Human Operator's Weight Perception of an Object Vertically Lifted with a Power Assist System

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***Abstract*—**This paper attempts to design a power assist system for maneuvering heavy objects in industries based on human operator's perception of object weight. The perceived weight of an object maneuvered with a 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 forces in accordance with the actual weight of the object. This faulty force programming gives faulty motion to the power assist system and jeopardizes its maneuverability, ease of use, human-friendliness, safety etc. The research presented herein, firstly, subjectively determines the optimum maneuverability conditions for lifting objects with a power assist system, secondly, establishes a psychophysical relationship between the actual weights of objects and the perceived weights of the same objects by human operators when the objects are vertically lifted with the power assist system as well as analyzes human's manipulative force characteristics for lifting objects with the system, thirdly, compares human's manipulative force characteristics for lifting power assisted objects with that for lifting actual objects, and finally, attempts to use these findings to design the feedback position control law for the power assist system. This type of psychophysical considerations with power assist system enhances maneuverability, operability, ease of use, human-friendliness, safety etc. of the system in an optimal fashion.

Keywords: *power assist system, feedback position control, maneuverability, psychophysics, weight perception.*

I. INTRODUCTION

With the turn of the twenty first century, the barriers between robots and humans are falling. In the near future, many aspects of our lives will be encompassed by tasks performed in cooperation with robots. The applications of robots in home automation, industrial production, mining, agricultural production, logistics and transportation, medical operations, rehabilitation etc. will be indispensable. As a result, robots need to be made human-friendly and to execute tasks in cooperation with humans [1]. Power assist system is one of the very latest types of human-robot cooperation. 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 and hence suitable power assist systems for maneuvering heavy objects in industries are still demanding. Again, it is experienced that, when an object is maneuvered with a power assist system, velocity of the object is proportional to the forces applied on the object by the human operator. Human operator's anticipatory force programming depends on how the operator perceives the weight of an object before it is lifted. Theoretically, a power assist system always makes an object lighter to maneuver through lowering the required forces applied by human by dint of control law. For this reason, the weight of an object perceived by the operator while maneuvering it with a power assist system is always very much less than the actual weight of the object. This is why, the forces required to carry an object with a power assist system are supposed to be lower than the forces required when the object is not carried with a power assist system. But, the human operator cannot differentiate between the perceived weight of an object carried with a power assist system and the actual weight of the object especially during the initial trials of lifting and eventually applies forces in accordance with the actual weight of the object. The operator may be slightly able to guess the weight of the object after repeated trials of lifting, but it cannot be accurate and natural. Moreover, it imposes extraneous cognitive work load on the operator. As a result, the applied forces by the operator are incorrect and this incorrect force programming causes many problems such as velocity of the object suddenly becomes very high, the operator becomes fearful while maneuvering the object, the object may not be maneuvered to the desired location, the system may lose maneuverability as well as stability, the system may cause fatal accident etc.

The aforementioned practical problems are experienced with almost all types of power assist systems directly or indirectly. We hypothesize that, these problems are experienced because the psychophysical and cognitive aspects especially human operator's weight perception are not being considered in the design and control of power assist systems. Though several control methods for power assist systems have already been developed, control methods that consider human characteristics and weight perception in order to make human-friendly power assist systems for maneuvering heavy objects are usually not seen. This paper attempts to design a 1DOF (vertically up-down) power assist system for lifting heavy objects in industries based on human characteristics especially human's perception of object weight and manipulative force programming.

II. EXPERIMENTAL DEVICE

A. Construction of the Power Assist System

A simple 1DOF power assist system was developed using a 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 using nuts and bolts and the board was vertically attached with the wall. An object, at a time, could be tied with the ball nut (linear slider, load carrier) of the ball screw assembly through a force sensor (foil strain gage type, NEC Ltd.) and be lifted by a human. Three rectangular boxes were made by bending aluminum sheet (thickness: 0.5 mm) and were used as the objects. The dimensions (length x width x height) of the boxes 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 that resulted in a volume ratio of 1:1.4:1.86. 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. The object tied with the force sensor was to keep on the soft surface of a table before it was lifted. Pitch, shaft length and linear speed of the screw were 0.003 meter, 0.2 meter and 9 meter/minute respectively. The height of the object from the floor was adjusted according to the neutral posture (best work zone) conditions of OSHA guidelines [3]. The objects were very light and hence the system was free from vibration. The detailed construction is illustrated in Fig.1. Experimental set-up of the system is depicted in Fig.2. Additionally, a noise filter (Type: LF-205A) was mounted to prevent electrical noises from the power supply line. The computer gave 16-bit BUS data.

B. Dynamic Modeling of the Power Assist System

According to Fig.3, the equation of motion of the system (real system) can be derived as the following:

$$m\ddot{x} + K\dot{x} + mg + F = f_a + f_h. \quad (1)$$

But, the actual (targeted) system works as the following:

$$m\ddot{x} + mg = f_h. \quad (2)$$

Where, $m\ddot{x}$ = inertia force and mg = gravity force.

The variables in (1) and (2) are defined as the following:

f_a = Actuating force of the servomotor
f_h = Vertical lifting force applied by human operator
F = Friction force in ball screw assembly
K = Viscosity of the linear slider
m = Mass of the object
x = Linear displacement of the object.

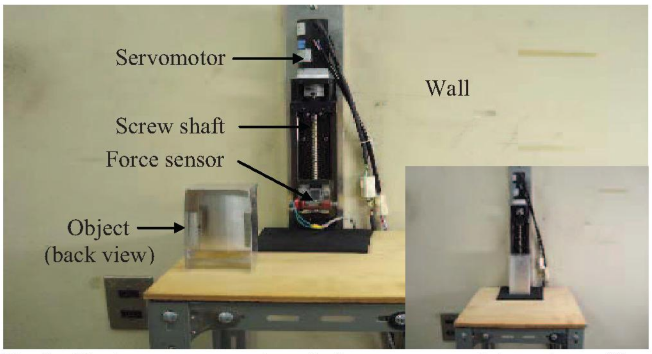

Fig.1: Various components of the power assist system. The complete system is also inset right.

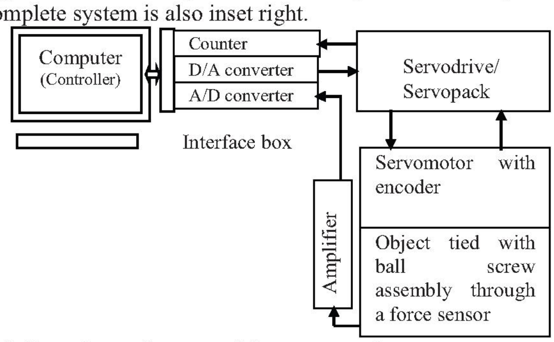

Fig.2: Experimental set-up of the power assist system.

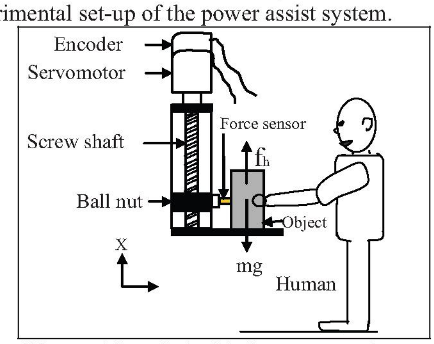

Fig.3: Human lifts an object tied with the power assist system.

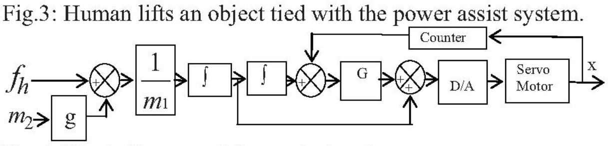

Fig.4: Block diagram of the control system.

According to basic physics, the local effects induced by gravity and acceleration are identical and cannot be separated by any physical experiment. But, Zatsiorsky V.M. et al. [4] proved experimentally that, for lifting tasks, people can recognize the effects of the gravitational and inertial force components differently. Nevertheless, their research possesses some limitations such as their research does not give any idea about the internal relationship between the gravity force and the inertia force themselves, especially their research does not address whether the human possesses any perceptual difference between the realization processes of the gravity and inertia force components. As an attempt to introduce the psychophysical considerations in dynamic modeling of the power assist system, we hypothesize (2) as the following:

$$m_1\ddot{x} + m_2 g = f_h. \quad (3)$$

Where, $m_1\ddot{x}$ = inertia force and $m_2 g$ = gravity force.

$m_1 = m_2 = m$ is considered for all the psychological experiments [4], but we think that, $m_1 = m_2 \neq m$ or $m_1 \neq m_2 \neq m$ and hence $m_1\ddot{x} \neq m_2 g$ as perceived by the operator while lifting an object with a power assist system. We hypothesize that, human commits a wrong by considering the actual weight and the perceived weight same. We also hypothesize that, human considers the actual weight and the perceived weight same as the human considers the two 'masses' used in both inertia force and gravity force same. In order to realize a difference between the actual weight and the perceived weight, the human operator needs to think the two 'masses' different before applying force (feedforward or anticipatory force) to the power assist system. Block diagram of the control system based on (3) is shown in Fig.4, where G denotes gain, D/A indicates D/A converter and $\int$ refers to integral. Control method used for this system is feedback position control method. The servomotor is in velocity control mode.

III. EXPERIMENTS AND RESULTS

A. Experiments

Equation 4, derived from (3), was adopted as the control law and was simulated in MATLAB (The MathWorks Inc.) environment for various sets of values of m_1 and m_2.

$$\dot{x} = \int \frac{1}{m_1}(f_h - m_2 g)dt. \qquad (4)$$

During simulation, values of m_1 and m_2 were set randomly from Table 1 that contains 12 sets of values of m_1 and m_2.

Table 1: Values of m_1 and m_2

m_1	m_2		
2	0.5	1	1.5
1.5	0.5	1	1.5
1	0.5	1	1.5
0.5	0.5	1	1.5

Five mechanical engineering students of Mie University, aged between 22 and 28 years, 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.

1) Experiment 1: System Evaluation

This experiment evaluates the maneuverability of the power assist system. Some basic requirements of a power assist system regarding its maneuverability have been mentioned in [5].However, we think that only the light (less force required), natural, human-friendly and safe system can render the consistent feelings of ease of use and comfort, though too much light system may be unsafe, uneasy and uncomfortable. Hence, we finally considered operator's ease of use and comfort as the evaluation criteria for maneuverability of the power assist system. In this experiment, following a demonstration by the experimenter, the subject lifted an object of a particular size with the power assist system only one time for each set of values of m_1 and m_2.The experimenter randomly set the values of m_1 and m_2 and strictly maintained its confidentiality. 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 following a demonstration of the experimenter. The time between consecutive lifts was approximately 50 seconds. While lifting the object for a particular set of values of m_1 and m_2, the subject subjectively evaluated how he felt to lift the object for that particular set of values of m_1 and m_2 and rated his feelings of maneuverability as any one of the following 5 rating alternatives. Maneuvering the object was:

1. Very Easy & Comfortable (score: +2)
2. Easy & Comfortable (score: +1)
3. Borderline (score: 0)
4. Uneasy & Uncomfortable (score: -1)
5. Very Uneasy & Uncomfortable (score: -2).

All five subjects rated their feelings regarding the maneuverability of the system for objects of three different sizes (small, medium, large) independently for each set of values of m_1 and m_2. Force and displacement data for all trials were also saved. The subjects' ratings as per the aforementioned 5-point bipolar & equal-interval subjective rating scale [6] were then analyzed and 'mean maneuverability scores' for the system at each set of values of m_1 and m_2 were determined. When a subject lifts an object tied with the power assist system, we call this object a 'power assisted object'. During this experiment, the whole experimental device of the power assist system except the 'power assisted object' was covered with a piece of cloth. Hence, the subject saw the 'power assisted object' only and could not realize the power assist system behind the object.

2) Experiment 2: Weight Comparison

This experiment searched a psychophysical relationship between the actual weight and the perceived weight of object lifted with the power assist system. The simulated weight (m_2) of the 'power assisted object' was its actual weight and when the simulated weight was perceived by the subject while lifting the object, then it was the perceived weight. Besides the three 'power assisted objects' of three different sizes, three actual objects (boxes) of three different sizes (small, medium, large) were also made. The actual objects were usual objects and were not physically connected to the power assist system in any way. The shape, dimensions, material and outlook of an actual object of a particular size were same to that of the 'power assisted object' of that particular size. Hence, the subject did not see any visual difference between the 'power assisted object' and the actual object of a particular size. However, it was possible to change the weight of an actual object by attaching various masses across the interior of the front side of the object. During this experiment, the weight of the actual object of a particular size was sequentially changed in a descending order starting from 1.5 kg and ending to 0.1 kg while always maintaining an equal difference of 0.1kg (1.5kg,1.4kg,1.3kg,.... 0.3kg,0.2kg,0.1kg). These 15 weights of an actual object of a particular size were treated as the reference weights. For each set of values of m_1 and m_2 for a particular object size, the subject lifted the 'power assisted object' one time following a demonstration of the experimenter, maintained the lift for 1-2 seconds at a height of 0.1 meter from the initial position of the object, then released the object and then sequentially compared the perceived weight of the 'power assisted object' with 15 reference weights of the actual object of that particular size in a descending order and thus identified the value of the reference weight from where he started to feel the 'power assisted object' heavier than the actual object. The experimenter randomly set the values of m_1 and m_2 and strictly maintained its confidentiality. All five subjects performed this experiment for small, medium and large size objects independently.

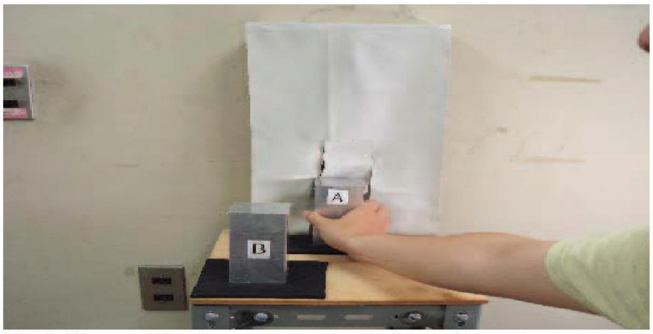

Fig.5: Human lifts the power assisted object (A) and compares its weight with the actual object (B).The main power assist system is hidden behind the power assisted object (A).

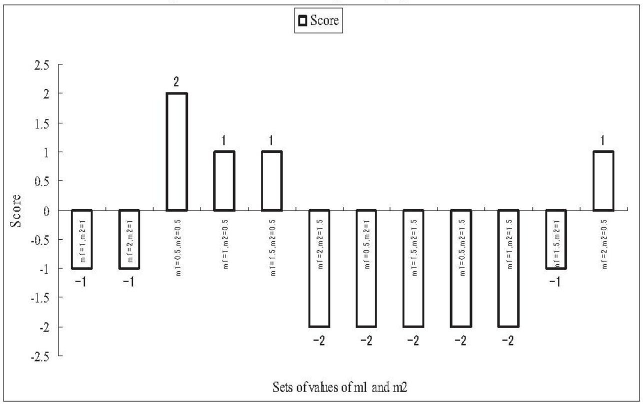

Fig.6: Mean evaluation scores of maneuverability for the system.

Force and displacement data for all trials were also saved. During this experiment, the whole experimental device of the power assist system except the 'power assisted object' was covered with a piece of cloth. The actual object was kept beside the ‘power assisted object’ for easy comparison. Hence, the subject could not understand any visual difference between the 'power assisted object' and the actual object. Weights of the actual objects were changed behind a screen to prevent the subjects from knowing the phenomenon of weight change. Sizes of the ‘power assisted objects’ were also changed in absence of the subjects. All objects (actual and power assisted) not being used during a given trial were kept behind the screen. Fig.5 illustrates the experimental procedure for experiment 2.

3) Experiment 3: Force data for actual objects

In this experiment, a force sensor (foil strain gage type, NEC Ltd.) was attached with an actual object (box). 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 following a demonstration of the experimenter. The vertical lifting forces applied by a subject to lift the actual object of a particular size at three different weight conditions (1.5kg, 1.0kg, 0.5kg) were measured and saved separately. The subject lifted the object of a particular size only one time at each weight condition. This experiment was conducted by all five subjects for small, medium and large size objects. Weight change of the actual objects was performed behind a screen.

In all three experiments, the subjects lifted the objects using right-handed power grip [3].The front side of each power assisted and actual object was 6 cm. Hence, the power grip span was also 6 cm and this optimal grip span was decided according to [7]. The subjects were encouraged to grasp the center of the object while lifting and they were also instructed to lift the object so that the grip axis is aligned vertically with the center of mass of the object in order to eliminate any rotational dynamics and torques [8].

B. Experimental Results & Analyses

1) Experiment 1: System Evaluation

Mean (of 5 subjects) subjective evaluation scores of maneuverability of the system at different sets of values of m_1 and m_2 were exactly same for small, medium and large size objects as shown in Fig.6.The results indicate that, maneuverability is not affected by visual size of object. The reason may be that, human evaluates maneuverability using haptic senses and sensorimotor feedback responses where visual size cue has no influence. However, haptic size cues and variations among subjects may influence maneuverability scores. The graph reveals that, only 4 sets of values of m_1 and m_2 got positive scores whereas the remaining 8 sets of values of m_1 and m_2 got negative scores. The set of values of m_1 and m_2 when m_1=0.5 and m_2=0.5 got the highest scores (+2). It means, the subjects felt very easy & comfortable to maneuver the objects tied with the power assist system only when m_1=0.5 and m_2=0.5. This is why, the set of values of m_1 and m_2 when m_1=0.5 and m_2=0.5 was declared as the best set of values of m_1 and m_2 for all subjects and for objects of all sizes. Hence, m_1=0.5 and m_2=0.5 is the set where all 5 subjects enjoyed the highest level of maneuverability for all 3 objects. These findings indicate the significance of our hypothesis that, we would not be able to sort out the positive sets (satisfactory level of maneuverability) of values of m_1 and m_2 from the negative sets (unsatisfactory level of maneuverability) of values of m_1 and m_2 for different sizes of objects unless we thought $m_1 = m_2 \neq m$ or $m_1 \neq m_2 \neq m$ instead of $m_1 = m_2 = m$ .The best set (m_1=0.5, m_2=0.5) is also the set of the smallest values of m_1 and m_2 in this experiment. If much smaller values of m_1 and m_2 are chosen randomly (say, m_1=0.2, m_2=0.3), the object is supposed to be much lighter, but it needs to clarify whether this is suitable for human psychology or not. Again, in zero-gravity or weightless condition when m_2=0, the object is supposed to be too much lighter as it was studied by Marc et al. [9] in actual environment and by Dominjon et al. [10] in virtual environment , but it is also unknown whether this fits human psychology or not. We still do not know whether the set of values of m_1=0.5 and m_2=0.5 is the best set only for the particular conditions of this experiment or this set will persist as the best set for all conditions in practical uses in industries. It means, it is yet to prove whether the best set is general and universal or not.

2) Experiment 2: Weight Comparison

For a subject and for a particular size of object, individual graph was drawn taking the simulated gravity weights (m_2) of all sets of values of m_1 and m_2 as the abscissa and the reference weight points for all sets of values of m_1 and m_2 from where the subject started to feel the 'power assisted object' heavier than the reference weights as the ordinate. Here, for a particular set of values of m_1 and m_2, the reference weight point from where a subject started to feel the 'power assisted object' heavier than the reference weight is assumed as the approximate perceived weight of the 'power assisted object' and the value of m_2 is considered as the actual weight of the 'power assisted object'. The relationship between the actual weight and the perceived weight of the 'power assisted object' judged by all five subjects for all three objects was exactly same as shown in Fig.7. The results indicate that, the relationship between actual weight and perceived weight is not affected by visual size of object. The reason may be that, determination of this relationship based on weight comparison purely depends on haptic senses where visual size cue has no influence.

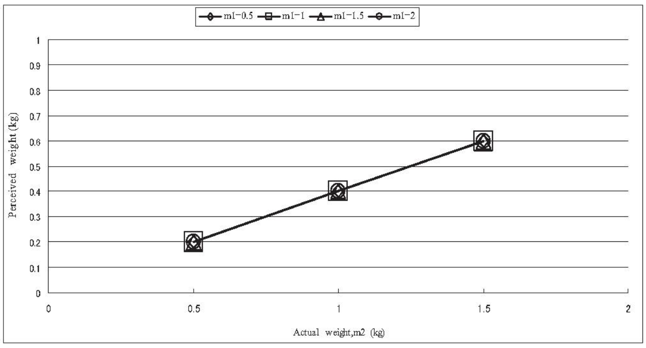

Fig.7: Relationship between actual weight and perceived weight.

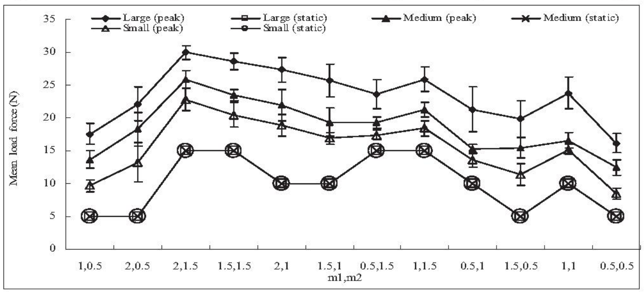

Fig.8: Mean peak load forces and static forces.

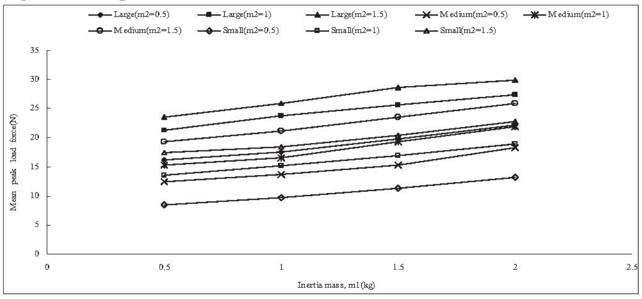

Fig.9: Relationship between m_1 and mean peak load forces.

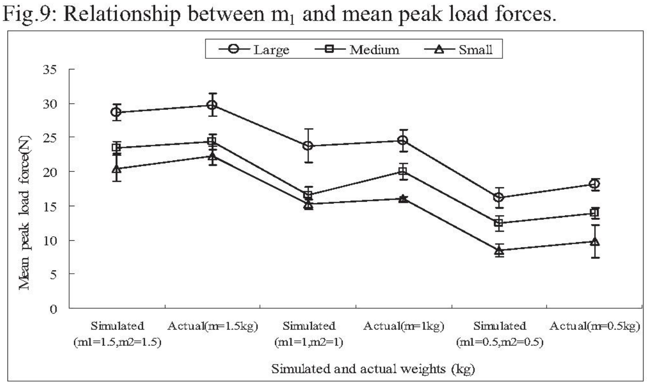

Fig.10: Mean peak load forces with standard deviations for simulated and actual objects in similar experimental conditions.

However, haptic size cues and variations among subjects may influence the relationship. Fig.7 shows that, the actual weight (m_2) and the perceived weight follow a linear relationship for all values of m_1. For the best set (m_1=0.5 and m_2=0.5) condition for all subjects and for all objects, the perceived weight is 0.2 kg, where the actual weight (m_2) is 0.5 kg. Hence, it can be decided that, the perceived weight is 40% of the actual weight of an object lifted with a power assist system. The result also shows that, humans donot feel the change of inertia mass (m_1) while lifting objects with a power assist system.Fig.8 shows the mean peak load forces (of five subjects) with standard deviations as well as mean static forces for different size of objects at different sets of values of m_1 and m_2.The results show that while lifting object with a power assist system, human always applies larger force than the actual weight of the object and at the best maneuverability condition the applied force is approximately 3.25 times, 2.5 times and 1.7 times larger than the actual weight (static force) of the large, medium and small objects respectively. Hence, the applied peak load forces are 2.5 times larger than the static forces on average. The results also show that, peak load forces are proportional to object size. These findings clearly associate with the findings of [11]. Theoretically, the vertical lifting force (f_h) is termed as load force [11]. The peak load force is usually produced during the initial phase of lifting. The static force is the load force required when the object is held stationary just after lifting [11].Fig.9 shows the linear relationship between m_1 and the mean peak load forces for objects of different sizes. These results are also supported by [4].Vertical acceleration was found proportional to visual size of object in [11].Again, m_1 is supposed to be proportional to perceived weight and hence visual size of object. Hence, acceleration is supposed to be proportional to m_1.It means, peak load force is always proportional to m_1 and this proportionality is stable and persistent, which is not to be hampered by any inverse relationship between m_1 and acceleration. We also found mean peak load forces proportional to m_2 for objects of all sizes. These results are also supported by [4].However, the slopes between m_2 and peak load forces were steeper than the slopes between m_1 and peak load forces. It indicates that, effect of m_2 on peak load force is stronger than that of m_1.

3) Experiment 3: Force data for actual objects

Fig.10 compares the mean peak load forces for simulated objects of experiment 2 with that of actual objects of experiment 3 for objects of different sizes. Fig.10 shows that, in the similar experimental conditions, human applies slightly larger amount of forces to the actual objects than to the power assisted objects. The reason may be that, human naturally expects a slight relief while working with any assistive device or it may be an advantage of the assistive system itself. Mean peak load forces are also proportional to object size, which is obviously supported by [11].

IV.DISCUSSION

We have obtained several results in our current research project. The first result is that, we have identified the best set of values of m_1 and m_2 for the power assist system for which humans enjoy the highest level of maneuverability. Some good (positive) sets of values of m_1 and m_2 have also been identified at which humans may enjoy high level of maneuverability. The second result is that, we have established a psychophysical relationship between the actual weight and the perceived weight of an object carried with a power assist system. Human's load force characteristics for manipulating objects with a power assist system have also been demonstrated. The third result is that, we have identified the distinctive features of human's force characteristics between object manipulation in actual and power assisted environment. During the initial first lifting, peak load force is proportional to the perceived weight of the object and the perceived weight is proportional to visual size of the object [12]. As the perceived weight of the 'power assisted object' in experiment 2 is 40% (two-fifth) of the actual weight at the best maneuverability condition (m_1=0.5,m_2=0.5), the peak load force applied by human during the initial first lifting should also be reduced to two-fifth of the currently applied peak load force. If we can supply two-fifth of the currently applied peak load force to the control system of the power assist system, the initial force programming will be optimum, which will result in optimum velocity to the object and the optimum velocity at the best maneuverability condition (m_1=0.5, m_2=0.5) will render optimum maneuverability, operability, ease of use, human-friendliness, safety etc. Hence, we need to include the relationship between the actual weight and the perceived weight in the control law. However, we are to satisfy two constraints regarding this inclusion. The first constraint is that, the peak load force must be greater than the weight of the object [11].The second constraint is that, this inclusion should not hamper the relationship of (3).The force data of the experiment 2 and 3 reveal that, human's force programming for lifting objects is a combination of feedforward and feedback control processes, which is supported by [12]. The reason may be that, the human uses feedforward or anticipatory control method to program the load force on the basis of the visually perceived weight of the object, where the perceived weight is proportional to the visual size of the object [11]. But, after only 100 mili-seconds of initial first lifting [13], the human comes to understand the actual weight of the object from the haptic senses and sensorimotor feedback responses and then adjusts the load force in accordance with the actual weight of the object even though the object sizes may be different. The force data also show that, though the force programming is dominated by feedforward size cue (central motor command) [11], sometimes feedback somatosensory sensing overrules feedforward perception. It might be interesting to determine the transition point from where the haptic perception (feedback) starts to overrule the feedforward visual perception (size cue). Again, the findings of the experiment 2 and 3 do not violate the well-established size-weight illusion [12] as the objects of different sizes were lifted independently in these experiments. Evaluation methodologies of human factors used in both experiment 1 and 2 are subjective instead of objective. Nevertheless, the subjective evaluations of our experiments are to be reliable because subjective evaluations in technical domains have already been proven efficacious in [14].However, the accuracy of the experiment 1 may be further enhanced by transforming the rating scale from 5-point to 7-point and by improving the quality of the evaluation alternatives and evaluation criteria and by increasing the number of subjects and trials [6]. The accuracy of the experiment 2 may be increased by adding more reference weights in the reference weight series and by increasing the number of subjects and trials.

V. CONCLUSION

This paper successfully addresses human's perception of object weight for lifting object with a power assist system. In the near future, human's manipulative force characteristics and the psychophysical relationship between the actual weight and the perceived weight will be included in the control law of the power assist system at the best maneuverability condition, which will optimize the peak load force. We are optimist that, this endeavor will rationally optimize the maneuverability, operability, safety, ease of use, human-friendliness and other requirements of power assist systems for maneuvering heavy objects in particular and of other types of power assist systems in general. New and advanced evaluation methods of maneuverability will be searched. Factors affecting maneuverability and lightness will be addressed. Advanced psychophysical scaling for weight perception will be searched. New and advanced control methods for the power assist system will also be searched. The system will be upgraded from 1DOF to multi-DOF system. Psychophysical considerations for other types of power assist systems or other types of human-robot interaction will also be addressed.

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