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A Psychophysical Model of the Power Assist System for Lifting Objects

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

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

I. INTRODUCTION

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

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

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

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

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

II. THE EXPERIMENTAL POWER ASSIST SYSTEM

A. Construction of the Power Assist System

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

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

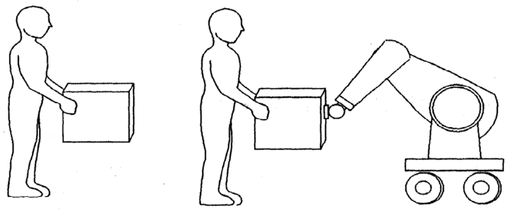

Fig.1. In the left side, a human lifts an object manually. In the right side, the same human lifts the same object with a power assist robot. When the human lifts the object manually, he/she feels the actual weight of the object. We consider the load force, $f_h = m\ddot{x} + mg$ as the desired dynamics for lifting objects manually, where m is the actual mass of the object and x is the displacement of the object. Here, human uses the same mass parameter (m) for programming the inertial force ($m\ddot{x}$) and the gravitational force (mg) because the perception and the reality regarding the object weight are same in this case. On the contrary, when the human lifts the same object with the power assist robot, he/she does not feel the actual weight of the object, rather he/she feels a scaled down portion of the weight. Hence, if the human programs the inertial and the gravitational forces based on m, the load force would be too excessive and the excessive load force would give excessive motion to the power assist robot. We hypothesize that, human's perception of object weight due to inertial force may be different from the perceived weight due to gravitational force for lifting object with the power assist robot. Hence, human must consider the mass parameter for the inertial force different from that for the gravitational force and both of the mass parameters should also be considered smaller than the actual mass of the object (m). It means, the desired dynamics for lifting objects with the power assist robot should be $f_h = m_1\ddot{x} + m_2 g$; where m_1 is the mass of the object to be used to program the inertial force, m_2 is the mass of the same object to be used to program the gravitational force, $m_1 \neq m_2 \neq m$, $m_1 \ll m, m_2 \ll m$ and hence $m_1\ddot{x} \neq m_2 g$.

Fig.2. The left photo, from left to right, shows the front sides of the large, medium and small power assisted object respectively. The right photo, from left to right, shows the back sides of the large, medium and small power assisted object respectively. Two rectangular metal pieces with hole in the center of each are attached with the interior of the left and right sides of each box. The holes help the box be tied with the force sensor of the system.

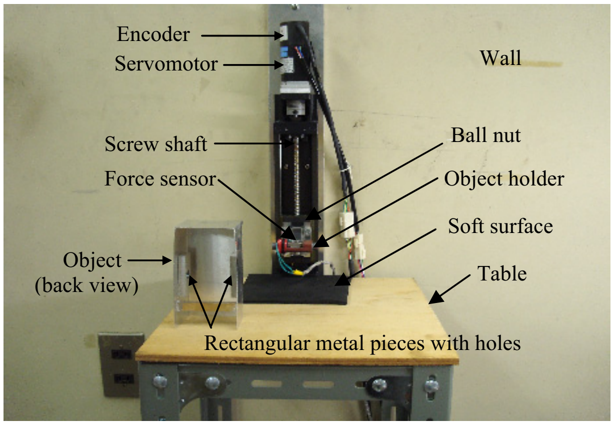

Fig.3. Various components of the main power assist device. The back view of the object (box) is also seen in the figure. Two rectangular metal pieces with hole in the center of each are attached with the interior of the left and right sides of each box. The holes help the box be tied with the force sensor through the object holder.

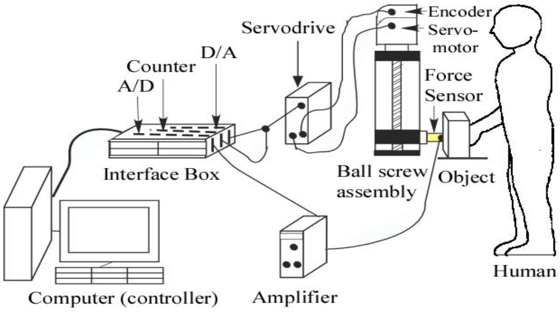

Fig.4. Experimental set-up of the complete 1DOF power assist system.

B. Dynamic Modeling of the Power Assist System

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

$$m\ddot{x}_d + mg = f_{h.} \tag{1}$$

Where,

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

According to basic physics, the local effects induced by gravity and acceleration on load force are identical and cannot be separated by any physical experiment, but Zatsiorsky *et al.*

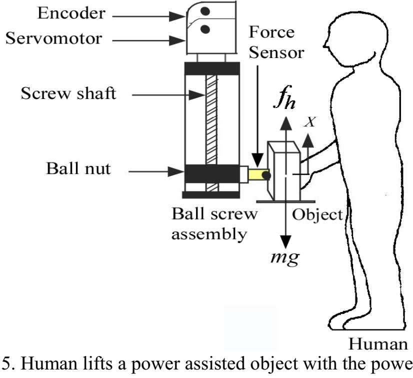

Fig.5. Human lifts a power assisted object with the power assist system.

disproved it [10]. However, Zatsiorsky *et al.* did not address whether or not the human possesses any perceptual differences between the mass parameters of the gravitational and the inertial forces. As an attempt to introduce the weight perceptual consideration in the dynamic modeling of the power assist system, we hypothesized (1) as (2), where $m_1\ddot{x}_d$ refers to inertial force and $m_2 g$ refers to gravitational force.

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

Both m_1 and m_2 stand for mass. In our hypothesis, m_1 forms inertial force and m_2 forms gravitational force. Difference between m_1 and m_2 arises due to the difference between human's perception and reality regarding the weight of the object lifted with the power assist system.

Usually, $m_1 = m_2 = m$ is considered for all psychological experiments, but we hypothesized that, $m_1 \neq m_2 \neq m$, $m_1 \ll m$, $m_2 \ll m$, and hence $m_1\ddot{x}_d \neq m_2 g$ would be considered by the human while lifting an object with the power assist system. The human makes a mistake when lifting an object with the power assist system because the human considers that the actual weight and the perceived weight are equal. The hypothesis means that the human makes the mistake because the human considers that the two 'masses' used in inertial and gravitational forces are equal to the actual mass of the object ($m_1 = m_2 = m$). In order to realize a difference between the actual weight and the perceived weight, the human needs to think that the two 'masses' used in inertial and gravitational forces are different and less than the actual mass of the object ($m_1 \neq m_2 \neq m, m_1 \ll m,\ m_2 \ll m$) . We derived (3), (4) and (5) from (2).

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

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

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

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

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

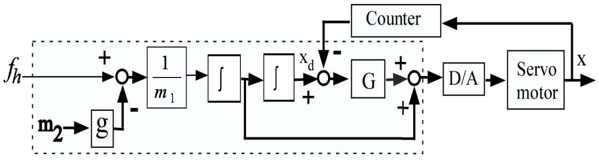

Fig.6. Block diagram of the control system of the power assist system. G denotes feedback gain, D/A indicates D/A converter, ∫ refers to integral and x denotes the actual displacement. Feedback position control method is used for this system. The servomotor is in velocity control mode.

III. EXPERIMENTS

A. Experiment 1:Determination of Optimum Gravitational Mass (m_2)

1) Objectives

The first objective of this experiment was to psychophysically determine the optimum gravitational mass (m_2) for the dynamics of the power assist system based on operator's weight perception that would provide optimum maneuverability, safety, naturalness etc. of the system. The second objective was to study the feasibility of zero-gravity (m_2=0) condition for lifting objects with the system.

2) Subjects

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

3) Design of Experiment

The independent variables of this experiment were m_2 and visual size of object. The dependent variables were maneuverability and peak load force.

4) Method

In this experiment, we simulated the system shown in Fig.6 using MATLAB. We fixed the value of m_1 at 0.5. The value of m_1 was fixed because m_1 does not affect weight perception and maneuverability [9].However, we changed the values of m_2.The values of m_2 were 0.5, 0.45, 0.4, 0.35, 0.3, 0.25, 0.2, 0.15, 0.1, 0.05 and 0.The values of m_2 higher than 0.5 were not considered because those values would not produce optimum maneuverability [9].During this experiment, following a demonstration by the experimenter, the subject lifted the object with the power assist system only one time for each value of m_2 separately. The experimenter randomly set the value of m_2 and strictly maintained its confidentiality. While lifting the object for a particular value of m_2, the subject subjectively evaluated how he felt to lift the object for that particular value of m_2 and then rated (scored) his feelings of maneuverability as any one of the following rating alternatives of a 7-point bipolar & equal-interval subjective rating scale [11]: (i) Undoubtedly best (score: +3), (ii) Conspicuously better (score: +2), (iii)Moderately better (score: +1), (iv) Alike (score: 0), (v) Moderately worse (score:-1), (vi) Conspicuously worse (score:-2), and (vii) Undoubtedly worst (score:-3).

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

All five subjects rated their feelings regarding the maneuverability of the system for objects of three different sizes (small, medium, large) independently for each value of m_2. Force data for each trial were also saved separately.

B. Experiment 2: Determination of Optimum Inertial Mass(m_1)

The objective of this experiment was to understand the effects of m_1 on system stability and to determine the optimum value of m_1 from the stability point of view. This experiment was conducted by only one subject using only one object (medium size).The independent variable of this experiment was m_1 and the dependent variable was stability of the system.

In this experiment, we simulated the system shown in Fig.6 using MATLAB. The value of m_2 was fixed at 0.05.The experimenter sequentially changed the value of m_1 in a descending order staring from 0.5 and ending to 0 while always maintaining an equal difference of 0.05 between two adjacent values of m_1.During each trial of lifting, the experimenter set the value of m_1 and then the subject lifted the object approximately 0.1 meter, maintained the lift for 1-2 seconds and then released the object. During each trial of lifting, the subject subjectively checked whether or not there were any oscillations. In this experiment, absence of oscillations was considered as the criterion of system stability. The subject also examined the severity of the oscillations.

IV. RESULTS AND ANALYSES

A. Results of Experiment 1

We calculated the means of the scores of the 5 subjects for each maneuverability criterion for each value of m_2 for each size of object separately. Means (n=5) of the scores for the maneuverability criteria with standard deviations for different values of m_2 for the medium size object are shown in Fig.7. The figure shows that, humans enjoy the highest level of mobility, positioning and naturalness as well as the least fatigue in hand muscle for m_2=0.05 condition. Motion control for m_2=0.05 condition is also satisfactory. We also see that for zero-gravity condition (m_2=0), positioning, motion control and naturalness are lower than that for m_2=0.05 and m_2=0.1 conditions. Hence, we decided 0.05 as the best value of m_2 for the dynamics of the power assist system for lifting objects.

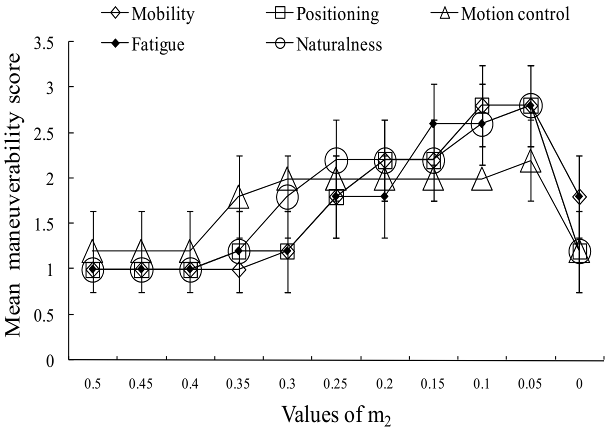

Fig.7. Means (n=5) of the scores for the maneuverability criteria with standard deviations for different values of m_2 for the medium size object.

Two-way (visual size of object, subject) analyses of variance (ANOVAs) were performed on the evaluation scores for each maneuverability criterion separately for each value of m_2.Total number of ANOVAs was 5 x 11=55.The results show that the effects of visual sizes of objects on maneuverability were not significant ($F_{2,8}$<1 for each case).However, variations in haptic size cues might affect the maneuverability. Again, variations in maneuverability scores between the subjects were at all not significant ($F_{4,8}$<1 for each case). It means that the findings may be used as a general model.

The results in Fig.7 show that positioning, motion control and naturalness are lower for zero-gravity condition (m_2=0). Again, fatigue and reduction in mobility may be caused for zero gravity condition due to numbness in hand muscle. These problems occur for the zero-gravity condition because the humans lose some haptic information for the zero-gravity condition that reduces humans' weight perception ability [12], [13]. On the other hand, the larger values of m_2 do not produce expected mobility, positioning, motion control and naturalness because the objects always show a tendency to go downward for comparatively larger values of m_2. Again, the larger values of m_2 may produce fatigue in hand muscle.

We derived the peak load force for each trial and determined the means of the peak load forces of the 5 subjects for each value of m_2 for different sizes of objects separately. Mean peak load forces with standard deviations for different values of m_2 for different sizes of objects are shown in Fig.8.The figure shows that peak load forces decrease with the decreases in the values of m_2.The peak load forces are the least for m_2=0.05 condition. The reduced peak load forces for m_2=0.05 condition optimize the motions and maneuverability and ensure human's safety when lifting objects with the system. Peak load forces are proportional to object sizes [14].

Two-way (visual size of object, subject) ANOVAs were performed on the peak load forces for m_2=0 and m_2=0.05 conditions separately. The results show that the effects of

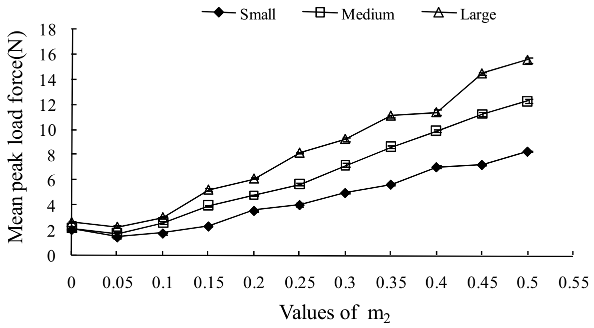

Fig.8.Mean (n=5) peak load forces with standard deviations for different values of m_2 for different sizes of objects.

visual sizes of objects on peak load forces were highly significant ($F_{2,8}$=122.19, $p<0.01$ for m_2=0; $F_{2,8}$=117.85, $p<0.01$ for m_2=0.05).However, variations in peak load forces between subjects were not significant ($F_{4,8}$=0.36 for m_2=0; $F_{4,8}$=1.10, $p>0.1$ for m_2=0.05).

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

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

B. Results of Experiment 2

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

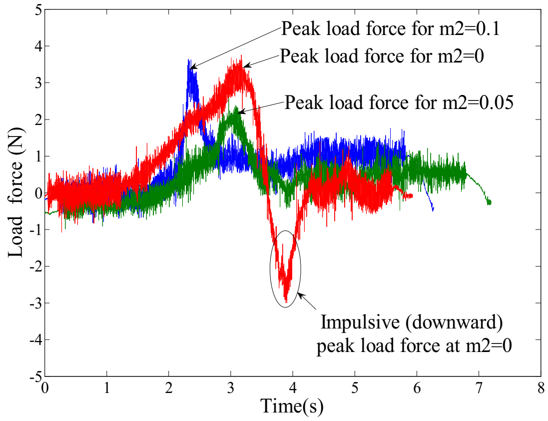

Fig.9. Time trajectories of the load forces for m_2=0.1, 0.05 and 0 conditions for a representative subject for the large object. The impulsive and irregular nature of the peak load force at zero-gravity (m_2=0) is also shown (encircled).

TABLE I. OSCILLATIONS AT DIFFERENT INERTIAL MASS

Value of m_1	**Results**	**Remarks**
0.5	No oscillations	Acceptable value of m_1
0.45	No oscillations	Acceptable value of m_1
0.4	No oscillations	Acceptable value of m_1
0.35	No oscillations	Acceptable value of m_1
0.3	No oscillations	The optimum value of m_1
0.25	Oscillations start	Unacceptable value of m_1
0.2	Oscillations	Unacceptable value of m_1
0.15	Strong oscillations	Unacceptable value of m_1
0.1	Severe oscillations	Unacceptable value of m_1
0.05	Not examined	Unacceptable value of m_1
0	Not examined	Unacceptable value of m_1

C. The Combined Results of Experiment 1 and 2

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

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

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

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

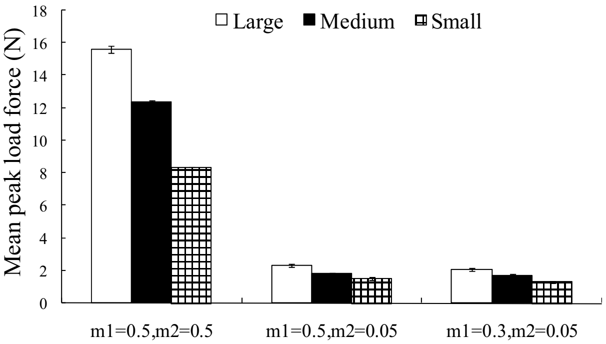

Fig.10. Mean peak load forces with standard deviations for a) m_1=0.5, m_2=0.5, b) m_1=0.5, m_2=0.05, and c) m_1=0.3, m_2=0.05 for different objects.

load forces. The peak load forces are also proportional to object sizes [14].

V. GENERAL DISCUSSION

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

The findings of experiment 1 (i.e.,m_2=0.05 as the optimum) provide optimum perceived heaviness, maneuverability, ease of use etc. while lifting objects with the system. This experiment also reduces the peak load forces that optimize the motions of the objects lifted with the system. The experiment 2 ensures the stability of the system. The combined results of the two experiments further reduce the peak load forces that may further optimize the motions. The optimized motions may help avoid injuries, risks, vibrations and jerks on human body when lifting objects with the system and thus may ensure human's safety while working with the system. Here, the optimality has been determined heuristically and subjectively based on human's feelings and experiences. Hence, the findings associate with the objectives of the research.

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

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

VI. CONCLUSION

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

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