (i) we included weight perception in dynamics and control, (ii) we improved the control using a human-features-based control algorithm, (iii) we proposed novelty in power-assist applications, (iv) we brought novelty in experiment objectives and procedures, (v) we analyzed weight perception, motions, forces etc. with novel contexts, (vi) we discovered the relationship between time constant and perceived weight, (vii) we demonstrated how to control motion and perceived heaviness separately and simultaneously, (viii) we applied psychophysical and biomimetic approach to robotic system design etc. It is possible to compare the methods and results derived in this paper to that derived in other similar works. Niinuma *et al.* developed a power assisted system to lift objects [15]. Takubo *et al.* developed a PARS for manipulating objects [16]. Doi *et al.* developed a pneumatic PARS for lifting objects [17].Hara proposed a power-assisted cart system to transfer objects[37] etc. Kazerooni [38] and Hayashi *et al.* [39] proposed power assist systems for object manipulation. However, their system configurations were exoskeleton type, and hence were not suitable for manipulating heavy industrial objects. Again, no research as mentioned above considered human's weight perception, load forces and object's motions to develop and modify the control of the PARS. This is why the aforementioned PARSs could not produce satisfactory interactions between human users and the robots. The novel relationship between mechanical time constant and system characteristics such as perceived heaviness, motions etc. was never addressed by any researcher. Hence, the findings of this paper are novel and significant to optimize the human-robot interactions for power assist robots for manipulating objects.

In (2), we hypothesized that $m_1 \neq m_2 \neq m$, and $m_1 << m$, $m_2 << m$. However, in section d.ii Step 2 we used m_1=1.5, m_2=1.5; m_1=1, m_2=1; m_1=0.5, m_2=0.5. Values of m_1 and m_2 were fixed at m_1=0.5, m_2=0.5 in steps 3 & 4. In fact, we used the same values for m_1 and m_2 in the experiments to compare power-assisted manipulation to manual manipulation at similar conditions. Again, m_1=0.5, m_2=0.5 were derived as the best values for the system in [22]. However, m_1 could be completely different from m_2 for the best values if more values of m_1 and m_2 were used in the simulation [22].Hence, using the same value of m_1 and m_2 in some experiment conditions is not against our hypothesis, and this is different from using only one m because the control programming is different for these two cases.

The values of m_2 used in this paper do not mean the actual masses of PAOs to be manipulated in industries; rather they mean the values that should be used to develop the control for getting satisfactory system characteristics and performances. We could not use a real robotic system and heavy objects, but we used a simulated system, low simulated and actual weights (between 0.5kg and 1.5kg), and small object sizes for the following reasons: (i) we, at this stage, want to reduce the costs of developing the real system because a real system suitable for manipulating heavy objects is expensive [16]-[17], (ii) we want to compare the findings of this paper to that of other psychological experiment results available in literatures, 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 such as naturalness, best feelings etc.) [25]-[26],[30],[40], (iii) we want to use the preliminary findings of this paper (e.g., design ideas, assumptions, hypotheses, dynamic modeling, control programming, system characteristics reflecting human-robot interactions such as relationship between time constant and perceived weights, force and motion characteristics etc.) to develop a real robot capable of manipulating heavy objects in near future [11], [18], [20]-[22],[27]-[29]. We believe that the findings we have derived will work (but magnitudes may change) for heavy and large size objects. It may be true that the findings are incomplete until we validate those using heavy objects and a real robot. But, it is also true that the findings are novel, important, useful and thus have potential for developing real robots for manipulating heavy objects.

There was no possibility of object slip and the subjects did not experience any slip of the objects when doing experiments in the present setup. We think that slip prevention is related to the configuration of the real robot systems. We will configure the real robot system in such a way that the configuration will prevent slipping the objects. We will improve the object grasping devices and its surface conditions (friction) for the real system so that slip does not occur. However, operator's training and awareness are also important to prevent slip.

We put m_2=0.5kg in the experiment and the human who lifts the object with the system feels 40% of m_2 value, i.e. 0.2kg [27]. It means that the human will feel only 0.2kg even when he will lift a very heavy object (such as 20kg) with the real system in industry because the load will be carried by the robot system (not by the human) and human's cooperation (grasping and applying forces) will control the motions (displacement, velocity, acceleration) of the lifted object. Hence, it will be possible for the human to lift heavy objects with only one hand and the whole body will not need to be used. This is the benefit of the power assist system that it reduces human's burden and makes the works easy. Use of one hand or two hands, lift posture and lift start position definitely affect the results, and the results are slightly different for these variations. However, the differences are not very high as we found in another research [27]. We suggest that appropriate grasping method (one hand or two hands), lift posture and lift start position should be decided and adjusted for particular tasks considering the task requirements.

Seki *et al.* [19] introduced some basic requirements of a general PARS. However, we think that the required conditions for an industrial PARS to manipulate heavy objects in industries may be identified with a broader perspective as the following: (i) perceived heaviness should be optimum, (ii) manipulative force (load force) should be slightly larger than the perceived heaviness, (iii) motions, maneuverability, stability, safety, naturalness, ease of use, comfort (absence of fatigue), situational awareness of user, system efficiency, manipulating speed etc. should be optimum, (iv) the PARS should be enough flexible to adjust with objects of different shapes, sizes, weights etc., (v) objects can be manipulated with the system in various DOFs such as vertical, horizontal and rotational, (vi) the PARS should produce satisfactory performances even in worst-cases, uncertain, rapid changing situations, disturbances etc., (vii) the PARS should satisfy operator's biomechanical requirements etc. It is assumed that the optimum heaviness and motion as derived in this paper will play the pivotal role to satisfy these requirements. The results of this paper along with our previous works related to the development of power assist devices and the investigations on human characteristics as well as our future extension works are to satisfy all of the design requirements for the proposed industrial robotic system [27],[32].

VIII. CONCLUSIONS AND FUTURE WORKS

We developed a 1 DOF PARS for manipulating objects. We analyzed weight perception, load force and its rate, object motion etc. for lifting objects manually and with power-assist and successfully determined a relationship between mechanical time constant and perceived heaviness. Relationships among perceived heaviness, load force and its rate, and motion were determined. It was proved that motion is related to load force magnitude, and perceived heaviness is related to load force rate. Therefore, techniques to optimize motion and perceived heaviness independently and simultaneously were demonstrated. This paper thus brings novelty in the applications of power assist robots, applies bionic and psychophysical approaches to power assist robot design and includes human features in robot dynamics and control to improve system performances and human-robot interactions in terms of maneuverability (perceived heaviness), motion, safety etc.

The results were derived following bionic approaches as the knowledge on human characteristics was used to suggest improving the robot performances. Psychophysics was used that determined relationships between physical stimuli and sensory responses. All the hypotheses adopted were addressed properly. The results are novel in fields of robotics and can contribute to develop human-friendly power assist robots for manipulating heavy objects in industries that would optimize interactions between human users and robots.

We will verify and validate the results using heavy objects and real robots in near future. Experiments in torque control mode of the servomotor as well as with a direct-drive motor will be conducted to verify the results. The system will be upgraded to a real multi-DOF system and the results will be investigated for other DOFs. The results will be theoretically analyzed and mathematical reasoning behind each empirical finding will be searched.

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