

Study on human operator's weight
perception of an object carried with a
power assist system

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Study on human operator's weight perception of an object carried with a power assist system

by

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A thesis
submitted to the Division of Mechanical
Engineering of the Graduate School of Engineering
at Mie University
in partial fulfillment of the requirements for the
degree of

**Master of Science
in
Engineering**

Advisor: Professor Dr. Ryojun IKEURA

February, 2008
Tsu, Mie, Japan

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Abstract

When an object is carried with a power assist system, velocity of the object is proportional to the forces (grip, load) applied on the object by the human operator. Human operator's force programming depends on how the operator perceives the weight of the object. A power assist system always makes the object lighter to maneuver through lowering the required forces applied by human by dint of control law. Hence, the weight of the object perceived by the operator while maneuvering the object with a power assist system is always very much less than the actual weight of the object. This is why, the forces (grip, load) required to carry an object with a power assist system are supposed to be lower than that of when the object is not carried with a power assist system (carried manually). But, the human operator always thinks the perceptual weight equal to the actual weight and applies forces in accordance with the actual weight of the object. Hence, the applied forces by the operator are incorrect (usually very much larger) and this incorrect force programming causes many problems such as- (1) object velocity suddenly becomes very high (2) the operator becomes fearful while maneuvering the object (3) the object may not be maneuvered to the desired destination (4) the system may lose maneuverability as well as stability (5) the system may cause fatal accident etc.

This research addresses, firstly, the establishment of a set of psychophysical relationships between the actual weight and the perceptual weight of the objects carried with a power assist system considering the operator's cognitive sensations and, secondly, the design of the control law for the power assist system depending on these psychophysical relationships. In this research, a simple 1DOF (vertically up-down) power assist system was developed for lifting objects and an object tied with the power assist system through a force sensor was lifted by human operator. The system was simulated in MATLAB environment for various sets of values of object weight and the lifted weight of the object (perceptual weight) was subjectively compared with the reference weight of its actual counterpart (actual weight). The optimum relationships between the simulated (perceptual) weight and the actual weight were subjectively determined and used to design the control law. The research findings are to enhance the maneuverability as well as safety and stability of the power assist system.

Declaration

I hereby declare that, I am the sole performer, author, and producer of this thesis. I also declare that, I did not submit this thesis or a part of it to anywhere for any degree, diploma or award, except for publication.

S.M.Mizanoor Rahman

February, 2008

Tsu, Mie, Japan

Authorization

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Dedication

To those who are trying their best to develop human friendly power assist systems for the benefits, advantages and welfare of the mankind as a whole.

Contents

1	Introduction	
1.1	Objective.....	1
1.2	Significance.....	2
1.3	Challenges.....	3
1.4	Contributions.....	4
1.5	Summary & Outline.....	5
2	Background	
2.1	Human-Robot Cooperation.....	7
2.2	Power Assist Systems.....	8
2.3	Perception & Psychophysics.....	11
2.4	Summary.....	15
3	Literature Review/Related Works	
3.1	Literature Review on power assist systems.....	17
3.2	Literature Review on weight perception of object.....	19
3.3	Summary.....	25
4	Construction of the Power Assist System	
4.1	The Experimental Devices.....	26
4.2	Experimental Set-up.....	28
4.3	Description of the Apparatus and Equipment.....	28
4.4	Dynamic Modeling of the System.....	31
4.5	Block Diagram of the Control System.....	34
4.6	Summary.....	34
5	Experiments & Results	
5.1	Experiments.....	35
5.2	Experimental Data.....	37
5.3	Experimental Results and Analyses.....	52
5.4	Summary.....	59
6	Conclusion	
6.1	Discussions.....	60
6.2	Contributions.....	61
6.3	Limitations	61
6.4	Future Directions.....	61
	Appendices	62
	Bibliography	64

Chapter 1: Introduction

1.1 Objective

The main objective of this thesis research is to consider the human operator's perception of object weight when the human operator carries the object with a power assist system and to design the control law for the power assist system based on human operator's weight perception of the object.

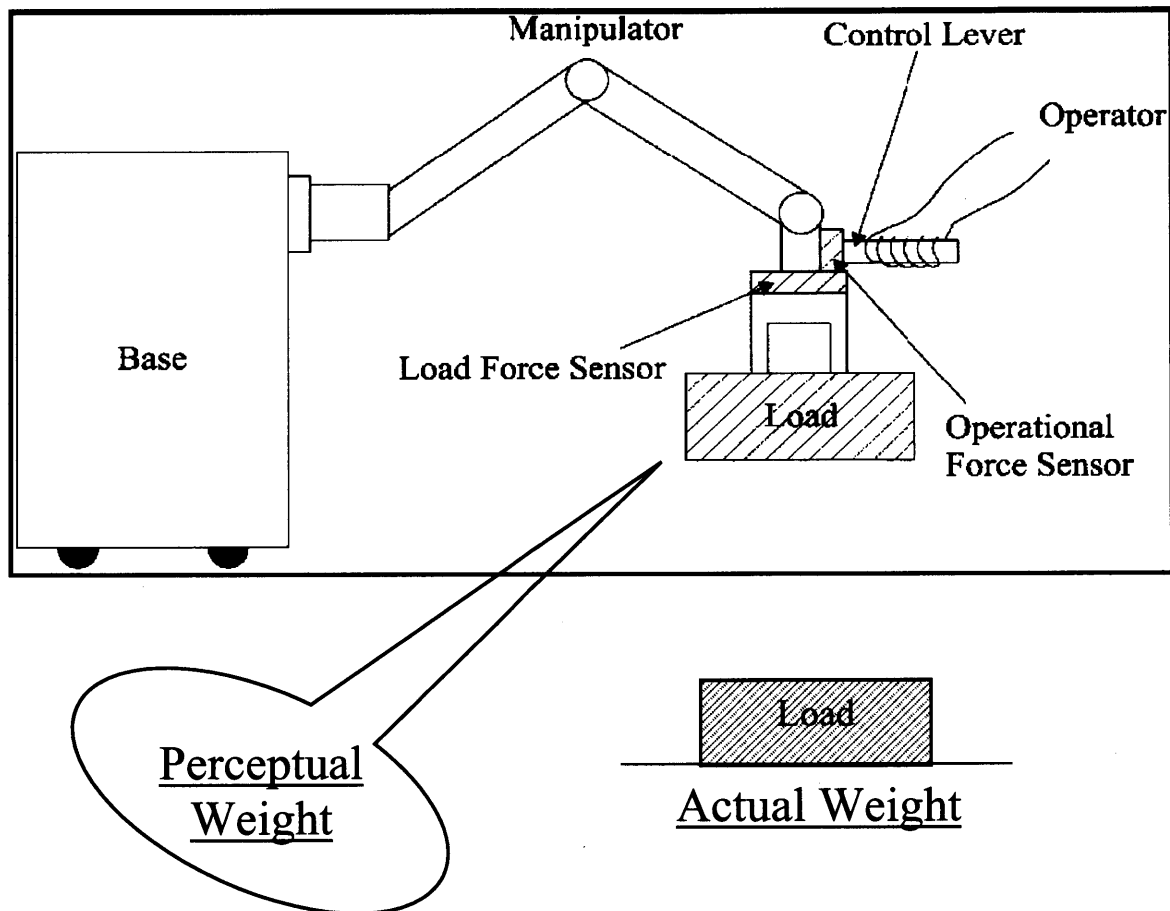


Fig1: Actual and perceptual weight of an object carried with a power assist system [22]

A power assist system always makes the object lighter to maneuver by lowering the required forces applied by human. Hence, the weight of the object perceived by the operator while maneuvering the object with a power assist system is always very much less than the actual weight of the object. But, the human operator always thinks the perceptual weight equal to the actual weight, which causes error in programming of forces to maneuver the object. The faulty force programming hampers safety, stability and maneuverability of the power assist system.

The main objective of this thesis research is-

- 1 To establish a set of psychophysical relationships between the actual weight and the perceptual weight of the object maneuvered with a power assist system considering the operator's cognitive sensations,
- 2 To design the control law for the power assist system depending on these psychophysical relationships between the actual weight and the perceptual weight of the object maneuvered with a power assist system.

The research findings are to enhance stability, safety, senses of security, operability, ease of use, efficiency and maneuverability of the power assist system as a whole.

1.2 Significance

It is experienced with different types of power assist systems that, when an object is maneuvered with a power assist system, velocity of the object is proportional to the forces (grip, load) applied on the object by the human operator. Human operator's force programming depends on how the operator perceives the weight of the object. A power assist system always makes the object lighter to maneuver through lowering the required forces applied by human by dint of control law. Hence, the weight of the object perceived by the operator while maneuvering the object with a power assist system is always very much less than the actual weight of the object. This is why, the forces (grip, load) required to carry an object with a power assist system are supposed to be lower than that of when the object is not carried with a power assist system (carried manually). But, the human operator always thinks the perceptual weight equal to the actual weight and applies forces in accordance with the actual weight of the object. Hence, the applied forces by the operator are incorrect (usually very much larger) and this incorrect force programming causes many problems such as-

1. Velocity of object suddenly becomes very high
2. The operator becomes fearful while maneuvering the object
3. The object may not be maneuvered to the desired destination/location
4. The system may lose maneuverability as well as stability
5. The system may cause fatal accident etc.

The above practical problems are experienced not only with the power assist systems designed for maneuvering objects, but also with almost all types of power assist systems directly or indirectly. We hypothesize that, these problems with power assist systems are experienced for the reasons as perceptual, psychophysical and cognitive aspects especially human operator's weight perception of object maneuvered with power assist systems are not being considered in the design and control of power assist systems. Though several control methods for the robots cooperating with human especially for power assist systems have already been developed, control methods considering human characteristics and perception in order to make human-friendly robots and human-friendly power assist systems are very few and rare.

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.

Hence, it seems necessary and significant to develop at least a model of power assist system where the proper combination of human characteristics like the perceptual, psychophysical and cognitive aspects of human are seriously considered in the design and control strategies of power assist system. As the power assist systems for maneuvering objects in industries are very demanding, combination of human characteristics like the perceptual, psychophysical and cognitive aspects of human especially human operator's weight perception of objects are to be considered first in design and control strategies of power assist systems for maneuvering objects in industries.

From the above points of view, the current project on power assist system with consideration of human operator's weight perception is undoubtedly demanding and significant.

1.3 Challenges

The execution of research on the current project of power assist system is hindered by a number of problems. In order to succeed in this project, the challenges are to overcome these problems. A few of the common problems with power assist systems are described below:

Vibration: Vibration is one of the dangerous problems with the power assist systems. There may have many reasons of vibration such as excessive weight of the object carried with the power assist system, mass-spring system of the force sensor, time-lag between the force sensor and the control system, electrical and electronic noise etc. Vibration always hampers the system and some times destroys the system completely. It is necessary to control the vibration of the power assist system in order to obtain optimum performance from the system.

Actuator Saturation: In power assist system, it is a serious problem that the maneuverability and the stability are degraded when the actuators are saturated. To avoid this, it may be helpful to compensate for gravity and dynamic load by different ratios. If the human applies larger force, the voltage exceeds its limit and the system does not work correctly. It is a challenge to face actuator saturation in a power assist system.

Noises & disturbances: One of the most common (and easily correctable) problems that may adversely affect control signals is electrical "noise" or interference. The more interference there is on the power line, the more difficult it is for actuator mechanism to detect signals from controllers. It's like trying to have a conversation in a room when the music is playing too loud. But, the noise filter, blocks (hinders) that interference, preventing it from polluting the power line. Common sources of interference include refrigerators, freezers, plug-in fluorescent fixtures, aquarium filters, fountains, low-voltage lighting, fans, or anything with a motor. The sound and heat produced in servomechanism of power assist system may also cause noise or disturbances for the

system. In order to get desired performance from the power assist system, it is also a challenge to avoid noise and disturbances.

Adjustment with Human: Power assist system is designed so that human can work cooperatively with the robot or robotic systems. Hence, proper adjustment and suitability between human and the robot or the robotic system are mandatory in order to make the power assist system effective. In this regard, human's ease, safety, desire, intention, comfort, psychology, perception etc are supposed to be considered in the design and development of power assist system. However, the consideration of human factors in power assist system is almost untouched and hence it is still a challenge to be addressed.

Control Methods: Selection of appropriate control methods is a vital factor in design and control of power assist system. Effectiveness of the power assist system significantly depends on the effectiveness and suitability of the control methods. Hence, appropriateness in selecting control method is a great challenge in design and development of a power assist system.

Accuracy: Accuracy in output is a great demand for a power assist system. In order to achieve desired accuracy in power assist system, it is still a challenge to select appropriate and accurate devices, instruments, actuating elements etc in design and development of a power assist system.

Moreover, capacity of force sensors, number of force sensors, stability of the system etc are vital issues and challenges to be considered.

1.4 Contributions

The current project on power assist system with consideration of human operator's weight perception has a number of potential contributions. Only a few of the principal contributions of the current project are described below:

1. Human cannot do all works in all environments himself/herself as human's ability is limited. On the contrary, robots can do works enormously for long time even in hard and adverse situations where humans cannot dare to proceed. But, the works done by robots alone sometimes may not fulfill the desire and quality demanded by the people. This theme has given birth to the concept of human-robot cooperation. 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 application 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. Control systems for such robots need to be designed to cooperate with humans. Again, progress in modern technologies as well as growing social demands require human-friendly robots and human like characteristics in the robots [1]. Power assist system is a special type of human-robot cooperation. This system is based on the philosophy: "Human's ability to perform physical tasks is limited not

by his/her intellect, but by his/her physical strength". Hence, if we can augment the physical ability and strength of human by employing power assist system, then the power assist system can perform many significant and difficult tasks successfully that cannot be done by humans or robots alone.

If the current project on power assist system becomes successful, a new horizon in the fields of human-robot cooperation, especially in the fields of power assist systems will be opened, which will pave the ways to the enhanced applications of robots in home automation, industrial production, mining, agricultural production, logistics and transportation, medical operations, rehabilitation etc. Thus, this project will certainly improve the quality of life (QOL), life security, industrial productivity, the global economy etc.

2. The current project on power assist system considers human factors in design of robotic systems and its control laws. If this project is successful, the emerging power assist systems will be human friendly and will be adjustable and suitable to human's desire, intention, ease, comfort, psychology and perception. Thus, the emerging power assist systems will be more effective, productive, safe and comfortable.
3. The main purpose of the current project is to design power assist system for maneuvering large and heavy objects in various types of industries like manufacturing industries, ship building, mining, civil construction, logistics and transportation, disaster management etc. These industries will be benefited directly in many ways if the current project becomes successful. However, the hypothesis tested in the current project may be applicable to any type of power assist system. Hence, this project will increase the suitability of all types of power assist systems.
4. This project considers almost all current challenges (problems) with power assist systems. It considers vibration control, avoidance of actuator saturation, control of noises and disturbances, adjustment with human factors, employment of advanced control methods, high level of accuracy, stability and safety of the system etc as a whole. Hence, this power assist system may be a model for all types of power assist systems.

1.5 Summary & Outline

In this thesis research, a simple 1DOF (vertically up-down) power assist system was developed for lifting objects and an object tied with the power assist system through force sensor was lifted by human operator. The system was simulated in MATLAB environment for various sets of values of object weight and the lifted weights of the object were subjectively compared with the reference weights of their actual counterparts. The optimum relationship between the simulated (perceptual) and the actual weights was subjectively determined and used to design the control law.

Chapter 2 contains the background necessary for the current thesis research. The background includes a brief introduction of human-robot cooperation, theory, concepts and advancement of power assist systems, a brief introduction of human's perception and psychophysics, size-weight illusions etc.

Chapter 3 includes related works and literature reviews on both power assist systems and human's perception and psychophysics especially human's weight perception.

Chapter 4 contains the construction of the power assist system. This chapter specifically includes the devices, apparatus & equipment used to develop the power assist system, experimental set-up of the system, dynamic modeling of the system, block diagram of the control systems etc.

Chapter 5 contains the experiments, experimental data, results and analyses.

Chapter 6 contains a conclusion. This concluding chapter contains a general discussion on this thesis research, contributions of this research, limitations of this research, future directions of this research etc. Appendices and bibliography follow Chapter 6.

Chapter 2: Background

2.1 Human-Robot Cooperation

Human cannot do all works in all environments himself/herself as human's ability is limited. On the contrary, robots can do works enormously for long time even in hard and adverse situations where humans cannot dare to proceed. But, the works done by robots alone sometimes may not fulfill the desire and quality demanded by the people. This theme has given birth to the concept of human-robot cooperation. Human-robot cooperation usually means executing the same tasks by robot and human in cooperation that may help achieve better work quality, work adjustment, productivity, safety and what not. Most robots are typically used for simple, repetitive tasks in environments isolated from humans. There is increasing demand for human-friendly robot technologies, with which robots could collaborate with humans sharing the same workspace, to expand robot applications from factory automation into such areas as construction work, shipping services, home and office tasks, etc. The human-robot cooperative systems are usually being designed in many forms such as master-slave mechanisms, haptic devices etc.

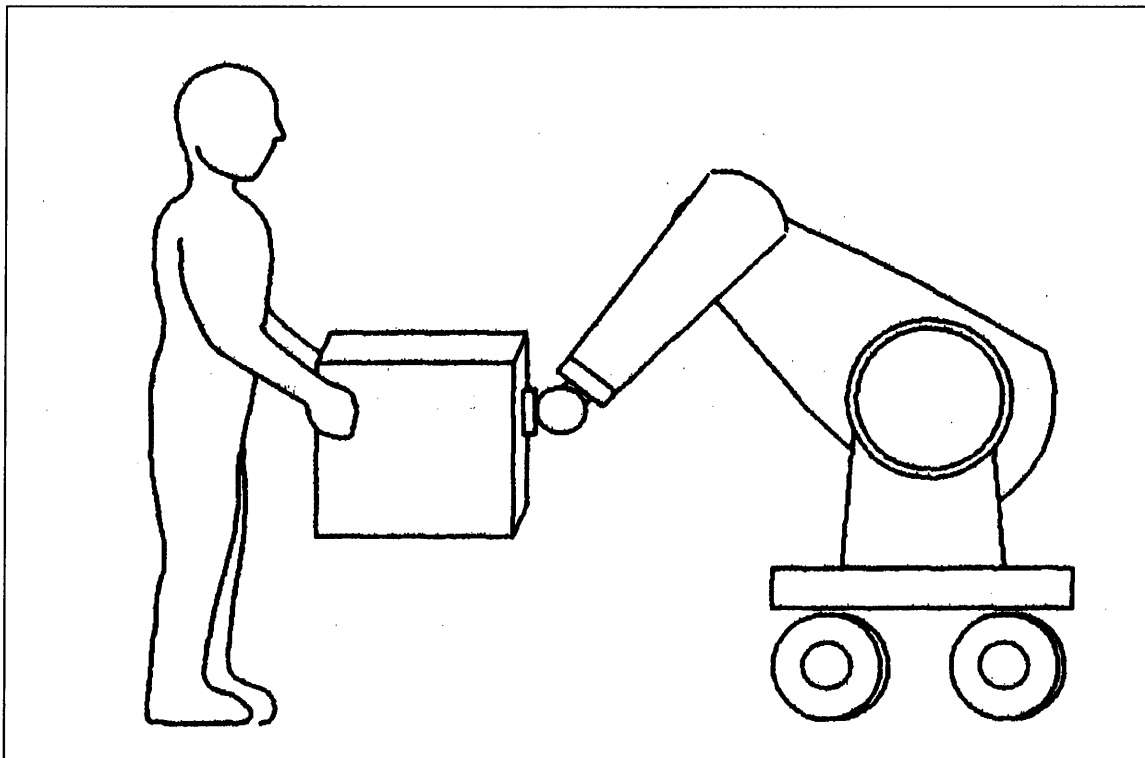


Figure 2: Human is maneuvering an object in cooperation with a robot [57]

In the near future many aspects of our lives will be encompassed by tasks performed in cooperation with robots. The application 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. Control systems for such robots need to be designed to cooperate with humans. Again, progress in modern technologies as well as growing social demands require human-friendly robots and human like characteristics in the robots. The human-friendly robots will be executing tasks in cooperation with humans [1]. Several control methods for the robots cooperating with human have been designed [2][3]. However, those control methods have been designed without considering human characteristics [1]. Ikeura et al. first introduced human arm characteristics in a cooperative task for developing a robot controller [4].

2.2 Power Assist Systems

Power assist system is a special type of human-robot cooperation. Power assist system assists the human to perform works with enhanced safety, sense of security, operability, ease of use etc by lowering the required forces applied by human (augmenting human strength or ability) and by adjusting the human to work motions and/or situations, where the human's intelligence spontaneously and centrally controls the command signal to the system. It transfers and shares both power & information signals. This system is effective at unstructured situations and frequently adapting/changing environments, where the autonomous robotic systems may be unfit. The power assist systems also possess several advantages over master-slave systems, haptic devices etc such as-

- Here direct contact between robot and human is available, which is usually not available in conventional master-slave, haptic devices
- Transference of both power & information signals
- Human feels a scaled-down effect of load
- Instant force feedback and reaction by human without a separate set of actuators
- Easy and quick to orient the load
- Human feels naturally while operating
- Human needs very little training to operate

"Power Assist" can be further defined as "augmenting the ability or adjusting to the situation when human operates and works". In particular, in case of supporting for elderly people and disabled people, the purpose of "power assist" is improvement of QOL (Quality of Life), that is, support for daily life. It has two meanings. One is support for self-help and the other is support for caring. The former is to support their self-sustained daily life, and the latter is to decrease burden of caregiver. In these support, we expect for the following as a consequence:

- We come to be able to realize desired motions and operations that were impossible
- We come to be able to operate with ease

--Requirements for power assist equipment --

The following are requirements for power assist equipment:

[1st Requirement]:

Amplification of human force, assistance of human motion.

This is realization of "power assist" itself, and we have problems such as its realization method and stability of human-robot system.

[2nd Requirement]:

Safety, sense of security, operability, ease of use.

This requirement doesn't appear as specific thing comparing with 1st requirement, and it is difficult to be taken into account. However, in order to make power assist equipment useful, this requirement is more important rather than 1st requirement.

At present, power assist systems are being used mostly for the purposes of-

- Supports to the aged and disabled people
- Maneuvering objects etc.

Again, at present, power assist systems are being used mostly in the forms of-

- Cooperation between human and a robot manipulator
- Cranes
- Bed system
- Hand gloves
- Exoskeleton (upper, lower)
- Inner-skeleton robot for human motion assist
- Wheelchairs, walking chair, tri-cycles
- Rescue robots etc.

A few of the forms are shown in the figures (from fig.3 to fig.12).

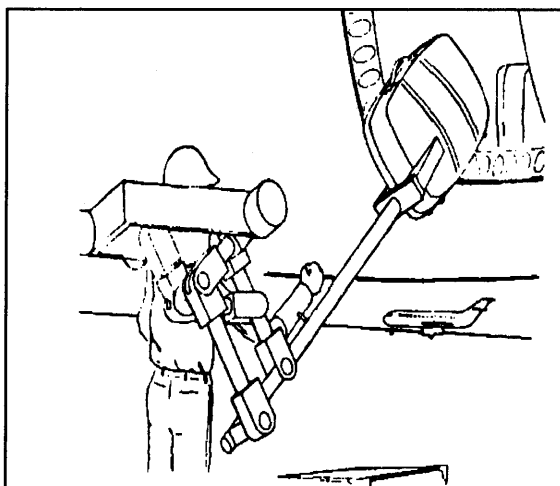


Fig.: 3: Power assist system for carrying object [5]

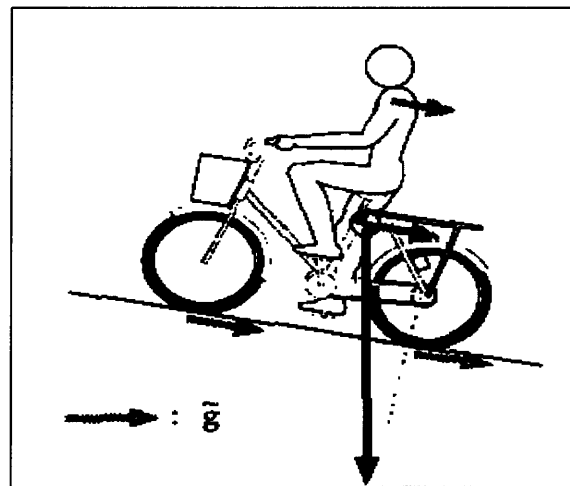


Fig. 4: Load-free control of power-assisted cycle [6]

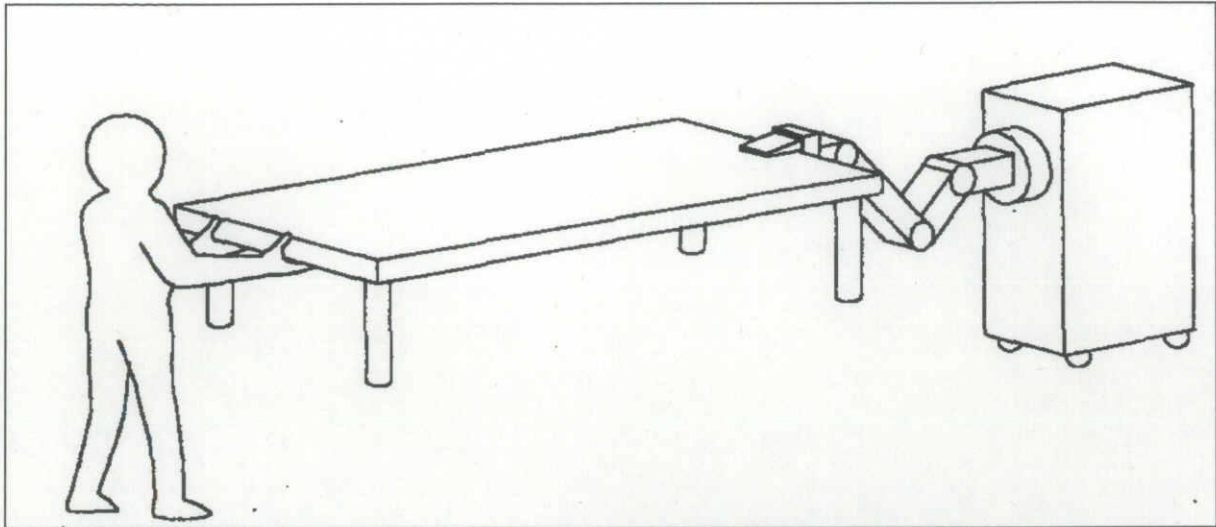


Figure 5: Power assist system for carrying a long object with a human [7]

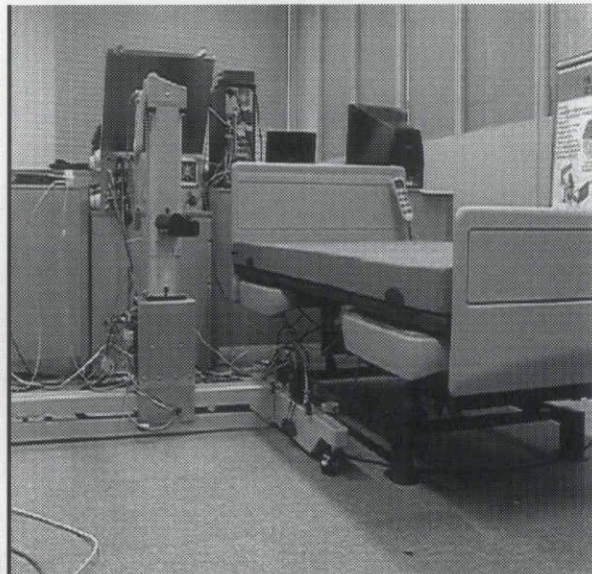
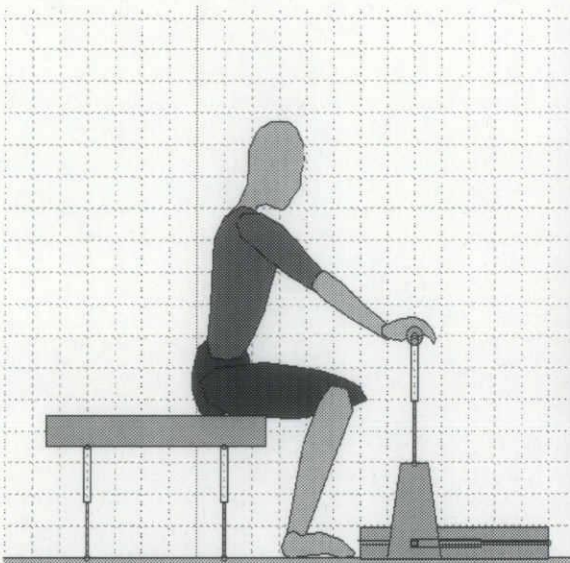


Figure 6: Force assistance system for standing-up motion from bed [8]

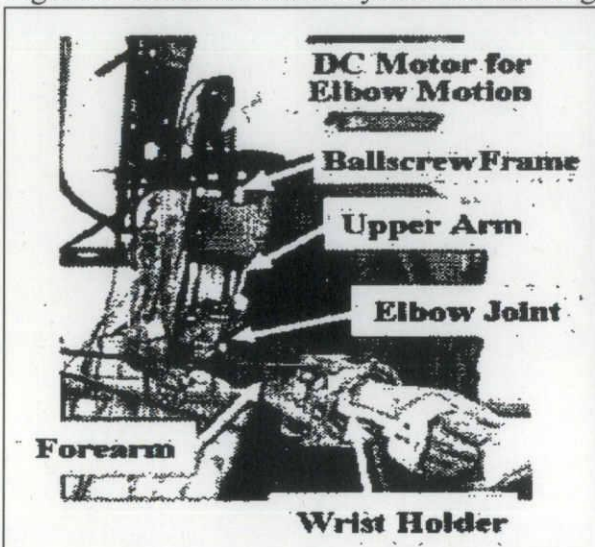


Fig.7: Concept of an inner skeleton robot for human motion assist [9]

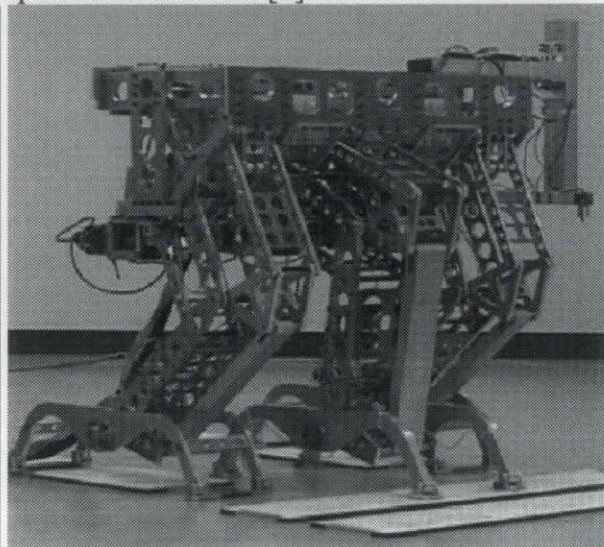


Figure 8: Power assisted walking chair [10]

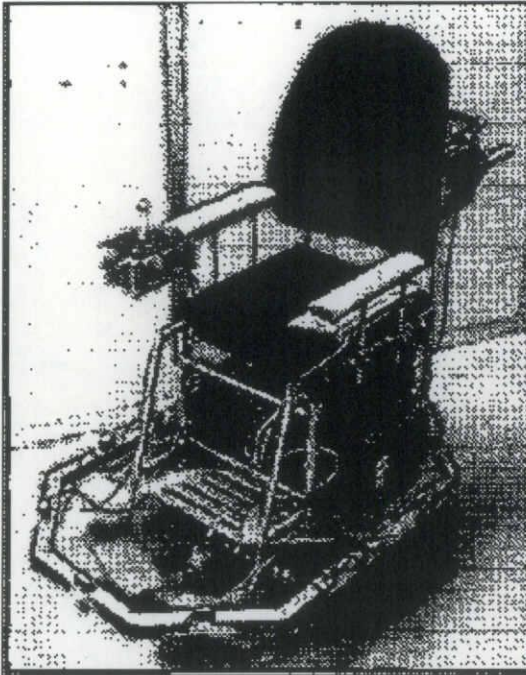


Figure 9: Power assisted wheel chair [11]

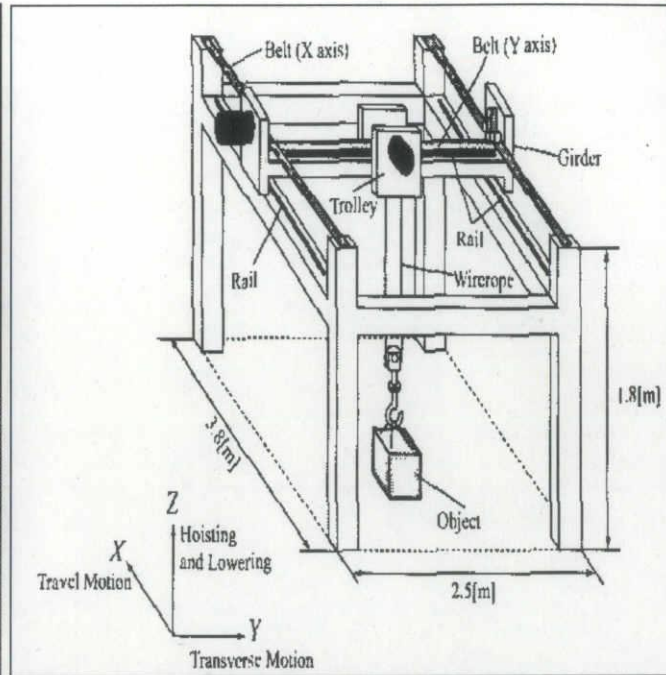


Figure 10: Power assisted crane system [12]

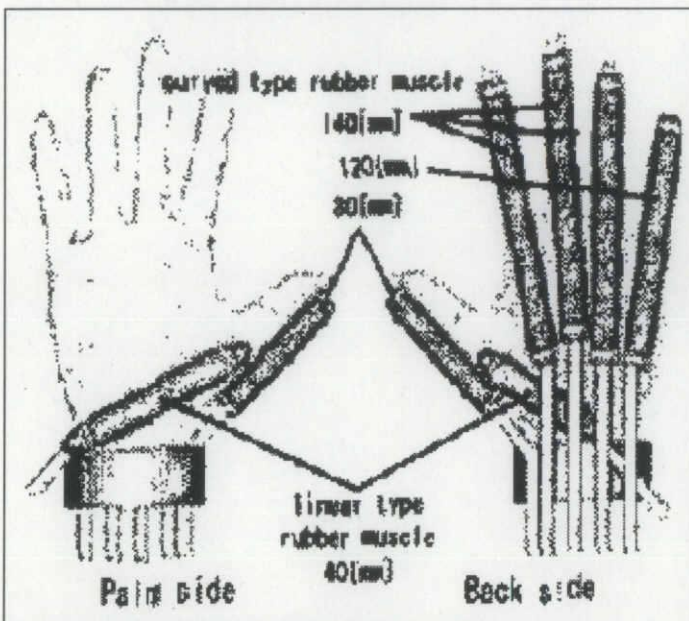


Figure 11: Power assisted glove [13]

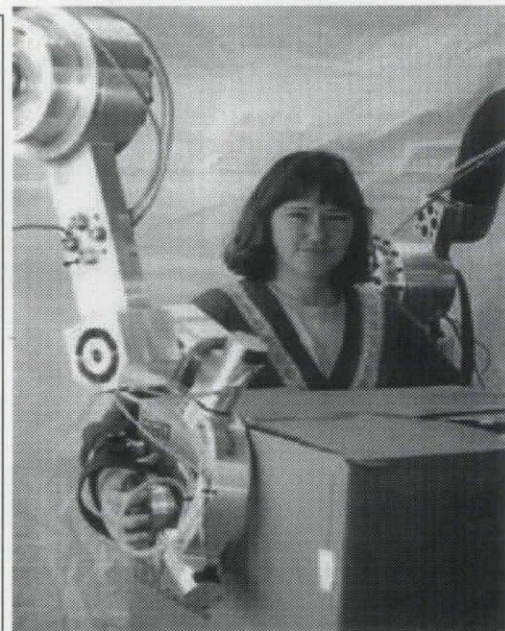


Fig. 12: Electric upper extremity exoskeleton [14]

2.3 Perception & Psychophysics

2.3.1 Perception

Perception may be defined as any one of the following-

1. Perception is the condition of being aware. That which exists in the mind as the product of careful mental activity. [answers.com, *Roget's II: The New Thesaurus*, 3rd edition, published by the Houghton Mifflin Co.]
2. Perception is becoming aware of something via the senses.[answers.com, Word Net]
3. Perception is the knowledge through the senses of the existence and properties of matter or the external world.[answers.com, Word Tutor]

4. Perception is the recognition and interpretation of sensory stimuli based chiefly on memory. The neurological processes by which such recognition and interpretation are effected.[*The American Heritage Dictionary of the English Language*, 4th edition, published by Houghton Mifflin Company]
5. In psychology and the cognitive sciences, perception is the process of acquiring, interpreting, selecting, and organizing sensory information. The word *perception* comes from the Latin *capere*, meaning "to take," the prefix *per* meaning "completely." [Wikipedia, the free encyclopedia]
6. Perception, in psychology, mental organization and interpretation of sensory information. Perception is influenced by a variety of factors, including the intensity and physical dimensions of the stimulus; such activities of the sense organs as effects of preceding stimulation; the subject's past experience; attention factors such as readiness to respond to a stimulus; and motivation and emotional state of the subject. [Columbia Electronic Encyclopedia, published by Columbia University Press]
7. Perception is the process of registering sensory stimuli as meaningful experience. The differences between sensation and perception have varied according to how the terms are defined. A common distinction is that sensations are simple sensory experiences, while percepts are complex constructions of simple elements joined through association. Another is that perception is more subject to the influence of learning. Perceptions may be influenced by expectations, needs, unconscious ideas, values, and conflicts. [Britannica Concise Encyclopedia, published by Encyclopedia Britannica, Inc.]
8. Perception is those subjective experiences of objects or events that ordinarily result from stimulation of the receptor organs of the body. This stimulation is transformed or encoded into neural activity (by specialized receptor mechanisms) and is relayed to more central regions of the nervous system where further neural processing occurs. [McGraw-Hill Encyclopedia of Science and Technology, 5th edition, published by The McGraw-Hill Companies, Inc.]
9. Perception is the process of gathering information through our senses (sight, sound, smell, taste, and touch), organizing and making sense of it.
10. Perception is the process by which we receive and interpret information from the world around us. [a2zpsychology.com]

There may have many types of perception .A few types of perception related to the research presented herein are discussed below:

2.3.1.1 Haptic perception

‘Haptic’ comes from a Greek term meaning 'able to lay hold of'. **Haptic**, from the Greek *Haphe*, means pertaining to the sense of touch.Haptic perception involves both **tactile perception** through the skin and **kinesthetic perception** of the position and movement of the joints and muscles. For example, if we hold a cube, we perceive it through the skin of our fingers and the position and motions of our fingers. Haptics in action means-

- Sensors in the skin and limbs
- Haptic Perception = Tactile Perception + Proprioceptive Perception + Kinesthetic Perception

Tactile perception means the perception of objects by touch through the skin only. Proprioception-from Latin *proprius*, meaning "one's own"- is the perception of the object by

the relative position of neighboring parts of the body. Kinesthetic perception is the perception of the object by the relative movement or motions of neighboring parts of the body. Proprioception and kinesthesia are often used interchangeably or sometimes proprioception may mean both position and motion of the body parts and hence may replace the term tactual. Haptic perception may also include vision, sound, pressure, temperature or torque. Figure 13 gives an introduction of haptic perception.

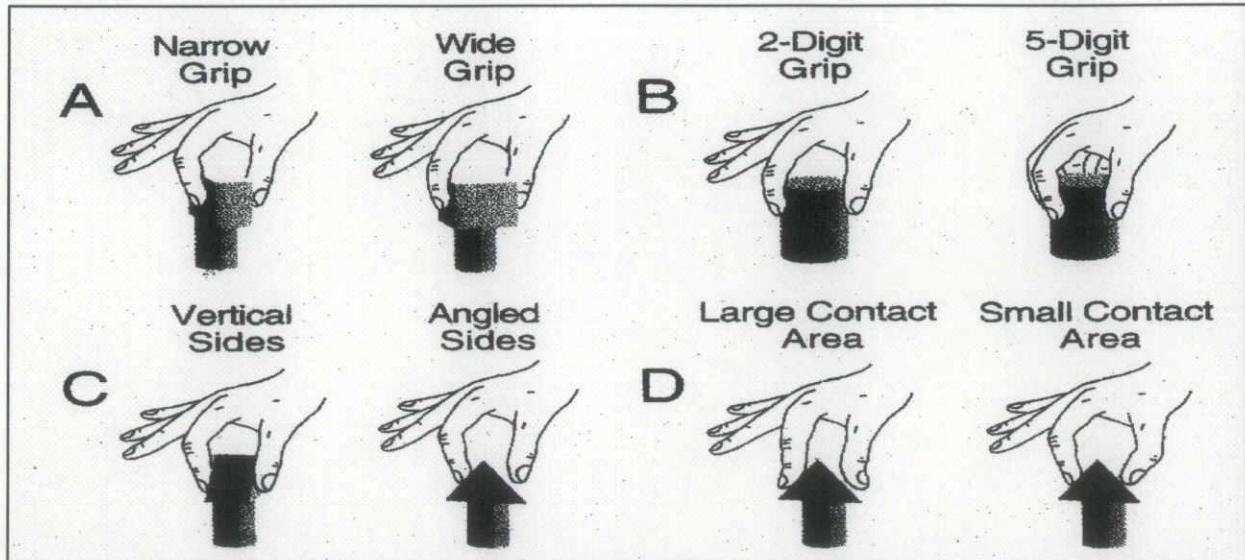


Fig.13: Haptic perception of objects with various grasp configurations [33]

2.3.1.2 Visual Perception

In psychology, visual perception is the ability to interpret visible light information reaching the eyes which is then made available for planning and action. The resulting perception is also known as eyesight, sight or vision. The various components involved in vision are known as the visual system. Though hearing, smell, touch, and taste perceptions have all been explored, vision has received the most attention as human uses vision in almost all types of perception directly or indirectly.

2.3.1.3 Weight Perception

Weight perception is the recognition and discrimination of the heaviness of a lifted object. It may be a combination of visual perception and haptic perception.

The following factors related to objects, human, situation and environment may affect weight perception of a lifted object:-

Volume, size (size-weight illusion), density, color, shape, material properties, contents, range of displacement, velocity of maneuvering, kinematics (way of lifting), packaging, decision making time/ maneuvering time, multi-display, how was kept before lifting, interruption in vision, new objects,

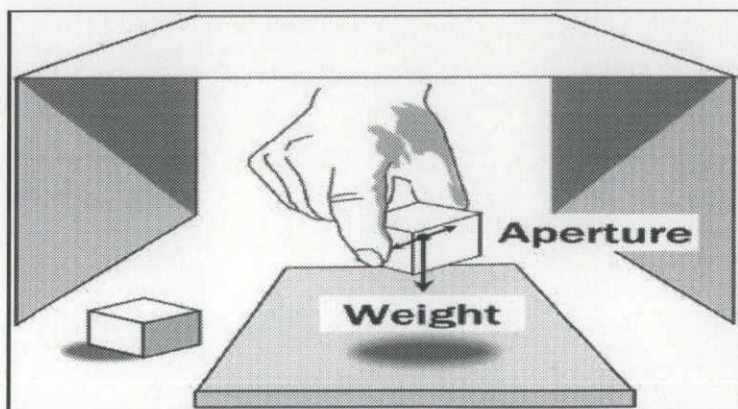


Fig.14: Weight perception of an object (without vision) [41]

proximity, similarity, connectedness, age, male/female, IQ level of operator, experience, transparency, working hours, location, isolation, intrinsic interest, visual direction (weight attraction), bottom-heavy, vertical/horizontal viewing, left/right side viewing, thermodynamics of mind, video and live observation , posture of the body & reach, habituation, anticipation, adaptation, fatigue/non fatigue of operator, quick and dirty screening , strength at various joints of arm and wrist of the operator , representational momentum of dynamic objects based on Newtonian physics principle or impetus theory , tactile acuity of the mass, use of left/right hand and fingers of the operator, contact point of fingers/body parts with sensor (tactile sensitivity of different body parts), static/active weight, spatial acuity (3D axes of the mass and the body of the operator), surface roughness of the mass , neural efficiency of the operator, etc. Figure 14 gives an introduction of weight perception.

2.3.2 Psychophysics

Psychophysics is a subdiscipline of psychology dealing with the relationship between physical stimuli and their subjective correlates, or percepts. Many of the classical techniques and theory of psychophysics were formulated in 1860 when Gustav Theodor Fechner published *Elemente der Psychophysik*. He coined the term "psychophysics", and described research relating physical stimuli with how they are perceived and set out the philosophical foundations of the field. Fechner wanted to develop a theory that could relate matter to the mind, by describing the relationship between the world and the way it is perceived . This relationship is Psychophysics. The most common use of psychophysics is in producing scales of human experience of various aspects of physical stimuli. This is of particular importance in human research. Areas of investigation in psychophysics include sensory thresholds, methods of measurement of sensitivity, and signal detection theory.

A threshold (or limen), is the point of intensity at which the participant can just detect the presence of, or difference in, a stimulus. Stimuli with intensities below the threshold are considered not detectable, however stimuli at values close to threshold will often be detectable some proportion of the time. Due to this, a threshold is considered to be the point at which a stimulus, or change in a stimulus, is detected some proportion p of the time. There are two kinds of thresholds: absolute and difference. An absolute threshold is the level of intensity of a stimulus at which the subject is able to detect the presence of the stimulus some proportion of the time (a p level of 50% is often used). An example of an absolute threshold is the number of hairs on the back of one's hand that must be touched before it can be felt - a participant may be unable to feel a single hair being touched, but may be able to feel two or three as this exceeds the threshold. A difference threshold is the magnitude of the *difference* between two stimuli of differing intensities that the participant is able to detect some proportion of the time (again, 50% is often used).

In discrimination experiments, the experimenter seeks to determine at what point the difference between two stimuli, such as two weights or two sounds, is detectable. The subject is presented with one stimulus, for example a weight, and is asked to say whether another weight is heavier or lighter (in some experiments, the subject may also say the two weights are the same). At the point of subjective equality (PSE), the subject perceives the two weights to be the same. The just noticeable difference (JND), or difference limen (DL), is the difference in stimuli that the subject notices some proportion p of the time (50% is usually used for p).

In psychophysics, experiments seek to determine whether the subject can detect a stimulus, identify it, differentiate between it and another stimulus, and describe the magnitude or nature of this difference. Psychophysical experiments have traditionally used three methods for

testing subjects' perception in stimulus detection and difference detection experiments: the method of limits, the method of constant stimuli, and the method of adjustment. There are some non-traditional methods of experimentation such as method of propellers, staircase procedure etc. [Wikipedia]

2.3.3 Size-weight illusion

When two visible objects of equal weight but of different density and size are lifted, the smaller object is judged to be the heavier than the larger object. This is size-weight illusion, which may derive from haptically and/or visually acquired size information, and/or from a subject's expectation or previous experience. [62]

There are two main theories for the basis of size-weight illusion: The Information Integration Theory (sensory based theory), Cognitive Based Theory (expectation and rationalization theory). The Information Integration Theory (sensory based theory) states that, size-weight illusion occurs due to the direct integration of weight information with the size information concurrently obtained, whether through visual or haptic senses, during lifting of an object. [63], [64]. Cognitive Theory (expectation and rationalization theory) states that size-weight illusion occurs due to some cognitive process in the perception of heaviness, such as expectation or rationalization based on the visual size of the target objects [30], [65], [66].

Expectation theory as explained by Ross [65] states that, the illusion is the result of a measuring system that takes into account the expected value of an object. For instance, it is a common expectation that the larger of two objects should be heavier than the smaller one. The idea of expectation explains why people generate larger grip and lift forces when lifting larger objects than when lifting smaller objects of the same weight and describes the size-weight illusion as a product of the mismatch between the expected weight and the sensory feedback obtained from the object's actual weight following lift-off. Generating greater-than-necessary forces for lifting may result in the perception of reduced heaviness, and vice versa.

Rationalization Theory as investigated by Mon-Williams and Murray [66] states that, the size-weight illusion induced by visual size cues arises due to a cognitive process in which the subjects form an awareness that the objects have the same weight and so attempt to rationalize, at a cognitive level, the discrepancy between the awareness that the objects are the same in weight and the actual sensory feedback in which the objects are perceived to vary in weight.

2.4 Summary

This chapter gives a brief introduction of power assist system, which includes its definition, purposes, characteristics, advantages, areas of applications etc. This chapter also highlights some basic concepts of human's perception, especially weight perception and two other related topics of weight perception: psychophysics and size-weight illusion.

The current research takes two areas into consideration: technical (power assist system) and psychological (weight perception of object carried with the system). In fact, this research aims to realize psychological phenomena into technical domains. This research may be termed as a psychological adjustment with technical devices or technical applications and translation of psychological aspects or the both. This research addresses humanization of technology or mechanization of human characteristics.

Hence, brief discussion on the basic concepts of power assist system and weight perception summarized in this chapter will not only help understand these two areas separately, but also

help combine these two areas in order to develop a tangible device (power assist system) on the basis of an intangible matter (weight perception).

Chapter 3: Literature Review/Related Works

3.1 Literature Review on power assist systems

Though a plethora of literatures on cooperation between humans and robots have already been developed, a few researches on “power assist system” have been published yet. The power assist systems are being used mostly for the purposes of maneuvering objects, giving supports to the aged and disabled people etc. These systems are being used mainly in the forms cooperation between human and a robot manipulator ,cranes, bed system, hand gloves, exoskeleton (upper, lower),inner-skeleton robot for human motion assist, wheelchairs, walking chair, tri-cycles ,rescue robots etc. Some of the recently published researches on “power assist system” are summarized below:

In early1960s, a power assist system called “Man-amplifier” was developed at Cornell Aeronautical Laboratory for the U.S. Air Force to manipulate heavy objects [15].During 1966-1971, another power assist system named “Hardiman” was developed by General Electric [15].During late 1980s, H. Kazerooni [5] [15]-[18] developed power assist systems called “Extenders” (or, Personnel Amplification Systems, PAS). Extenders are power assist devices worn by human that grasp and maneuver heavy objects in space. Recently, H. Kazerooni [19] has developed “human-assisted walking robots” for maneuvering heavy loads in isolated areas for an extended period of time. H. Kazerooni [14] has also developed lower extremity exoskeleton called “BLEEX” for bearing load.

During early 1990s, a power assist system resembling the “Virtual Tool” was proposed by K. Kosuge and T.Fukuda [20]. This research proposes an alternative control algorithm for the mechanical system which interferes with both an environment and a human operator (man-machine system). The algorithm is designed so as to control the dynamics of the mechanical system to imitate passive tool dynamics. The proposed control algorithm specifies the human force augmentation ratio and the maneuverability of the system.

T. Takubo et. al. [21] presented a robotic assistance system which enables a human to handle unwieldy long objects by providing only one point of support. The robot grasps one end of the object and helps the human operator carry it at the other end. The proposed control method uses a virtual nonholonomic constraint. The movement of the object is constrained as if it were being carried on a wheel attached to the object. This method prevents the object from slipping sideways and simplifies the carrying operation. In spite of the constraint, the object can reach any position and orientation due to the nonholonomy. Cooperative manipulation in a horizontal plane is considered first, and then it is extended to 6-DOF manipulation in 3-D space.

Hyoung-Ki Lee et. al. [22] presented a control algorithm for mobile power assist systems. In their scheme, the mobile base does not move until the center of gravity (C.G.) of the system goes outside the safety region. When C.G. reaches the boundary of the safety region, the base starts to move to recover the manipulator's initial configuration. By varying the parameters of a human impedance controller, the operator is warned by a force feedback that C.G. is on the

marginal safety region. Assigning a nonlinear mass-damper-spring impedance to the tip of the manipulator, their scheme is implemented.

Y. Hayashibara et. al. [23] deal with a power assists system that is used for attenuating the load force. In such system, it is a serious problem that the maneuverability and the stability are lost when the actuators are saturated. For avoiding that, the authors have proposed the power assist system with individual compensation ratios for gravity and dynamic load. In a research paper, based on the operational sensation, the authors confirm the validity of the proposed method and discuss how the compensation ratios should be determined through their experiments.

K. Tanie et. al. [7] proposed an assist system for carrying a long object with a human operator. When people carry such an object, they often grasp both ends and move it cooperatively. The authors' purpose was to establish how to design the assist system which can achieve such a task. It is difficult to apply conventional control laws. On the other hand, human can achieve such a task. Therefore, the authors measure the human cooperative behaviors and analyze them to find the cooperative rules. Based on the rules, the authors propose a control law of the assist system. Furthermore, they construct a prototype system and verify the validity of the control law.

During early 2000s, K.Terashima et. al. [12], [24]-[27] developed Power assisted cranes. At first, a power assist system for a traveling crane was presented. This system is realized by measuring the crane's swing angle, which is caused by the operator's direct movement of the object held by a traveling crane, and by moving the trolley and girder in the desired direction. Therefore, operators can move a heavy object freely using only slight force. This system is applied to an experimental traveling crane in the laboratory, and the effect of energy saved by the power assist is shown by measuring the heart rate of operator. This research was extended for both horizontal and vertical movements.

Recently, R.Ikeura et. al. [68] developed a control method for a power assist device used in factories. They proposed an improved system controlled by an adaptive control in which the local control method changes to a feedback or a feedforward control in the contact direction. The improved system detects collisions based on the difference between the actual input torque to the power assist device and reference input torque, which is calculated based on the estimated parameters of the manipulator dynamics. The effectiveness of the system was also shown.

R. Ikeura [69] recently developed another power assist system based on dynamic characteristics of human and support system.

Recently, H.Yamada et.al. [74] developed a pneumatic hand crane type power assist system for carrying load in vertical direction. Here, the acceleration of the load was found proportional to the operation force applied by the human operator. The control system included a human model. In the human model, the operation force of human was modeled as the sum of the feedforward force and the feedback force; however the feedforward force was dominant. As the feedforward force model included weight of the load, the feedforward force programming cannot be perfect unless the human operator can perceive the weight of the load correctly before applying force. Again, feedback force programming strategy cannot make the operation force programming correct, especially during the initial trials of maneuvering, as the operator needs experience to program feedback force.

3.2 Literature Review on weight perception of object

Perception of object weight is a very active area of research in the fields of psychology, psychophysics, virtual reality, haptics, cognitive systems etc. Recently, an enormous volume of research on weight perception of lifted objects is being carried out with great importance and interest. This research on weight perception of objects usually addresses different aspects of heaviness perception, size-weight illusion, forces (load, grip) programming, consideration of various factors influencing weight perception, grip strategies and procedures, lift strategies and procedures etc. A few of the very recent and related publications on weight perception of objects are discussed below:

Chang, E. C., & Goodale, M. A. [28] in a recent paper give an interesting explanation about size-weight illusion and human's force programming in lifting an object. It has been suggested earlier that the illusion arises from a mismatch between predicted and actual sensory feedback. This recent paper says that size-weight illusion is stronger when the subjects have no prior sensory information (say, object is lifted from a table) than when the subjects possess prior sensory information (say, object is lifted from subject's own palm of other hand), but size-weight illusion exists in both cases. Thus, this paper disproves that size-weight illusion arises from a mismatch between predicted and actual sensory feedback. This paper says that, when the subjects have no prior sensory information,

1. Subjects' grip force programming to lift an object depends on how the subjects perceive the object's size (and not on object's weight perception), when the subjects lift the object for the first time. It means, larger grip forces are applied for the larger objects, even though the objects' weight may be same.
2. But, from the second time of lifting of the same objects (repeated lifting), subjects' grip force programming to lift an object depends on object's haptic weight perception from previous sensory memory and feedback (and not on visual size perception). It means, equivalent grip forces are applied for all objects of equal weight, even though the objects' size may be different.

Flanagan, J.R., Beltzner, M.A. [30] reports, the size-weight illusion does not lessen even when the lifter is informed that the objects are equally weighted, and this illusion does not seem to weaken with repeated lifting. This illusion is strongest when the lifter has both haptic and visual cues, and is still powerful when the lifter has only visual cues (say, to lift using a string). Though, earlier it was assumed that the size-weight illusion is caused by a mismatch between predicted and actual sensory feedback (sensory mismatch hypothesis based on motor control theory), this paper disproves this sensory mismatch hypothesis and assumes that size-weight illusion may be caused by high-level purely cognitive and perceptual factors such as domain-specific semantic knowledge etc.

This paper says that, people's expectations about object weight are observed in their motor output during the initial load phase of lifting during which vertical load force is increased before lift-off. During the load phase, grip force and load force are increased in parallel to prevent slip. The rates of change of grip force and load force, which precisely depend on the perception of object weight, increase to a maximum and then decrease in anticipation of lift-off. These early peaks in the force rates are the result of feed forward or anticipatory control processes and thus index subjects' predictions of object weight. If people's predictions of object weight are faulty, then lift-off will occur either sooner than expected or not at all. When people lift objects of varying size but equal weight, the peak values of grip and load forces and force rates and vertical acceleration after lift-off increase with object size. This paper proves that, subject's force programming (grip, load) for initial first or second lifting

fully depends on the visual perception of object size. It means, larger forces (load, grip) are applied for the larger objects, even though the objects' weight may be same. But, after 5-10 lifting, subject's force programming (grip, load) for lifting fully depends on the haptic perception and immediate sensorimotor memory of object weight. It means, equivalent forces (load, grip) are applied for all objects of equal weight, even though the objects' sizes may be different.

This paper reports that, several factors influence the forces programming (grip, load) of the lifter. The factors are visual and haptic information about object size and shape, visual information about object weight distribution, object identity, immediate sensorimotor memory obtained from previous lifts with the same object.

A research by Kawai S. et. al. [46] proves experimentally in an augmented environment that, the size-weight illusion induced by only visual size cues is sensory based, and depends on an individual's integrated perception based on multimodal sensory information. This research argues that, size-weight illusion correlates with subject's sensitivity to weight difference but not subject's sensitivity to small differences in visual size. This research finally opines that, size-weight illusion may be basically and systematically induced by neural integration of visual or haptic information about size and sensorimotor information about weight, and may then be modified by highly cognitive factors such as expectation, experience or rationalization.

Zatsiorsky V.M., Gao F., Latash M.L in a recent research [29] proves experimentally that, for lifting tasks (1) as long as subjects hold the object statically, only the gravitational force (object weight) scales the load force and the grip force changes linearly with the load force (2) in dynamic situation (when the object is lifted vertically), the load force is the summation of the gravitational force (object weight) and inertial force (object mass \times acceleration) in the vertical direction, and the grip force changes with the load force according to an ellipse-like pattern.

According to basic physics, the local effects induced by gravity and acceleration are identical and cannot be separated by any physical experiment. But, **this research proves experimentally that, for lifting tasks, people can recognize the effects of the gravitational and inertial force components on load force differently** (, which is reflected through the differences in grip forces adjustment patterns).

But, this research paper has some limitations as the following:

- (1) It could not explain the reasons behind the differential effects of gravity and inertia on finger forces (load and grip forces)
- (2) Simultaneous changes of both effective gravitational force and inertial force were not studied
- (3) the internal relationship between the gravitational force and inertial force was not considered.

A recent paper by Daniel Eastough, Martin G. Edwards [31] shows by experiment that, not only position and size of the object but also object mass affect movement kinematics (grasp aperture, grasp velocity, lift velocity, lift delay, grasp angle, grip position etc) in prehension (to reach and grasp an object). This paper shows experimentally that, grasping objects of increased mass leads to a greater peak grasp aperture to ensure a secure grip position on the object, an increased lift delay to ensure appropriate grip force programming, an enhanced probability of gripping the object at its center of mass to provide ideal grip position and grip force, and a reduced peak lift velocity to save the object from dropping during the lift action.

Geoffrey P. Bingham[32] studied a principle called KSD (Kinematic Specification of Dynamics) in lifting an object in order to determine dynamic factors or kinetic quantities of a system (such as weight, force, stiffness/impedance) from the system's kinematic patterns or clues (such as lifting velocity & acceleration, lifting motion, lifting trajectory, leans performed to preserve balance during lifting etc). In this paper, through using the KSD principle, the author investigated how the lifters varied the kinematic patterns while lifting the weights and how and on what basis the changes in kinematic patterns might be scaled to perceive weights of the lifted objects by the observers.

However, the KSD was not unique, relation was somewhat nonlinear, it was difficult to model the relation mathematically etc. Again, this principle was formulated for the case when the lifter's action was observed by other observers and it might not be useful for the case when the lifter would himself/herself try to perceive the object weight during his/her own lifting of the object.

The paper by JR Flanagan & CA Bandomir [33] investigated how changes in grasp configuration affect perceived heaviness in a weight discrimination task. The results clearly demonstrate that perceived weight is influenced by grasp configuration. They show that objects are perceived to be lighter when lifting with (1) a wide grip in comparison with a narrow grip, (2) five digits in comparison with two digits, and (3) a large contact area in comparison with a small contact area. However, the angle of the contact surfaces did not influence perceived weight.

This paper states that, perceived weight increases when the total effort required to support a given load increases. This paper reports that, both central motor command (efferent) and peripheral signals (afferent responses; from skin, joints and muscles evoked by the object weight itself) affect weight perception, though their relative contribution may be different. This paper defines effort as the level of central motor drive (efferent signal) associated with lifting. This paper defines the total effort as the central motor drive associated with both lifting forces and forces only indirectly involved in lifting (say, grip force). The authors suggest that changes in central motor commands due to changes in total effort associated with grasp differences may influence perceived weight, at least under some conditions.

Amazeen EL, Turvey MT [34] and Kinoshita H, Bäckström L, Flanagan JR, Johansson RS [35] say that, rotational dynamics and torques have important contribution to weight perception. Hence, the subjects are to grasp the center of the object while lifting and be instructed to lift the object such that the grip axis would be aligned vertically with the center of mass of the object in order to try to eliminate rotational dynamics and torques.

Kawai, S. et. al. [36] proved experimentally using a virtual environment that during lifting an augmented object with a precision grip, grip and load forces demonstrated significant rates of increase as well as peak forces as the size of graphical images of the object increased in spite of the fact that extraneous haptic information regarding the physical object remained constant. By indicating a human tendency to rely - even unconsciously - on visual input to program the forces in the initial lifting phase, this finding provides further confirmation of previous research findings obtained in the physical environment; including the possibility of extraneous haptic effects.

The research by A.M. Gordon et. al. [37] proved experimentally that while lifting objects (boxes) of equal weight but different size with precision grip, the rate of increase of the

isometric grip and load forces initially during the lift, the peaks of the grip and load force and the vertical acceleration were all found to increase with the box size, though the size-weight illusion still existed. When lifting an object, the vertical force increases gradually until the object starts to move. The rate at which the vertical force increases depends on the anticipated weight of the object on the basis of object's visual size.

A.F. de C. Hamilton et. al. [38] proved experimentally that, when weight is lifted by a lifter and is judged by an observer, perceived weight by the observer increases linearly with the increase in the duration of the start of the early lift phase (lift delay increases). It is assumed that, this increased lift delay is to ensure appropriate grip force programming as proved in [31]. This paper informs that, when a subject lifts an object of unknown weight, it takes approximately 100ms for the motor system to detect and respond to the weight.

This research by Kawai, S. et. al. [39] suggests that small changes in size as haptically perceived by the fingertips have a direct influence on heaviness perception when comparing objects of equal density as well as when comparing objects of different densities. The finding, therefore, can be considered analogous to the size-weight illusion when comparing objects of different densities. The findings of this study also suggest the constant involvement of haptically perceived size in heaviness perception by humans along with the existence of a processing mechanism that integrates the factors of weight and haptically perceived size in which **heaviness increases either as weight increases or as haptically perceived size decreases, and vice versa.**

The results of this experiment indicated that equal differences in weight were more accurately perceived with a pair of higher density materials than for a pair of lower density materials. The results of this experiment indicated that perception is more accurate for heaviness than lightness regardless of material. It means, sensitivity to heaviness is greater than that for lightness. This research supports the concepts of [33] and [43].

This study by Kawai, S. et. al. [40] investigated the contributions of object weight, haptic size, and density to the accurate perception of heaviness or lightness in the process of discriminating differences in weight. This paper proves that, 1) a parallel increase or decrease in the factors of density and weight facilitates an accurate perception of heaviness or lightness 2) changes in opposite directions between the factors of density and weight result in remarkably inaccurate perception of heaviness or lightness. This research reports more difficulty during discriminating weight differences in different density conditions than in the constant density conditions.

A research by Kawai, S. et. al. [41] proves experimentally that, while lifting an object with precision grasp without having visual cues, the discernment of an object's heaviness depends on the integration of sensory information about object weight and haptically perceived size of finger aperture. That is, **when a subject lifts an object to judge heaviness without viewing the object, the perceived heaviness is most accurately predicted from the ratio of width-to-weight of the object.** Another research by Kawai, S. et al [42] verified the previous finding of heaviness perception in [41].

Gordon AM et. al. [43] reported that, haptically perceived size was used for force programming when blindfolded subjects touched an object by themselves before lifting it and force amplitude was set according to the haptically perceived size of the object. Gordon AM et al [44] states that, when the weight is not kept constant but varies in accordance with the volume, subjects apply a force to lift the object that is appropriate for the volume.

The research by Brenner E. et. al. [45] says that, force programming for lifting an object requires anticipation of the object's weight on the basis of its visual size. Not only the actual change in visual size, but also the illusory change in visual size influences the force used to lift the objects. When lifting an object, the vertical force increases gradually until the object starts to move. The rate at which the vertical force increases depends on the anticipated weight of the object on the basis of object's visual size. Thus, the time between the moment the object is grasped and the moment it starts to move provides information about the anticipated weight. If the subject expects the object to be heavier than it actually is, the subject will increase the vertical force slightly faster than he would otherwise, so that the object will start moving earlier than expected. If he expects it to be lighter, he will increase the force more slowly, so that the disk will start moving later than expected.

Another research by Kawai S. et. al. [47] suggests a smaller contribution of information on size to the force (grip, load) programming when lifting a small and lightweight object than when lifting a larger and heavier object. It means, when the handled objects are very small, the contribution of size information to the scaling of fingertip forces seems to be less important. The reason may be that, in this case, visual information may not always have definitive priority in force programming in lifting a task compared to other sensory modalities such as tactile or proprioceptive information.

A person's strategy for applying force while lifting an object is dependent upon visual cues. A study by Kawai S. et. al. [48] investigated the alteration of strategy in force programming when visual information about an object's size was obstructed (such as, darkened conditions, when sight is obstructed, when an object is shrouded by packaging etc) at the moment of lifting. This paper reports a several force programming strategies such as target strategy (in usual visual condition), feedback strategy, midway strategy, worst-case prediction strategy etc. This paper suggests experimentally that, when there is any doubt in force programming, subjects consider it as the worst-case and in order to ensure the most secure fit, the subjects apply a maximum force adequate for the largest object for all possible cases.

The paper by Miall, R.C. et. al. [49] reports that, the ability to judge the weight of a lifted object in the hand is thought to depend on both peripheral and central signals. Cutaneous mechanoreceptors and proprioceptors in the hand or arm can provide cues about the friction or pressure exerted by the object on the skin and about the force generated in joints and muscles to lift an object against gravity. This paper suggests that, weight judgments are not based solely on efferent or afferent signals, but on an integration of these signals with a representation of the body image. This paper suggests that, subjects usually judge an unchanged weight as heavier than the previous. This paper suggests that, forearm vibration of subject reduces accuracy in weight perception. This paper reports that changes in body posture and motions strongly influence on judgments of force control.

A paper by Westling G et. al. [50] reports that, one of the most important features of the hand is its prehensile capacity, i.e. the ability to grasp and hold objects. This paper suggests that, subjects decide optimal grip and load forces before applying the forces to the objects. This paper suggests experimentally that, when manipulating an object, a person adds a slightly increased but not extreme force to the minimal grip force necessary for holding it. This extra force was defined as a *safety margin*, which is needed to prevent accidental slipping and to avoid muscle fatigue, injuries and destruction of an object by excessive grip force. The safety margin varies from subject to subject. This paper reports that, three factors primarily

influence the magnitude of the grip force: object weight, friction between skin and object, safety margin.

Yasuharu Koike et. al. [51] discussed that, forward dynamic models capture the casual relationships between actions and their consequences. The brain constructs internal representations of the environment by integrating information from different sensory systems in the way that, our perceptual skills reflect the capabilities of the sensory systems to detect, analyze, and estimate objects in our environment, while our motor skills reflect the capabilities of the motor systems to plan, coordinate, and execute tasks. The nervous system learns to correct errors from external stimuli in two ways. One is feedback control, which monitors sensory signals and uses this information to act directly. The other is feed forward control, in which the nervous system predicts the future state using sensory information and initiates proactive strategies based on experience. This research also proved that, subject's hand stiffness, which is controlled in anticipation before contact, tended to be proportional to object weight and the stiffness value went to the peak just after the impact time. Thus, stiffness before contact is one of the indexes of weight estimation.

This result confirmed that, grip forces do not reflect the prediction of object weight. This research assumes that, grip force would be used as a command, but this is not reflected in the way the weight is felt directly. This research says that, stiffness level is affected by size information. This research also says that, a subject needs more than a 10% difference to be able to discriminate between the weights of two objects. This research also says that, while lifting object from visual cues, in order to judge the weight difference, both feed forward and feedback signals are used. The feed forward signal, such as the stiffness value, and the feedback signal, such as hand displacement, reflects the expected weight.

Deeb J. M et. al. [52] showed experimentally that, both male and female subjects with muscular fatigue in right arm perceive the weight to be less, which may lead to exert less force than needed to lift, carry, or support an object, possibly allowing the object to slip resulting in an accident or injury. This research showed experimentally that, male and female subjects perceive the weight differently without and with fatigued muscles.

When people lift objects of different size but equal weight, they initially employ too much force for the large object and too little force for the small object. However, over repeated lifts of the two objects, they learn to suppress the size-weight association used to estimate force requirements and appropriately scale their lifting forces to the true and equal weights of the objects. Thus, sensorimotor memory from previous lifts comes to dominate visual size information in terms of force prediction. The research by Flanagan J.R. et. al. [53] proved experimentally that, this sensorimotor memory is not transient, rather more stable. This research proved experimentally that, this sensorimotor memory is fully maintained for a period of 15 minutes and largely retained for 24 hours, even in the presence of potentially misleading visual size cues. This paper mentioned that, to lift an object, a vertical load force greater than the weight of the object must be applied.

A research by Biegstraaten M et. al.[54] proves by experiment that, when lifting an object, there is no direct relationship between the control of the reach-to-grasp movement of digits towards the object and the forces (grip, lift) applied at the surface of the object to lift it up. This research also proves, when reaching out for objects, the digits' paths curve so that they approach their positions of contact moving more or less perpendicularly to the object surface orientation. This increases the accuracy of positioning the digits and ensures that any forces

exerted at contact are nearly perpendicular to the object surface, so that friction can prevent the digits from slipping along the object surface. This research also proves, the impact force during contact is low. After impact, the digits spent about 200 ms in contact with the surface of the object before the object starts to lift. After impact, the digits first decelerated, and then they gradually built up grip and lift forces to lift the object.

M.N. McDonnell et. al. [55] prove experimentally that, due to the changes in biomechanics of hand for various grip types, grip type or grip strategy affects the amount of exerted grip force and the accuracy of scaling grip force to load force and its rate of change in lifting an object.

Marc O. et. al. [56] prove that, humans integrate visual and haptic information in a statistically optimal fashion. When no gravity, vision dominates over haptic sense for mass, as the absence of gravity removes some haptic information. This model states that, in weightless situation, the importance (weight) of the haptic sense in the visuo-haptic integration process decreases. As a result, the user feels the object much lighter.

3.3 Summary

This chapter, at first, introduces some significant researches on power assist system. The literature review reveals that, out of many applications of power assist systems, applications for carrying objects are more or less available, but applications for lifting heavy objects in industries are very limited. The researchers are addressing a few problems with power assist systems such as actuator saturation, mobility of the system etc, but some other important problems like consideration of human characteristics in design especially consideration of weight perception, system accuracy and stability, system safety and security, user friendliness, ease of use, maneuverability, operability etc are not being considered seriously. Hence, though the power assist systems are helpful to the humans, due to some limitations especially due to the limitation of not considering weight perception of objects in system design, the power assist systems have not yet been successful to be fully useful to the humanity.

On the other hand, this chapter also introduces some significant researches on weight perception of lifted objects. An enormous volume of research on weight perception of lifted objects has already been carried out with great importance and interest. This research on weight perception of lifted objects usually addresses different aspects of heaviness perception, size-weight illusion, force (grip, load) programming and force control strategies like feed forward and/or feedback force control, consideration of various factors influencing weight perception, reach-to-grasp strategies, grip strategies and procedures, lift strategies and procedures, situations during initial lifting, safety in lifting, difference between male and female in lifting, sensorimotor memory in lifting, situation in zero gravity in lifting etc. Though, these researches reveal important information for lifting objects, significant usage or applications of these research findings are usually not seen. The research findings on lifting objects seem to have no value, if these research findings can not be used for the benefits, advantages and welfare of the human beings.

The current research takes an initiative to combine the concepts of weight perception and the power assist system through the consideration of weight perception in the design and development of the power assist systems. If this project is successful, we will be able to see how the so far obtained research findings on weight perception help develop useful mechanical products. In this way, through this current research, the limitations of power assist systems will be overcome as well as the research findings on weight perception will see their applications in useful purposes.

Chapter 4: Construction of the Power Assist System

4.1 The Experimental Devices

A simple 1DOF (vertically up-down) power assist system was developed using ball-screw mechanism actuated by a servomotor. The ball-screw mechanism along with the servomotor was fixed on a metal board using screws and the board was vertically attached with the wall. An object tied with the load carrier of the ball-screw mechanism through a force sensor is lifted by a human operator. When the operator lifts the object, the human force is sensed by the force sensor and the force is sent to the control system. Thus, the human operator feels the object light to lift by dint of the control law. This is the power assist system in a nutshell.

Three (03) rectangular objects (boxes) of different sizes were made by bending aluminum (0.4 mm) sheet. The dimensions of the objects are as the following:

- Large Object
 1. Front Side = Back Side= 6 cm
 2. L.H.S.= R.H.S.= 5 cm
 3. Height =16 cm
- Medium Object
 1. Front Side = Back Side= 6 cm
 2. L.H.S.= R.H.S.= 5 cm
 3. Height =12 cm
- Small Object
 1. Front Side = Back Side= 6 cm
 2. L.H.S.= R.H.S.= 5 cm
 3. Height =8.7 cm

[N.B.: L.H.S.: Left Hand Side, R.H.S.: Right Hand Side]

Top side of each of the objects was covered with the same metal sheet (aluminum, 0.4 mm). The bottom side and the backside of each of the objects were open. Two small metal pieces (rectangular, thickness 10 mm) having hole (diameter 10 mm) in the center of each were attached with the interior of the L.H.S and R.H.S of the object (box) so that the center of the hole of each of the attached metal piece aligned with the center of the L.H.S and R.H.S of the object. The force sensor was built in the laboratory using the foil strain gage. The foil strain gage was pasted on a metal plate and one end of the plate was fixed with a wooden block. The holes of the two small metal pieces attached with each of the interior sides of the L.H.S and R.H.S of the object helped the object be tied with the holder of the wooden block. The other end of the metal plate on which the foil strain gage was pasted was fixed with the load carried of the ball-screw mechanism. An object could be tied, at a time, with the load carrier of the ball-screw mechanism through the force sensor. When an object is tied with the power assist system, we call it a 'power assisted object'. The height of the object from the floor of the laboratory and the distance between the object and the human operator were adjusted

according to the neutral posture (best work zone) conditions of OSHA guidelines so that the operator feels ergonomic and safe while lifting the object [58]. As the objects were made of very thin metal sheet, these were very light in weight and hence the system was free from vibration. The whole system is shown in the following figures:

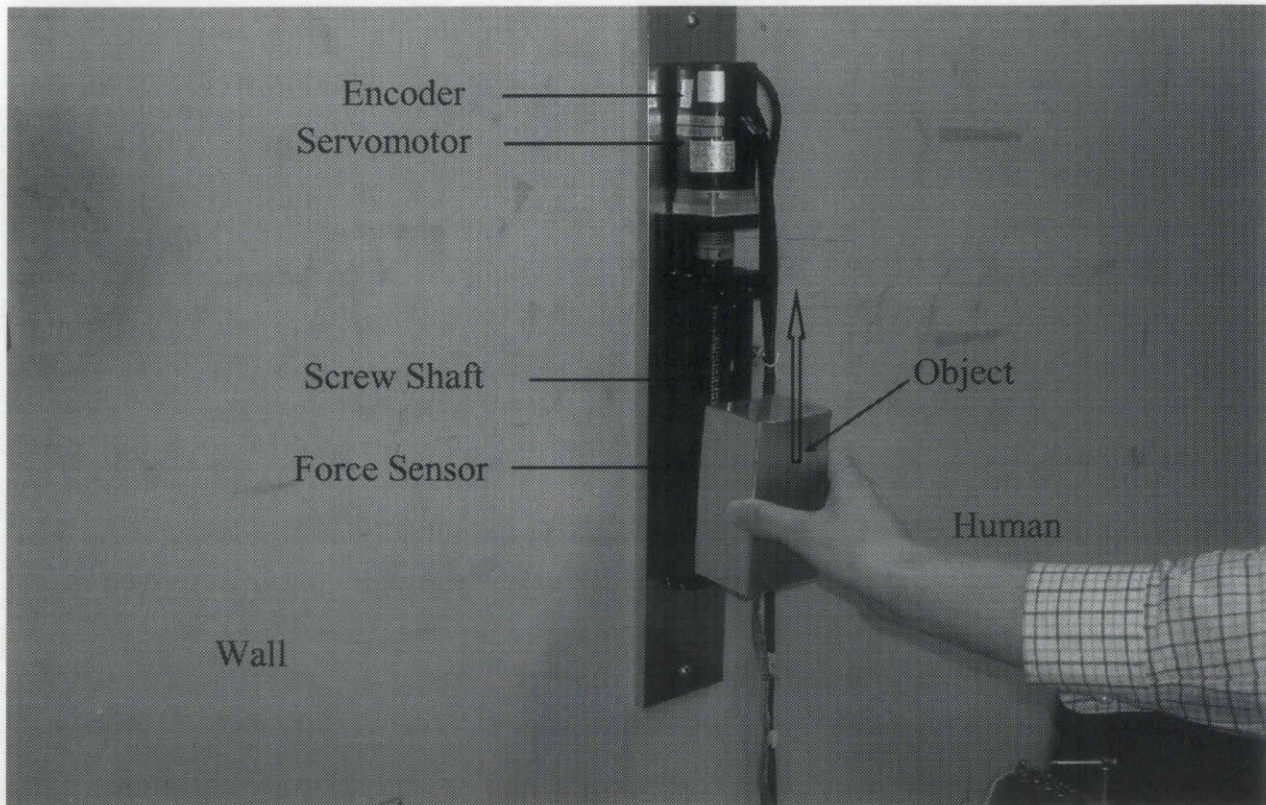


Fig.15: Human lifts an object with the 1 DOF power assist system of ball-screw mechanism actuated by a servomotor

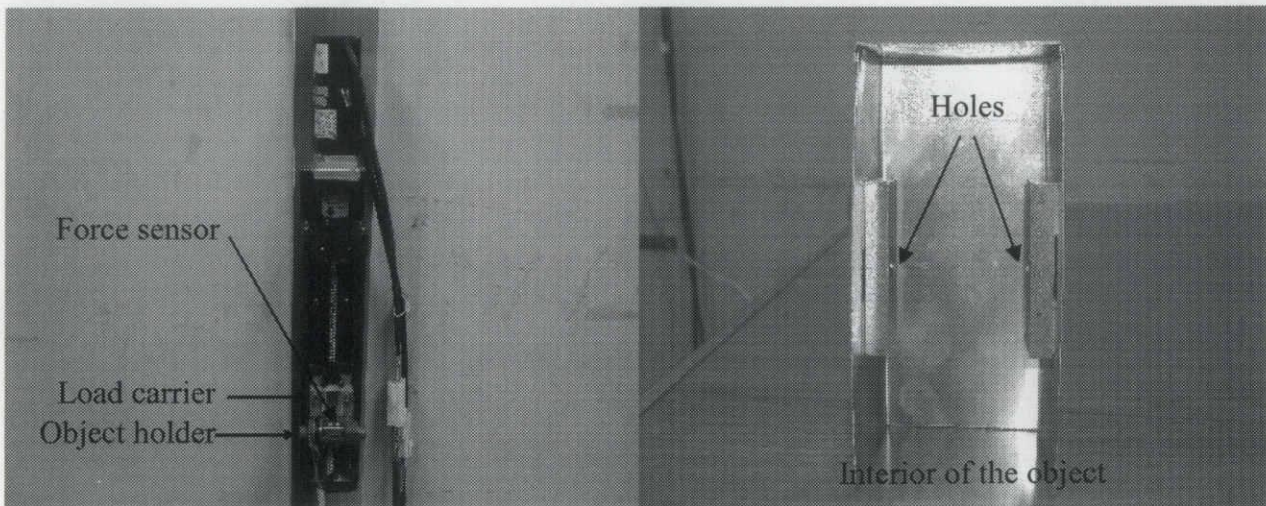


Fig. 16: Detailed picture of the force sensor and the interior view of the object

4.2 Experimental-Set up

Experimental set-up of the 1DOF power assist system is depicted below:

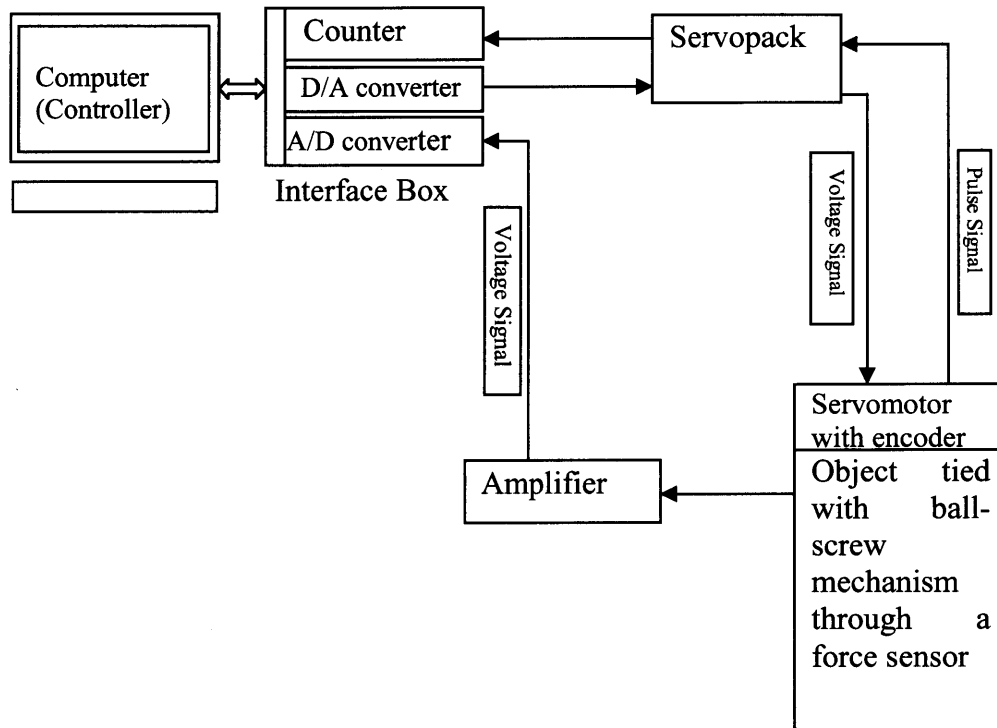


Figure17: Experimental set-up of the 1DOF power assist system

The power assist system was actuated by AC Servo Drives. In our case, the AC Servo Drives consist primarily of AC Servomotor with its controller, and Servopack. The servo pack receives a command signal (voltage signal) from the control system (controller in computer) through D/A converter, amplifies the signal, and transmits electric current to the servo motor in order to produce motion proportional to the commanded signal. The position sensor (encoder along with counter) attached with the servo motor reports the object's actual displacement back to the servo pack. The servo pack then compares the actual displacement with the commanded displacement. It then alters the commanded signal to the motor so as to correct for any error in the displacement. Human force is sensed by the force sensor attached with the load carrier. The force is sensed as voltage signal, amplified by the amplifier and then sent to the control system via the A/D converter. The human force gives acceleration to the object only.

4.3 Description of the Apparatus and Equipment

The computer system used in the experimental set-up was as the following:

Microsoft Windows XP
Professional

Version 2002
Service Pack 2
Intel (R)
Dell Dimension DX P061
Core (TM) 2 CPU
6400 @ 2.13 GHz
1.00 GB RAM

The computer gives 16-bit BUS data signals. MATLAB (The MathWorks, Inc., Version: R2006a) was installed in the computer. One Interface Box connected with the computer CPU contains a D/A board (Interface IBX-3329), an A/D board (Interface IBX-3148) and a Counter (Interface IBX-6201) board. The specifications of the Interface Box used in the experiment are as the following:

CONTEC CHASSIS, Taiwan
Model: FA-PAC (PC)
Type: F6RF
Ratings: AC115/230V, 50/60Hz

AC servo drives were used to actuate the system. In general, a servomechanism, or servo, is a device used to provide control of a desired operation through the use of feedback. It is a feedback system that consists of a sensing element, amplifier, and servomotor, used in the automatic control of a mechanical device. The term servomechanism, or servo for short, is sometimes used interchangeably with feedback control system (servo system). In a narrower sense, servomechanism refers to the feedback control of a single variable (feedback loop or servo loop). In the strictest sense, the term servomechanism is restricted to a feedback loop in which the controlled quantity or output is mechanical position or one of its derivatives (velocity and acceleration).

The AC Servo Drives were chosen for getting the following advantages/benefits:

1. Accurate control of motion
2. Maintenance of accuracy with mechanical load variations, input changes, changes in the environment, power supply fluctuations, and aging and deterioration of components (regulation and self-calibration)
3. Control of a high-power load from a low-power commanded signal (power amplification)
4. Their main advantage over traditional DC or AC motors is the addition of motor feedback. This feedback can be used to detect unwanted motion, or to ensure the accuracy of the commanded motion. The feedback is generally provided by an encoder of some sort. Servos, in constant speed changing use, have a better life cycle than typical a/c wound motors. Servo motors can also act as a brake by shunting off generated electricity from the motor itself.

It is said earlier that, in our case, the AC Servo Drives consist primarily of AC Servomotor with its controller, and Servopack. The AC Servomotor features a high power rating for achieving quick response. Specifications of the AC Servomotor and Servopack are given below:

AC Servomotor

Manufacturer: Yaskawa Electric Corporation, Japan (2000)

Name of the motor	AC Servomotor
Type	SGML-01BF12
W (rated output)	100W
V (power supply)	100V
r/min	3000
Encoder specifications	F:1024 P/R incremental encoder

SGML, Standard Generalized Markup Language

Servopack

Manufacturer: Yaskawa Electric Corporation, Japan

Type	SGDL-01BS
W (rated output)	100 W
V (power supply)	100V
Control mode	Speed/Torque

The ball screw mechanism converts rotary motion of the servomotor to linear motion efficiently. The screw shaft of the ball screw mechanism had single start (number of independent thread on the screw shaft). Screw pitch was 0.003 m and the screw lead was also 0.003 m. The land diameter (outside diameter) of the screw shaft was 10 mm. The length of the screw shaft was 20 cm. The length of the load carrier was 7 cm. Linear speed of the screw was $\text{rpm} \times \text{lead} = 3000 \times 0.003 = 9 \text{ m/min}$.

The force sensor was built in the laboratory using the foil strain gage. The foil strain gage was pasted on a metal plate and the plate was fixed with a wooden block for holding the object. The specifications of the force sensor are as the following:

Foil Strain Gage Type: N11-FA-1-120-23-P4-VSE1

Manufacturer: NEC San-ei Instruments Ltd.

In the current research project, the force sensor senses force only along the axis of vertical lift (upward-downward) and doesn't sense any torque or any force perpendicular to the axis of vertical lift.

The amplifier amplifies voltage signals received from the force sensor and sends the amplified voltage signals to the control systems (computer) through the A/D converter. In the experiment, an AC Strain Amplifier was used. The specifications are as the following:

Type: AS1203,

Manufacturer: NEC San-ei Instruments Ltd.

AC 100 V T0.1A

DC 12V T0.5A

Output +10V,-10V; 5mA, 30mA

A noise filter was mounted to prevent external electrical noise from the power supply line.
The specifications of the noise filter are as the following:

Type: LF-205A
AC.DC 250V, 5A
TV.AC 1500V

4.4 Dynamic Modeling of the System

A free body diagram of the dynamic system is shown in figure 18. In order to do dynamic modeling of the system, we identify the system parameters as the following:

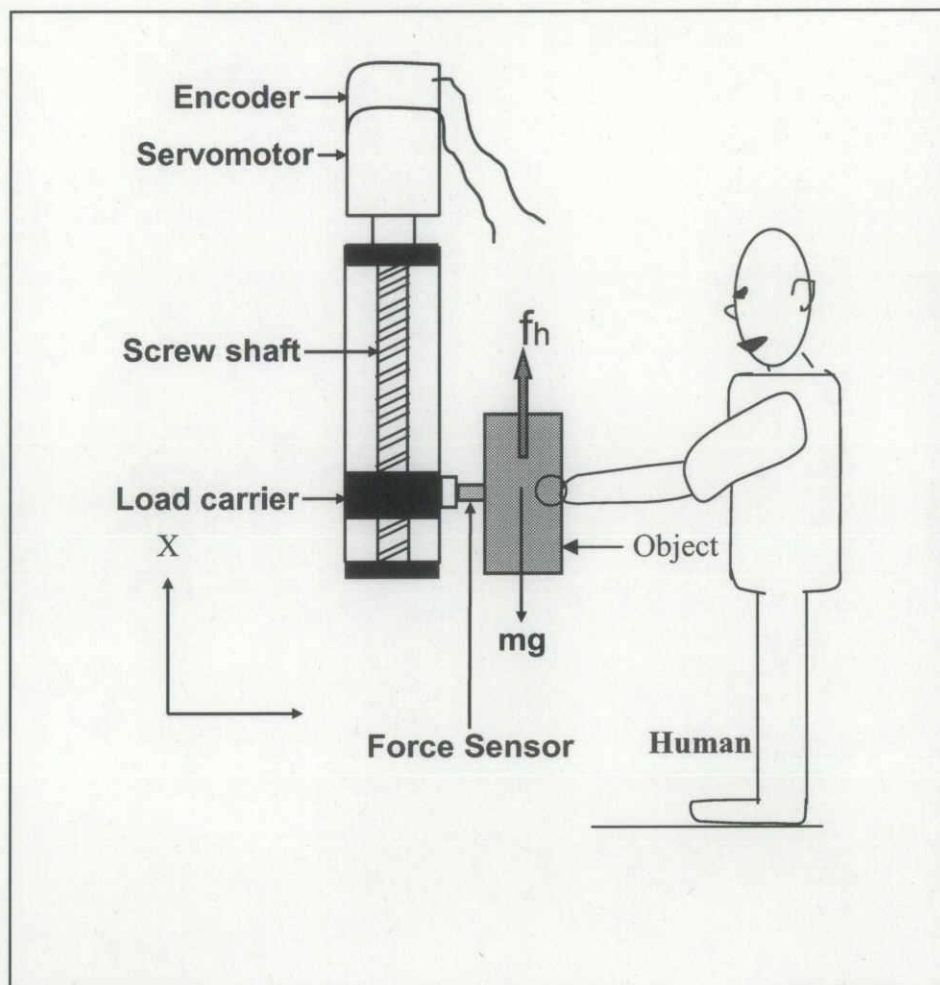


Figure 18: Human lifts an object with the 1DOF power assist system

f_a = Actuating force of the servomotor

f_h = Force applied by human operator

F = Friction force in ball - screw mechanism

K = Viscosity of the linear slider

m = Mass of the object

x = Linear displacement

Equation of motion of the system (**real system**) can be derived as the following:

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

But, the **actual (targeted)** system is as the following:

$$m\ddot{x} - mg = f_h$$

Zatsiorsky V.M. et.al. [29] in a recent research proves experimentally that, for lifting tasks (1) as long as subjects hold the object statically, only the gravitational force (object weight) scales the load force, and the grip force changes linearly with the load force (2) in dynamic situation (when the object is lifted vertically), the load force is the summation of the gravitational force (object weight) and inertial force (object mass x acceleration) in the vertical direction. 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. [29] proved experimentally that, for lifting tasks, people can recognize the effects of the gravitational and inertial force components on load force differently (which is reflected through the differences in grip forces adjustment patterns). Nevertheless, their research possesses some limitations as the following:

- (1) It could not explain the reasons behind the differential effects of gravity and inertia on human forces (load and grip forces)
- (2) Simultaneous changes of both effective gravitational force and inertial force were not studied
- (3) The internal relationship between the gravitational force and inertial force was not considered.

In our case, we would like to further extend the above findings by Zatsiorsky V.M. et.al. [29]. As our objective is to establish a psychophysical/cognitive relationship between the perceptual weight and the actual weight of the object carried with the power assist system, we need to include the psychophysical/cognitive considerations in Dynamic Modeling of the system as the following:

We, in our case, consider the above actual or targeted system as the following way:

$$m_1 \ddot{x} - m_2 g = f_h$$

Where,
 $m_1 \ddot{x}$ = Inertia force
 $m_2 g$ = Gravity force

$m_1 = m_2 = m$ is considered for most control systems of power assist applications, but, we think that, $m_1 \neq m_2$ 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 perceptual weight same. We also hypothesize that, human considers the actual weight and the perceptual 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 perceptual weight, the human operator needs to think the two 'masses' different before applying force to the power assist system.

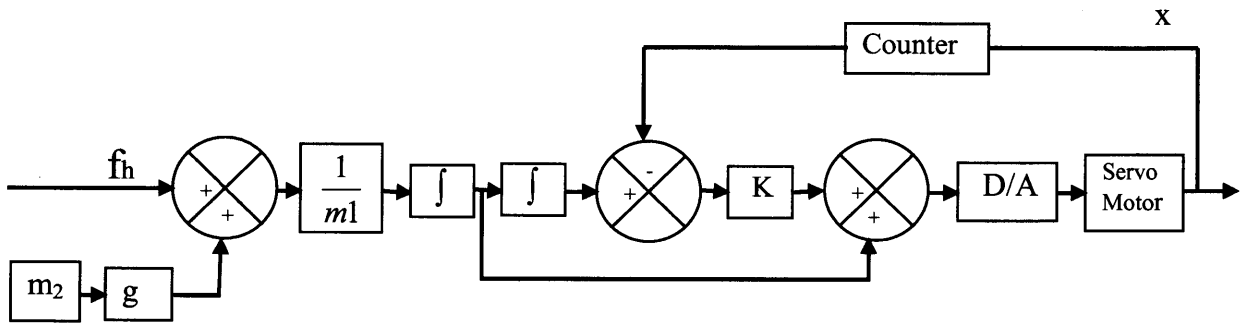
Hence, the **actual (targeted)** system with psychophysical/cognitive considerations takes the following form:

$$\begin{aligned} m_1 \ddot{x} - m_2 g &= f_h \\ \Rightarrow m_1 \ddot{x} &= f_h + m_2 g \\ \Rightarrow \ddot{x} &= \frac{1}{m_1} (f_h + m_2 g) \\ \Rightarrow \dot{x} &= \int \frac{1}{m_1} (f_h + m_2 g) dt \dots \dots \dots (2) \end{aligned}$$

This equation can be used as the velocity control law of the dynamic system.

4.5 Block Diagram of the Control System

Block Diagram of the control system is shown below. The control method is feedback position control method. The control program for the power assist system was designed in the MATLAB.



K: gain, x: displacement

Figure 19: Block Diagram of the control system of the power assist system

4.6 Summary

This chapter gives detailed descriptions of the construction and working principles of the power assist system. The descriptions include the physical construction of the power assist system, experimental set-up and the working mechanisms of the system, introduction of all devices and equipment used to construct the power assist system, dynamic modeling of the system along with psychophysical considerations, block diagram of the system etc. Thus, the so far works contained in this chapter make the power assist system ready to use for the purposes of experiments and analyses.

While designing and constructing the power assist system, special considerations were given to vibration control, control of electrical noises, system accuracy and stability, system safety and ergonomics, actuator saturation, human friendliness, cost effectiveness etc.

Chapter 5: Experiments & Results

5.1 Experiments

The following equation, adopted as the velocity control law, was simulated in MATLAB environment for various sets of values of m_1 and m_2 :

$$\dot{x} = \int \frac{1}{m_1} (f_h + m_2 g) dt \dots \dots \dots (2)$$

Values of m_1 and m_2 were set randomly from the following *Value Matrix*:

Table 1: Value Matrix

	m2		
m1=2	0.5	1	1.5
m1=1.5	0.5	1	1.5
m1=1	0.5	1	1.5
m1=0.5	0.5	1	1.5

5.1.1 Subjects

A physically & mentally healthy, naïve, aged 28 years, male, right-handed subject voluntarily participated in the experiment. The subject did not report any sensory, neurological, visual, muscular or cutaneous problems or impairments. The subject cleaned his hands before the experiment. The subject had neither prior experience with this system nor familiarity with the hypothesis being tested. No training was given to the subject, but instructions about the experiment were given to him. The experimental procedures were conducted in accordance with the ethical standards adopted by the university. The subject gave informed consent.

5.1.2. Experimental Procedures

5.1.2.1 Experiment 1: System Evaluation

It is seen from the value matrix in Table 1 that, there are $4 \times 3 = 12$ sets of values of m_1 and m_2 . In this experiment, the human operator (subject) lifts an object of a particular size with the power assist system for each set of values of m_1 and m_2 . While lifting the object for a particular set of values of m_1 and m_2 , the subject subjectively evaluates how he feels to lift the object for that particular set of values of m_1 and m_2 and then the subject rates his feelings as any one of the following:

- Maneuvering the object is Very Easy & Comfortable (VEC)
- Maneuvering the object is Easy & Comfortable (EC)
- Borderline (BL)
- Maneuvering the object is Slightly Difficult (SD)/Not So Easy & Comfortable (NSEC)
- Maneuvering the object is Difficult (D)/Very Difficult (VD) etc.

The subject rates his feelings about the system as described above on the basis of a predefined set of criteria. The criteria are described in Appendix A. The subject rates his feelings about the system for objects of three different sizes (large, medium, small) independently for each set of values of m_1 and m_2 . The subject's ratings about the system are then analyzed using a 5-point bipolar & equal-interval subjective rating scale[59]. VEC, EC, BL, SD/NSEC and D/VD are rating alternatives of the rating scale and are termed as '**descriptors**'.

5.1.2.2 Experiment 2: Weight Comparison

The subject lifts an object tied with the power assist system. We call this object a 'power assisted object'. As described earlier, we made 'power assisted objects' of three different sizes (large, medium and small). We simulate the weight of the 'power assisted object' of each size for various sets of values of m_1 and m_2 . Hence, the weight of the 'power assisted object' is simulated weight and as this simulated weight is perceived by the human operator while lifting the object, it is also the perceptual weight.

Besides the three 'power assisted objects' of three different sizes, we made three actual objects (boxes) of three different sizes (large, medium, small) by bending metal sheet (aluminum, 0.4 mm). The shape, dimensions, material and outlook appearance of an actual object of a particular size were same to that of the 'power assisted object' of that particular size. The self-weight of the actual objects was negligible as these were made of very thin metal sheet. However, it was possible to increase the weight of the actual objects by attaching/adding various masses across the interior of the front side of the objects (boxes). Each time, the center of any attached mass was aligned with the center of the interior of the front side of the object (box). Top side of each of the actual objects was also covered with the same metal sheet. The bottom side and the backside of each of the actual objects were open. Hence, the subject did not see any visual difference between the 'power assisted object' and the actual object of a particular size. Front and Back views of the actual object of medium size are shown in the figure 20 and 21 respectively.

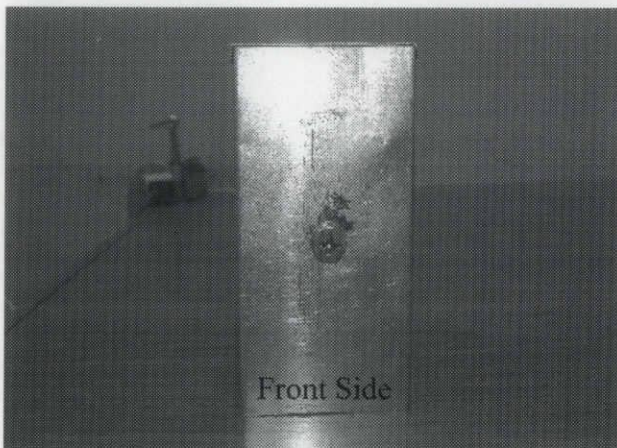


Fig.20: Front View of the actual object

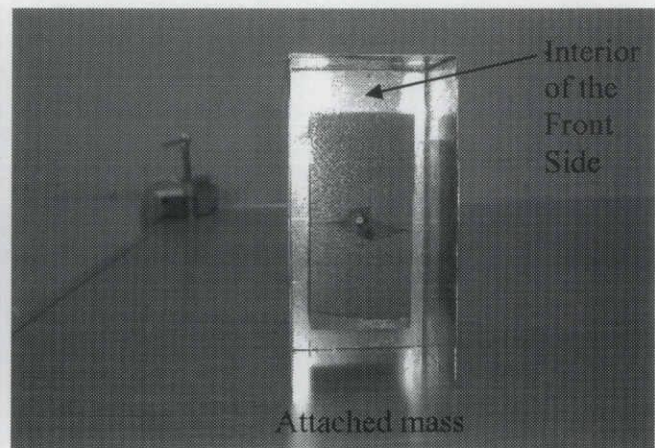


Fig.21 : Back view of the actual object

The weight of the actual object of each size was changed in a descending order starting from 1.5 kg to 0.1 kg (1.5 kg, 1 kg, 0.5 kg, 0.3 kg, 0.2 kg, and 0.1 kg). The weights of the actual objects are treated as the reference weights.

For each set of value of m_1 and m_2 , the subject compares the weight of the ‘power assisted object’ of a particular size with various weights of the actual object of that particular size. The subject compares weight between the ‘power assisted object’ and the actual object for objects of all three sizes (large, medium, small) independently for each set of values of m_1 and m_2 . The subject determines whether the ‘power assisted object’ of a particular size was heavier or lighter than the weights of the actual object of that particular size for each set of values of m_1 and m_2 . For each set of values of m_1 and m_2 for a particular object size, the subject identifies the value of the reference weight (actual weight) from where he starts to feel the ‘power assisted object’ heavier than the actual object.

In both experiment 1 and 2, the human operator lifts the power assisted object using right-handed power grip [58]. The front side of each of the 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 [60], [61]. The author encouraged the subject to grasp the center of the object while lifting and instructed him to lift the object such that the grip axis would be aligned vertically with the center of mass of the object in order to try to eliminate rotational dynamics and torques[33],[34],[35].

5.2 Experimental Data

Experimental data of both the Experiment 1 and Experiment 2 are shown below together for small, medium and large objects.

5.2.1 System Evaluation and Weight Comparison Data

Table 2: Experimental Data Sheet for large object

Object Size: Large

Sl. No.	Values of m_1 & m_2 set in the simulation		Actual/Ref. Wt. (kg)	Simulated /Perceptual Wt. is Heavier (H) or Lighter (L) than the Actual/Ref. Wt.	Evaluation of the overall system based on the predefined criteria
	m_1	m_2			
1	1	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			0.1	H	
2	2	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			0.1	H	
3	2	1.5	1.5	L	Difficult (D)
			1.0	L	
			0.5	H	

			0.3	H	
			0.2	H	
			0.1	H	
4	1.5	1.5	1.5	L	Difficult (D)
			1.0	L	
			<u>0.5</u>	H	
			0.3	H	
			0.2	H	
			0.1	H	
5	2	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
6	1.5	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
7	0.5	1.5	1.5	L	Very Difficult (VD)
			1.0	L	
			<u>0.5</u>	H	
			0.3	H	
			0.2	H	
			0.1	H	
8	1	1.5	1.5	L	Very Difficult (VD)
			1.0	L	
			<u>0.5</u>	H	
			0.3	H	
			0.2	H	
			0.1	H	
9	0.5	1	1.5	L	Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
10	1.5	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			<u>0.2</u>	H	
			0.1	H	

11	1	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
12	0.5	0.5	1.5	L	Very Easy & Comfortable (VEC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			<u>0.1</u>	H	

Table 3: Experimental Data Sheet for medium object

Object Size: Medium

Sl. No.	Values of m_1 & m_2 set in the simulation		Actual/Ref. Wt. (kg)	Simulated /Perceptual Wt. is Heavier (H) or Lighter (L) than the Actual/Ref. Wt.	Evaluation of the overall system based on the predefined criteria
	m_1	m_2			
1	1	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
2	2	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
3	0.5	0.5	1.5	L	Very Easy & Comfortable (VEC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			<u>0.1</u>	H	
4	1	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			<u>0.1</u>	H	

5	1.5	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			0.1	H	
6	2	1.5	1.5	L	Very Difficult (VD)
			1.0	L	
			0.5	H	
			0.3	H	
			0.2	H	
			0.1	H	
7	0.5	1	1.5	L	Difficult (D)
			1.0	L	
			0.5	L	
			0.3	H	
			0.2	H	
			0.1	H	
8	1.5	1.5	1.5	L	Difficult (D) or Very Difficult (VD)
			1.0	L	
			0.5	H	
			0.3	H	
			0.2	H	
			0.1	H	
9	0.5	1.5	1.5	L	Difficult (D) or Very Difficult (VD)
			1.0	L	
			0.5	H	
			0.3	H	
			0.2	H	
			0.1	H	
10	1	1.5	1.5	L	Difficult (D) or Very Difficult (VD)
			1.0	L	
			0.5	H	
			0.3	H	
			0.2	H	
			0.1	H	
11	1.5	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			0.3	H	
			0.2	H	
			0.1	H	
12	2	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	

			0.3	L	
			0.2	L	
			0.1	H	

Table 4: Experimental Data Sheet for small object

Object Size: Small

Sl. No.	Values of m_1 & m_2 set in the simulation		Actual/Ref. Wt. (kg)	Simulated /Perceptual Wt. is Heavier (H) or Lighter (L) than the Actual/Ref. Wt.	Evaluation of the overall system based on the predefined criteria
	m_1	m_2			
1	1	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	H	
			0.1	H	
2	2	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			0.1	H	
3	0.5	0.5	1.5	L	Very Easy & Comfortable (VEC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			0.1	H	
4	1	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			0.1	H	
5	1.5	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			0.1	H	

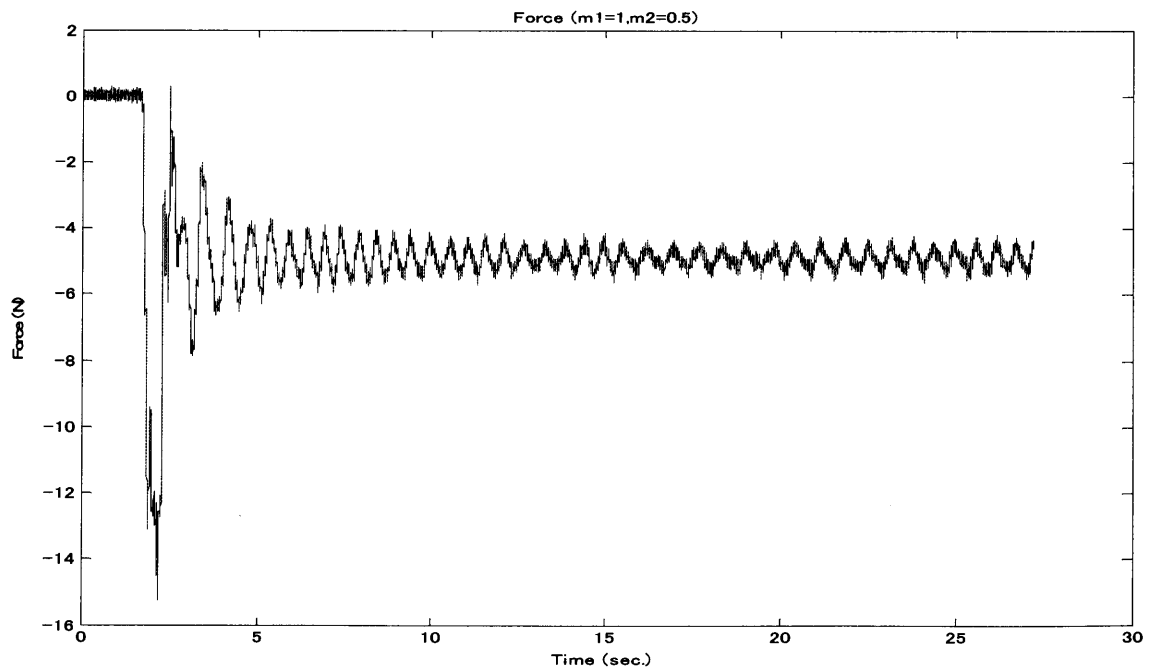
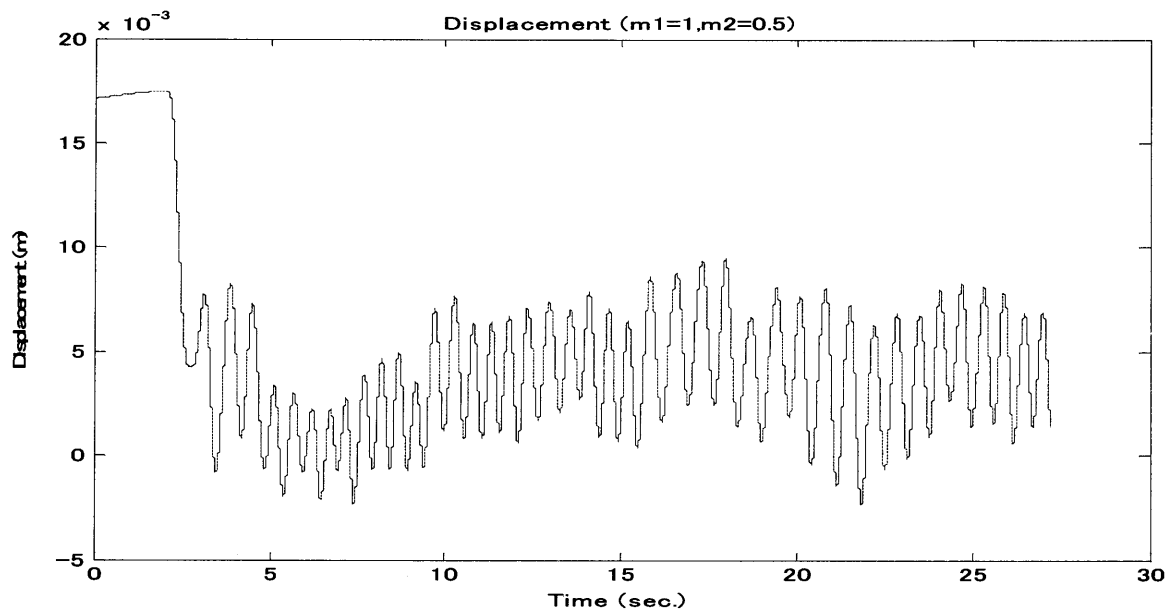
6	2	1.5	1.5	L	Difficult (D) or Very Difficult (VD)
			1.0	L	
			<u>0.5</u>	H	
			0.3	H	
			0.2	H	
			0.1	H	
7	0.5	1	1.5	L	Difficult (D)
			1.0	L	
			0.5	L	
			0.3	L	
			<u>0.2</u>	H	
			0.1	H	
8	1.5	1.5	1.5	L	Very Difficult (VD) or Difficult (D)
			1.0	L	
			<u>0.5</u>	H	
			0.3	H	
			0.2	H	
			0.1	H	
9	0.5	1.5	1.5	L	Very Difficult (VD) or Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
10	1	1.5	1.5	L	Very Difficult (VD) or Difficult (D)
			1.0	L	
			<u>0.5</u>	H	
			0.3	H	
			0.2	H	
			0.1	H	
11	1.5	1	1.5	L	Not So Easy & Comfortable (NSEC)/ Slightly Difficult (D)
			1.0	L	
			0.5	L	
			<u>0.3</u>	H	
			0.2	H	
			0.1	H	
12	2	0.5	1.5	L	Easy & Comfortable (EC)
			1.0	L	
			0.5	L	
			0.3	L	
			0.2	L	
			<u>0.1</u>	H	

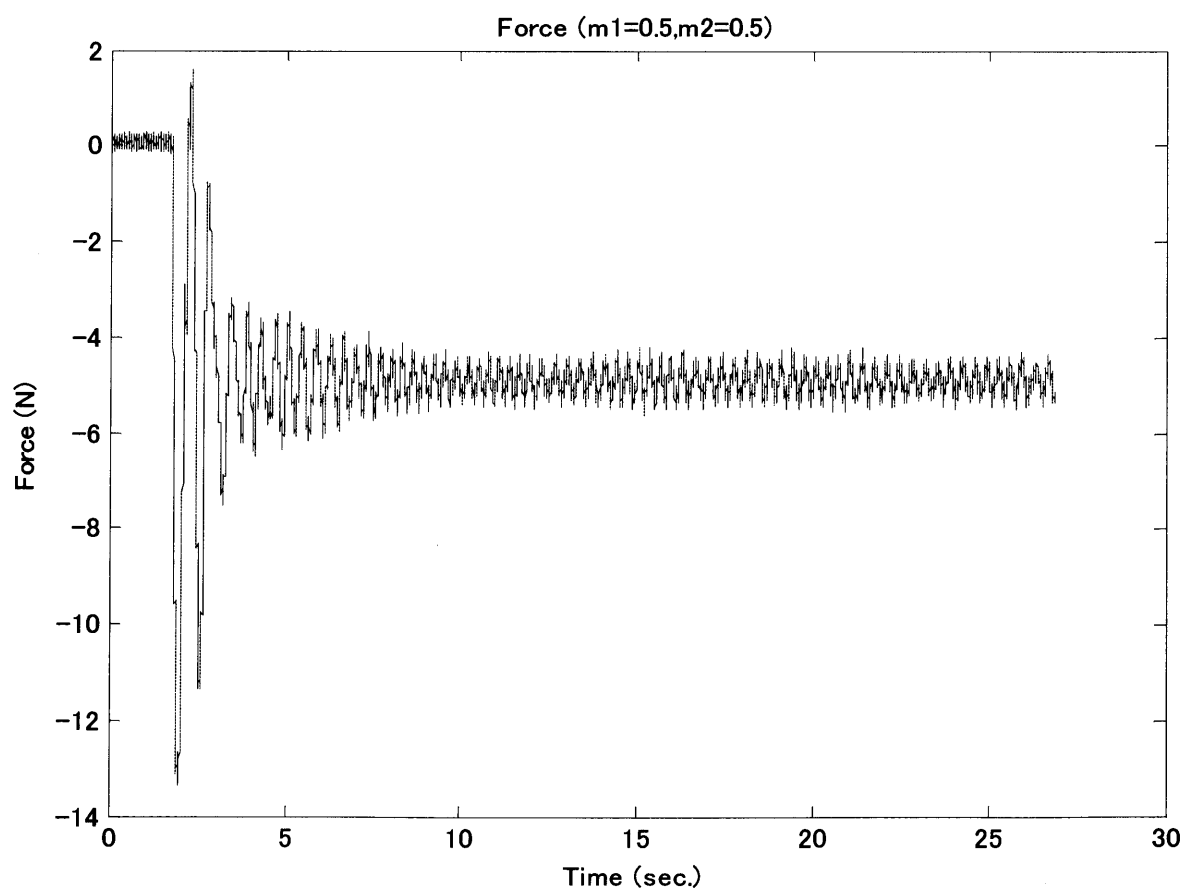
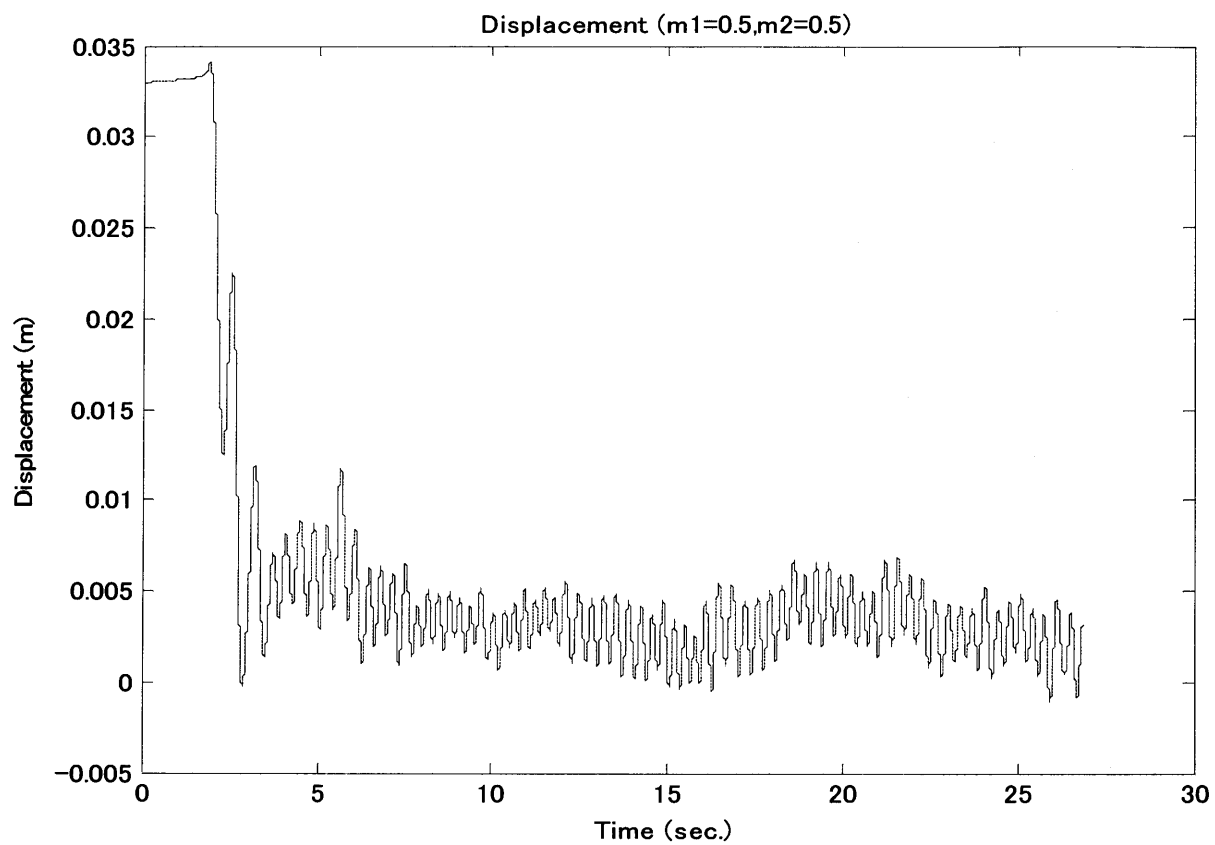
In the Actual/Ref. Wt. column of each table, the reference weight points (kg) from where the subject starts to feel the 'power assisted object' (simulated/perceptual weight) heavier than the reference weight were underlined. Each of these points indicates that, the exact value of the simulated/perceptual weight of the power assisted object simulated for a particular set of values of m_1 and m_2 lies between this weight point and the weight point immediately above this.

5.2.2 Displacement and Force Data

Displacement and Force data for each set of values of m_1 and m_2 for objects of different sizes were saved. Displacement data refers to the displacement of the object lifted with the power assist system and the Force data refers to the human's hand force applied to the object to lift it with the power assist system. The patterns of displacement and force data for different sets of values of m_1 and m_2 for different size of objects were more or less similar. Hence, a few displacement and force data for different sets of values of m_1 and m_2 for different size of objects are shown below as sample. Here, positive displacement indicates upward displacement and negative force indicates upward force.

Displacement and force data for large size object:





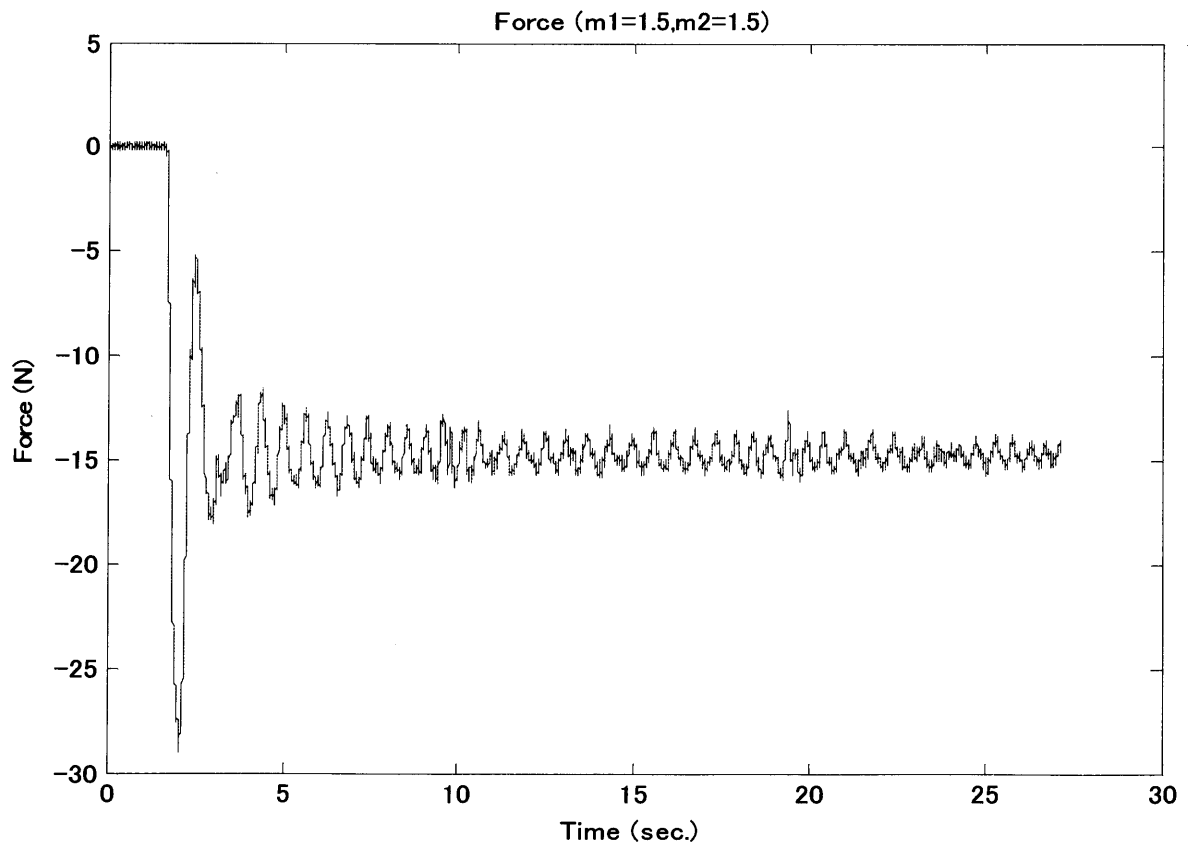
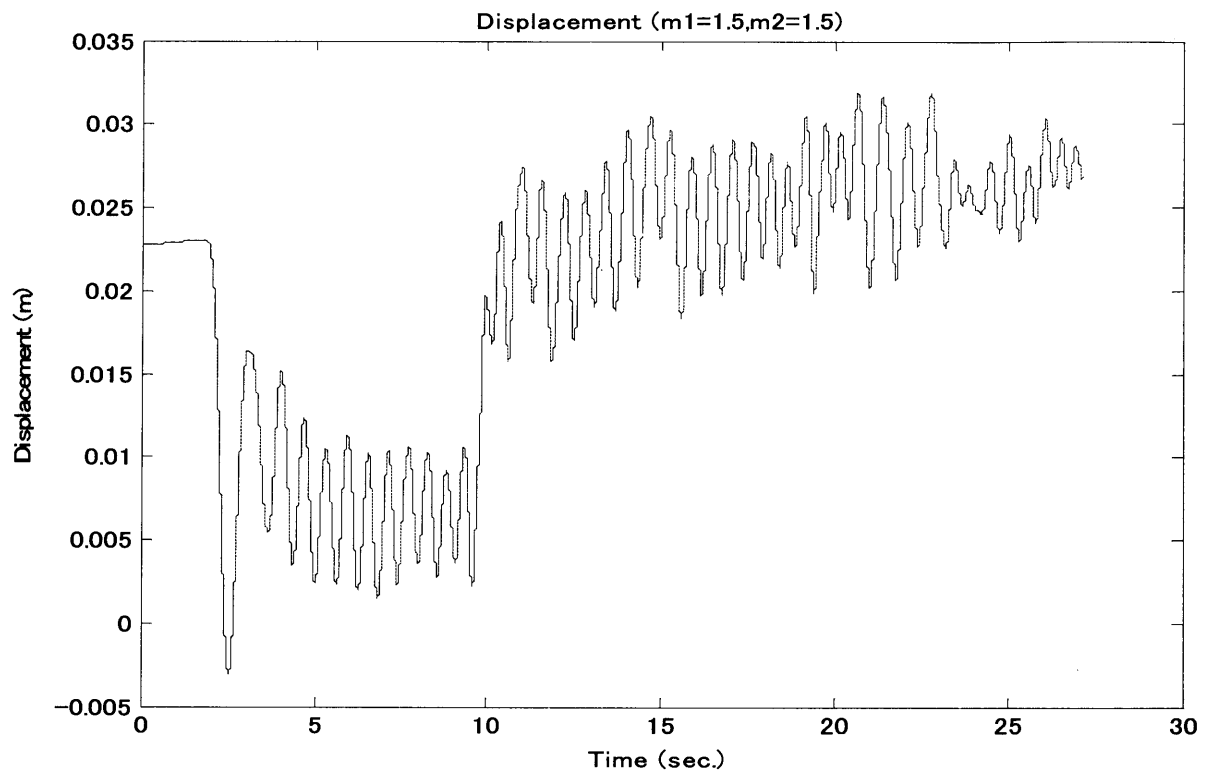
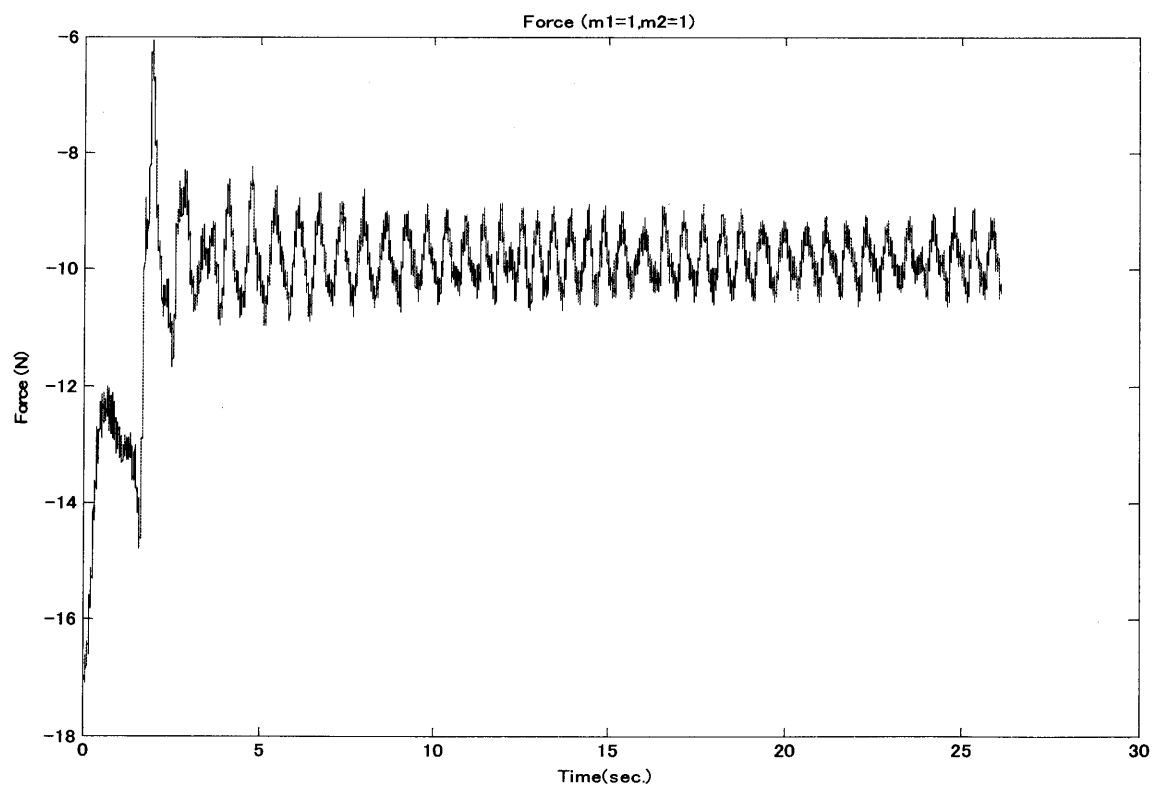
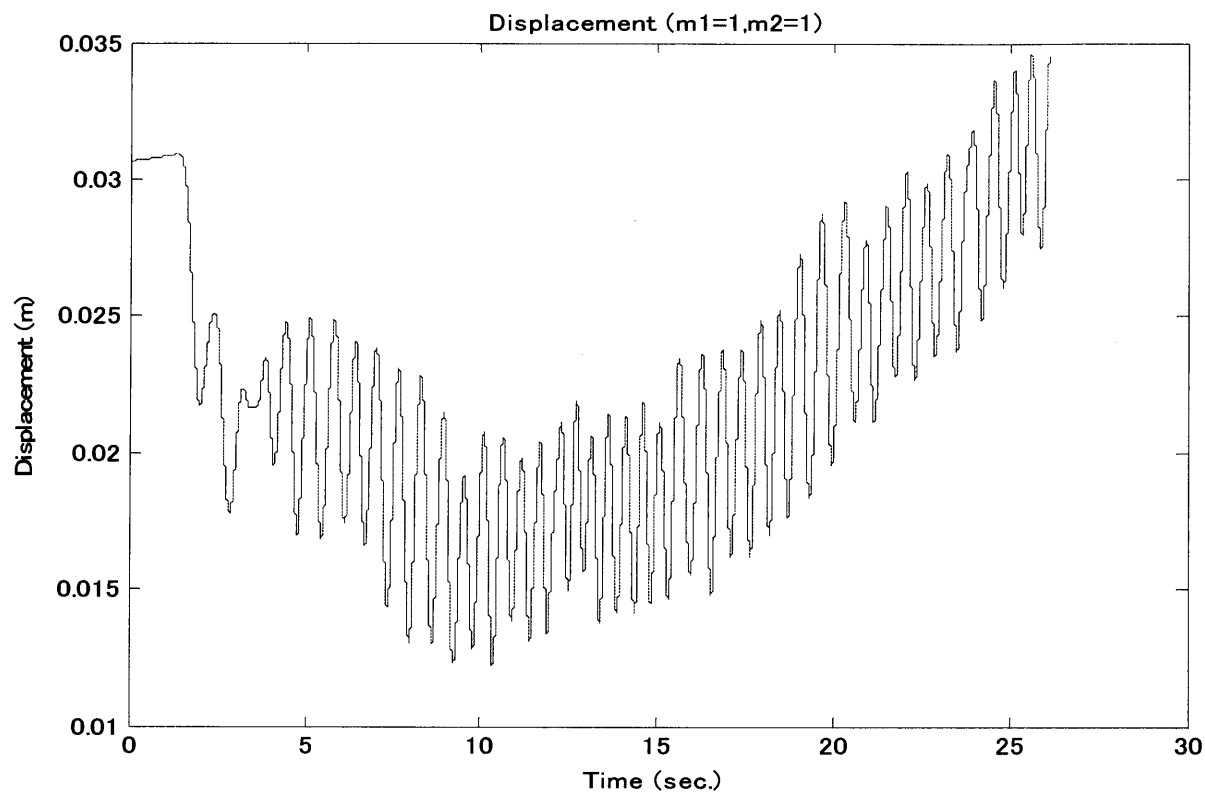
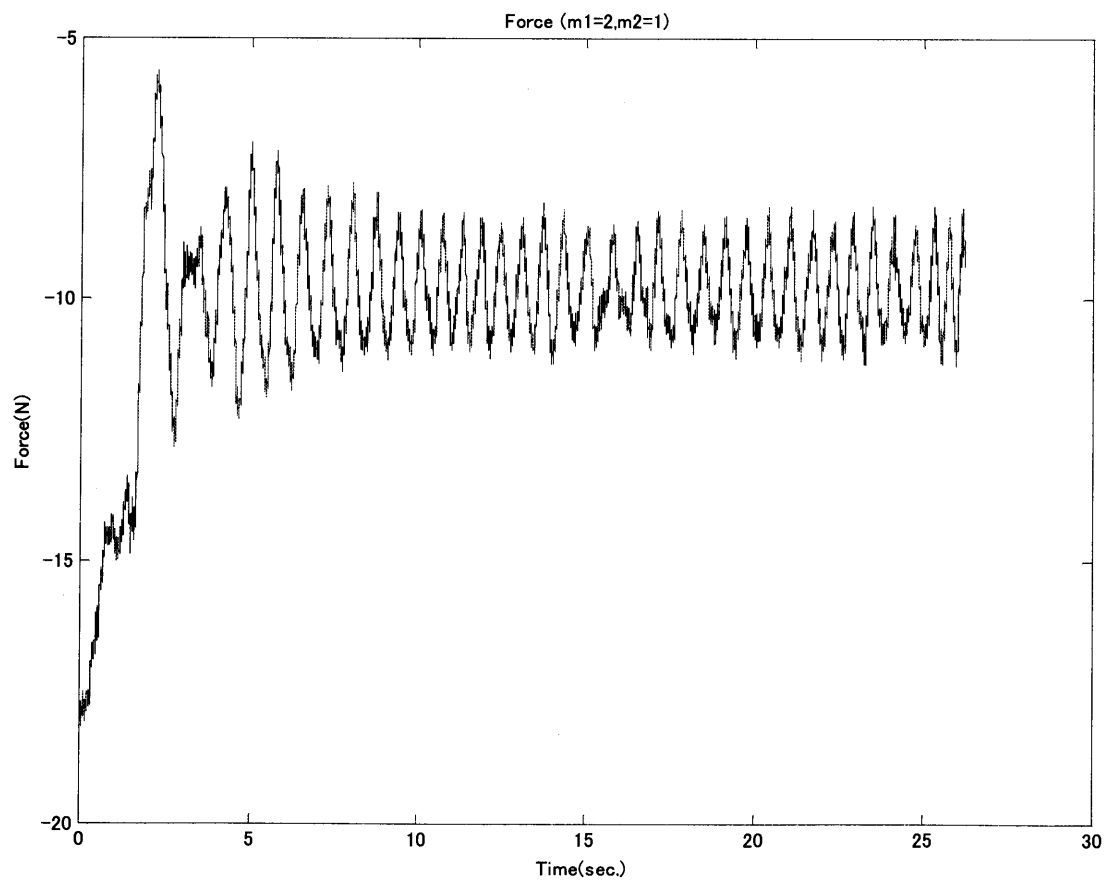
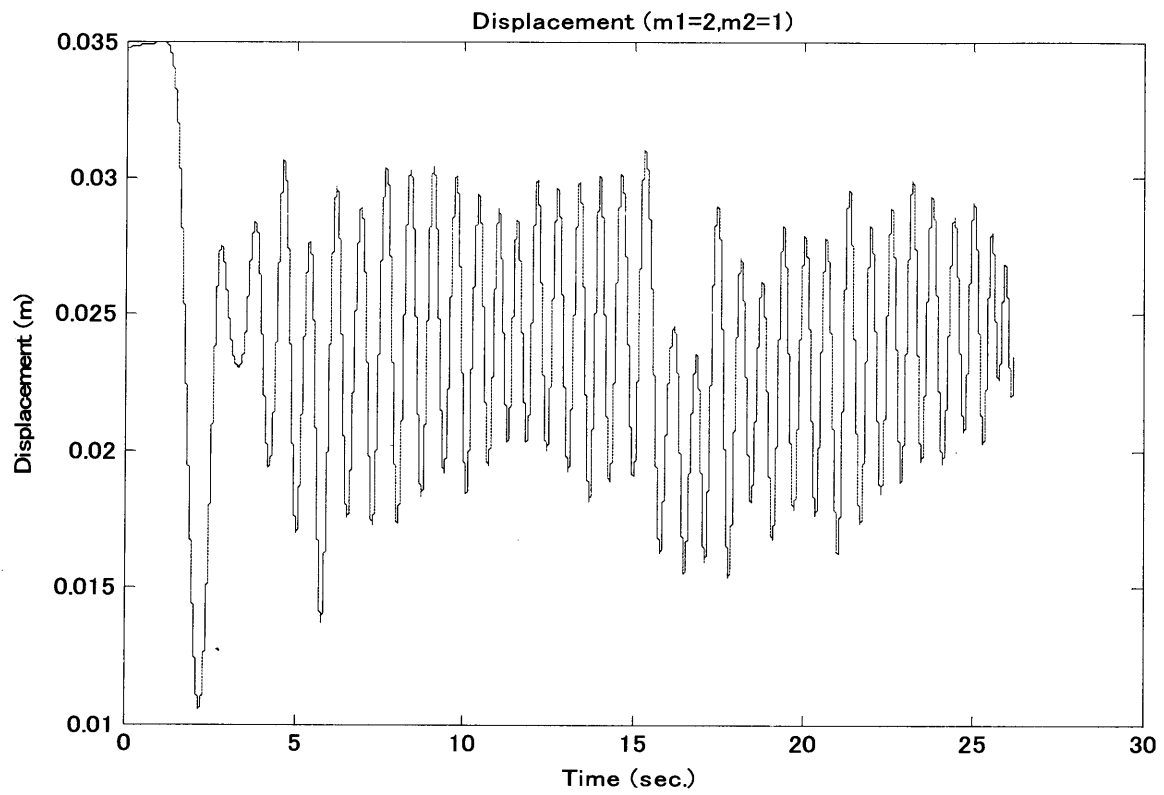


Figure 22: Displacement and force data for large size object for a few sets of values of m_1 and m_2

Displacement and force data for medium size object:





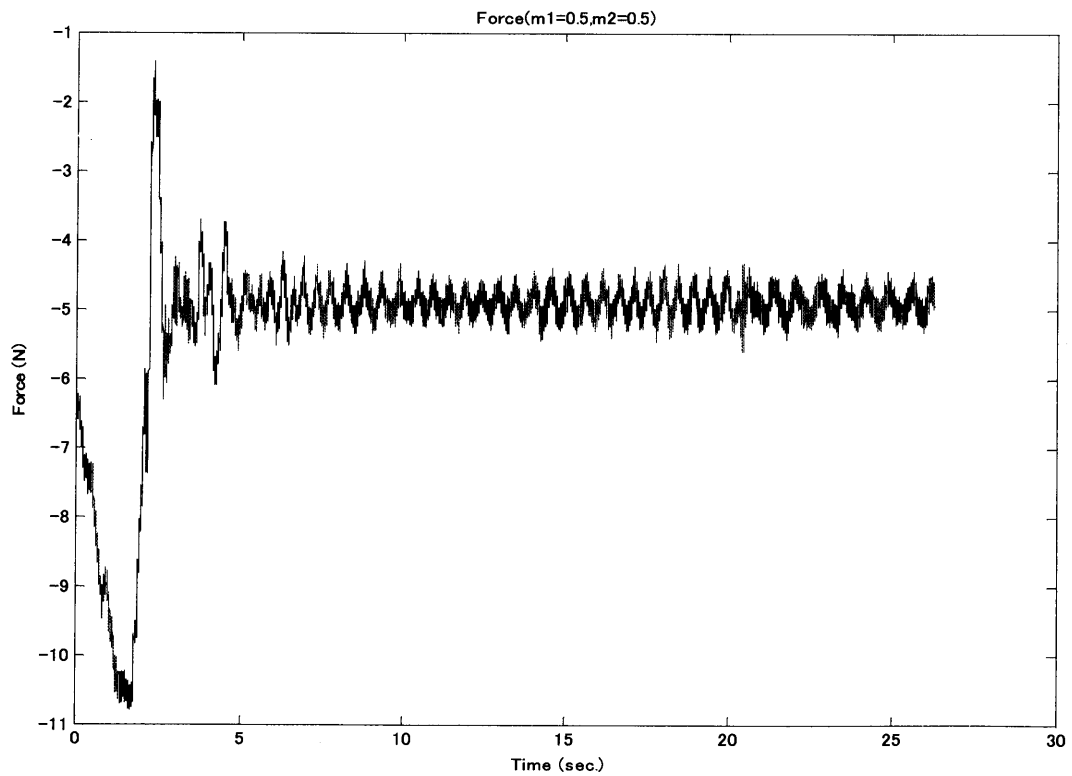
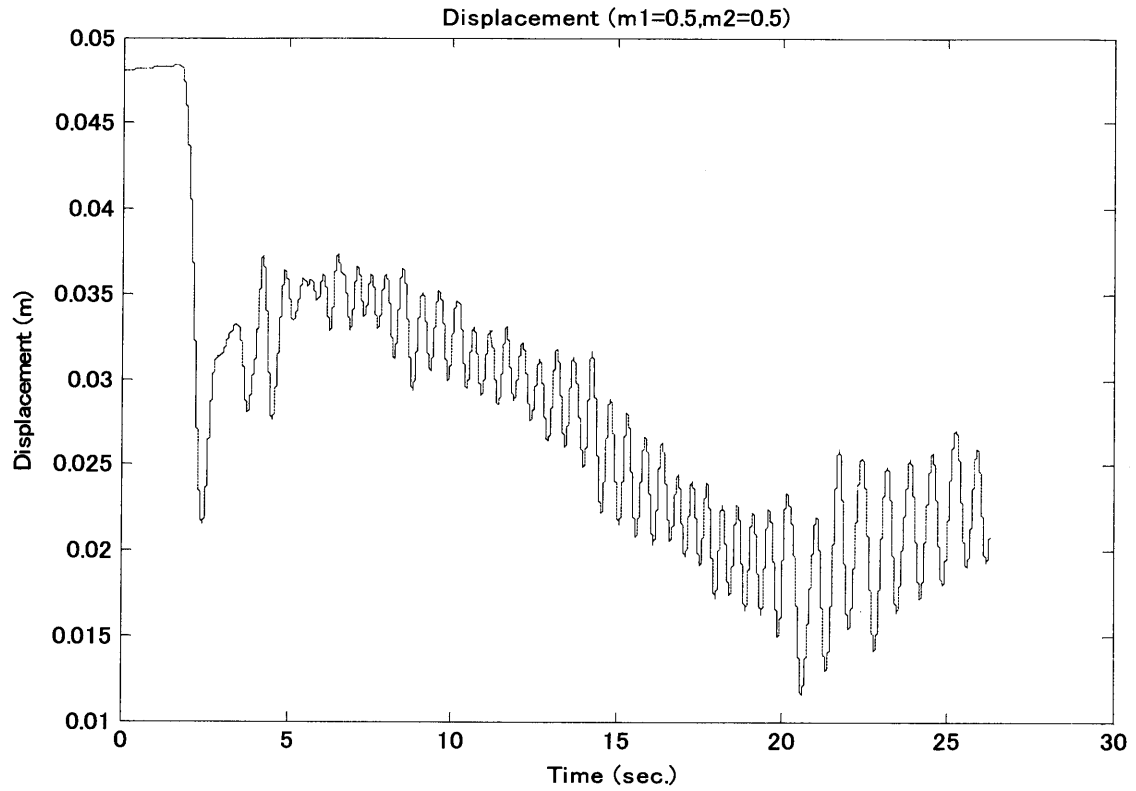
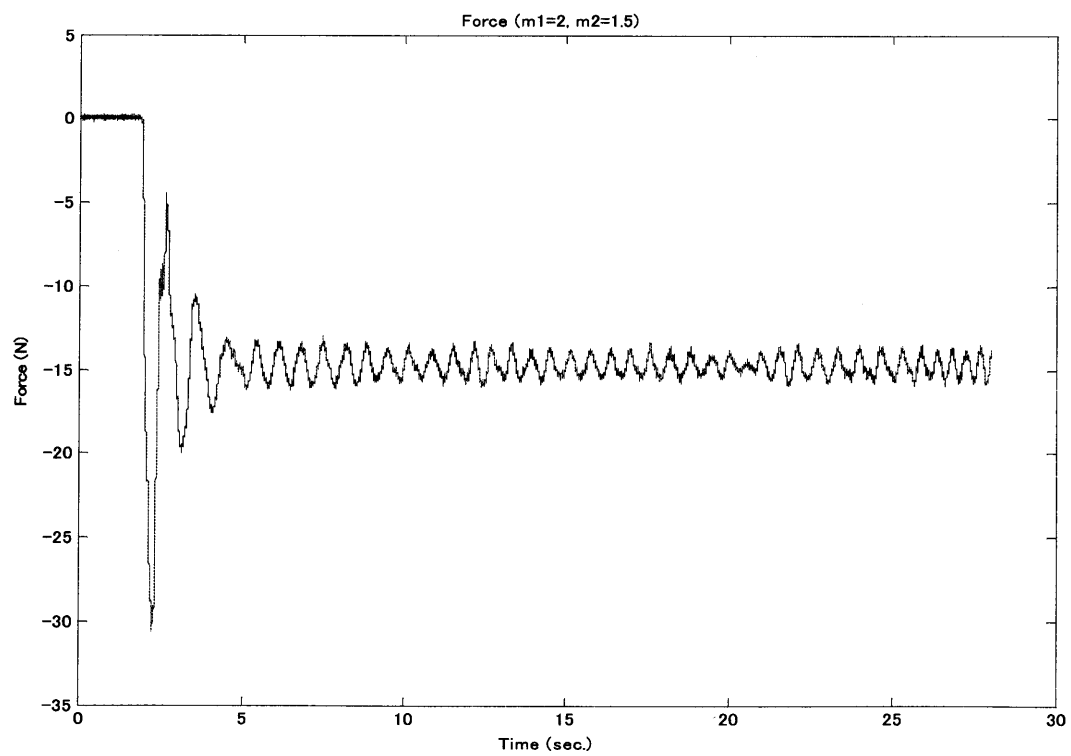
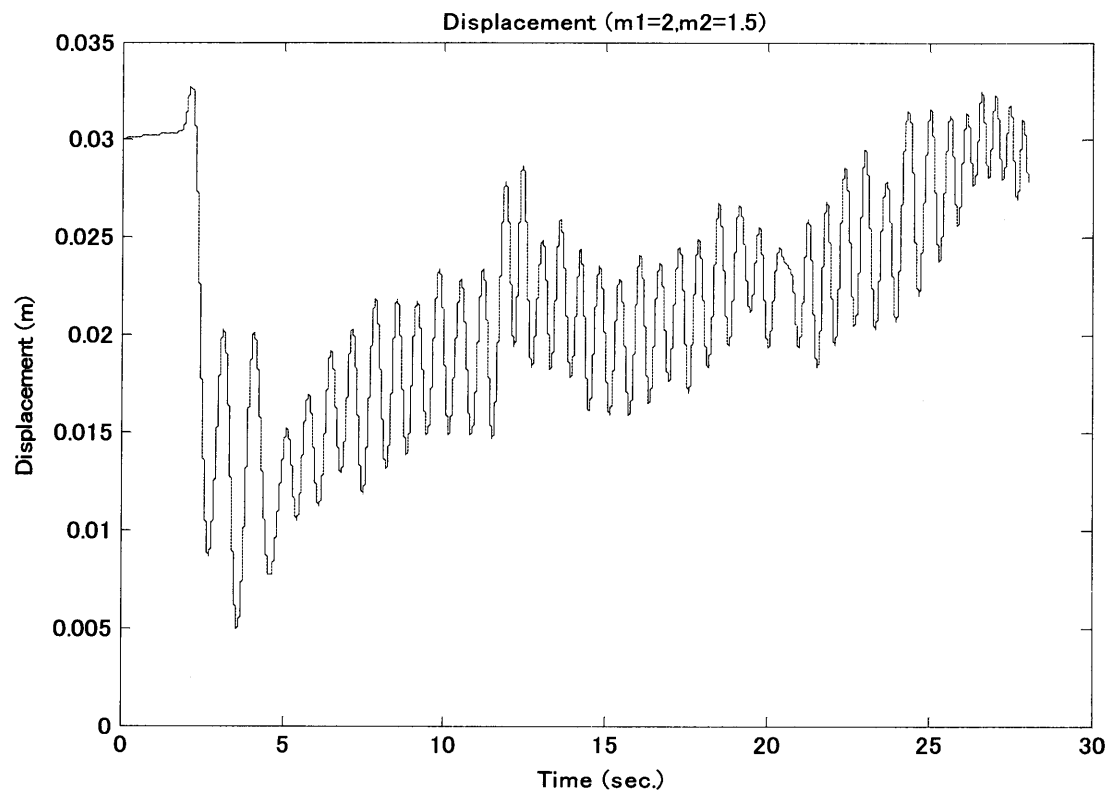
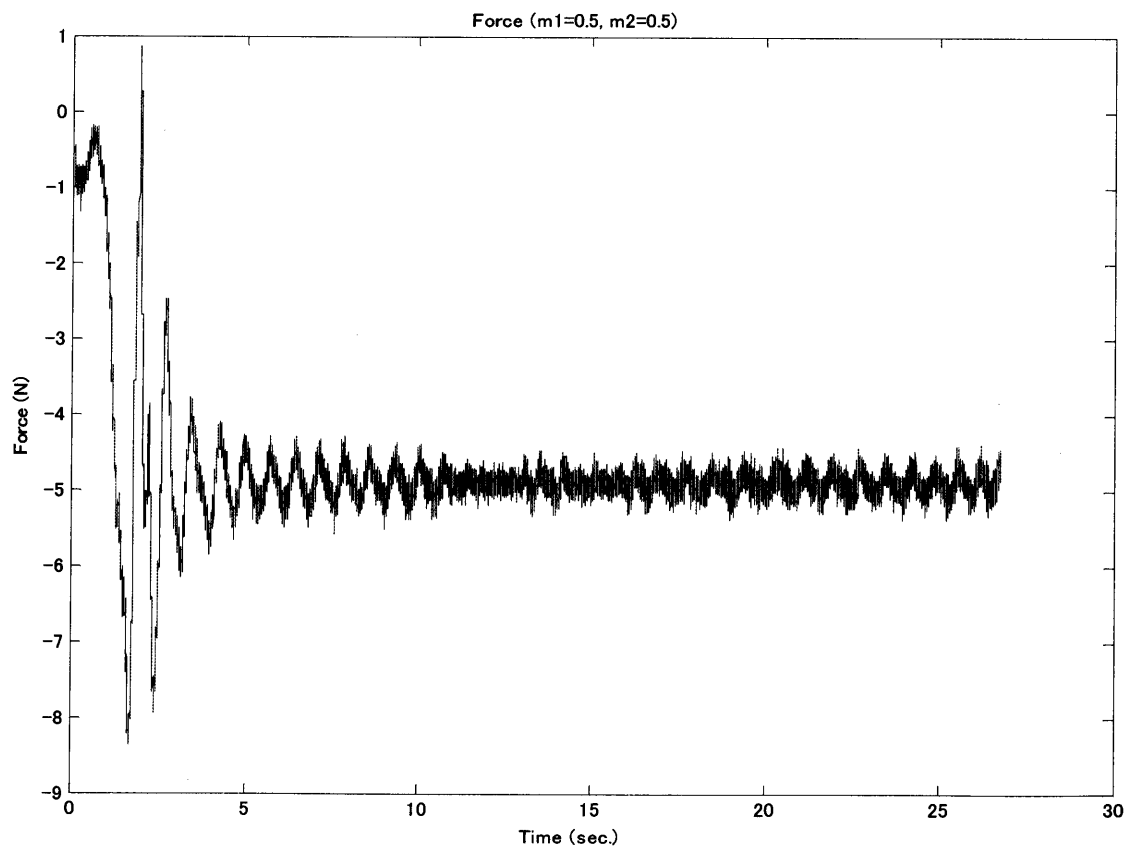
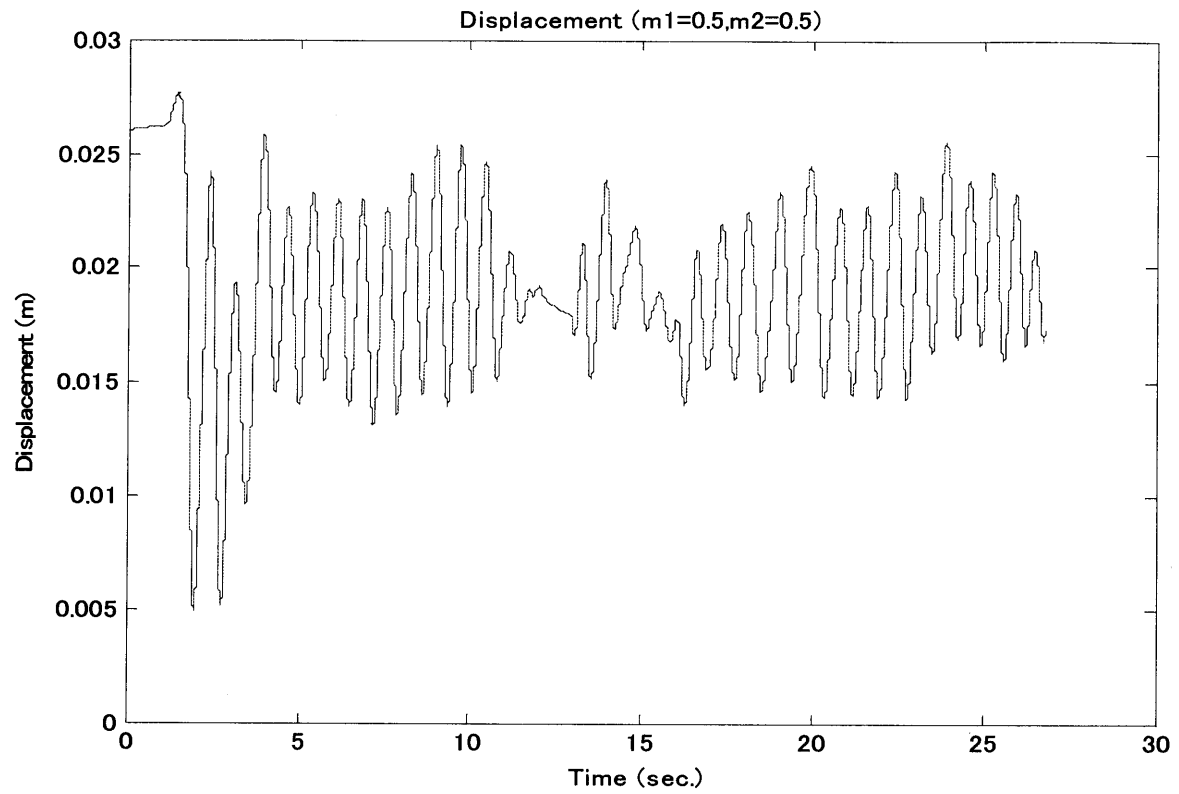


Figure 23: Displacement and force data for medium size object for a few sets of values of m_1 and m_2

Displacement and force data for small size object:





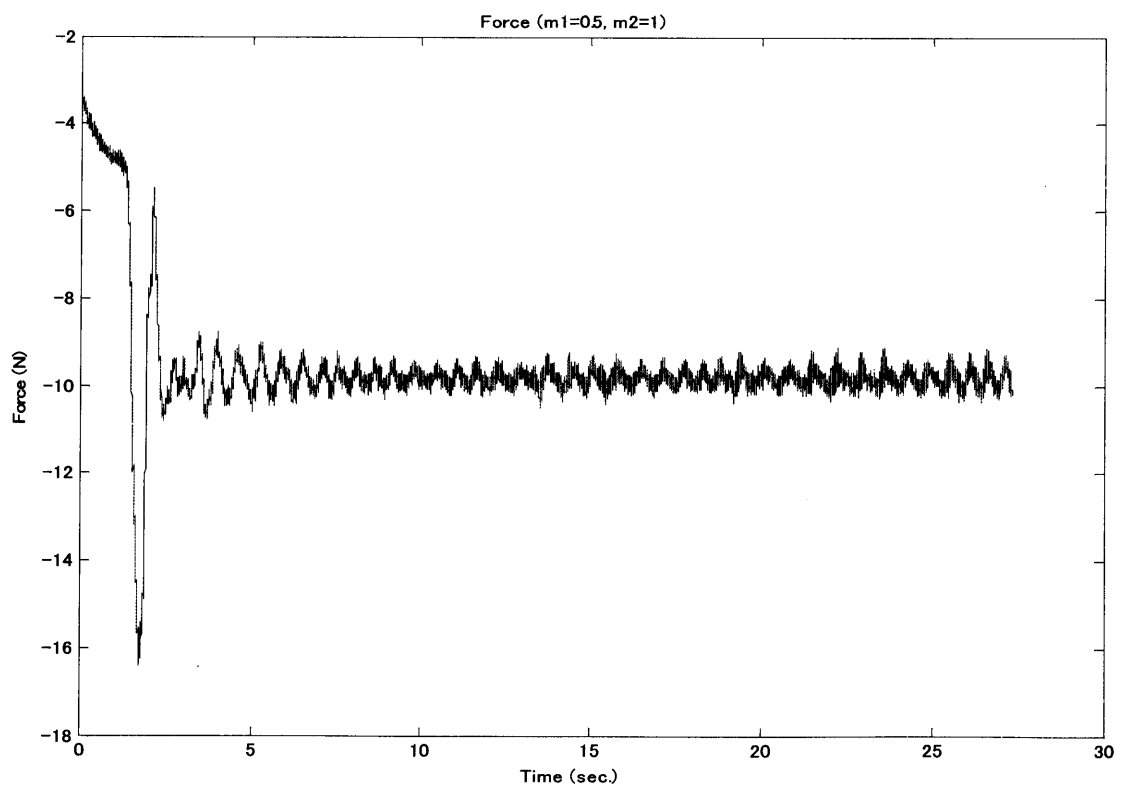
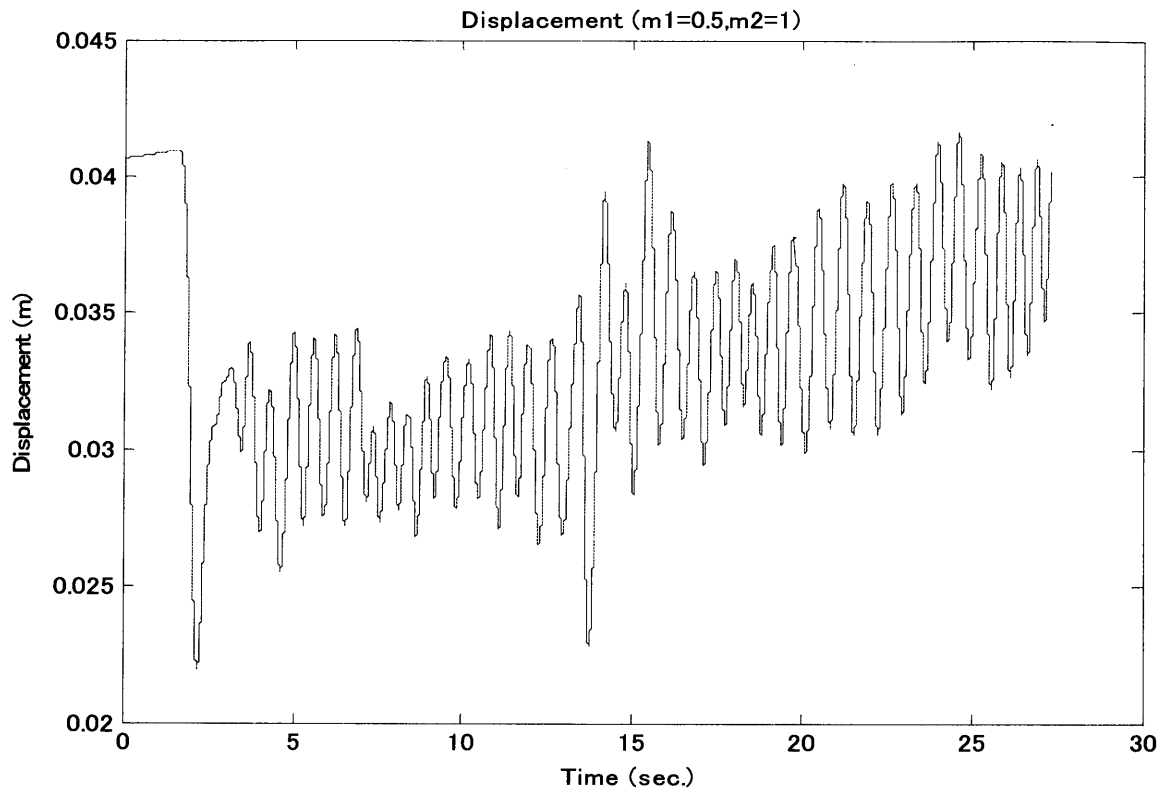


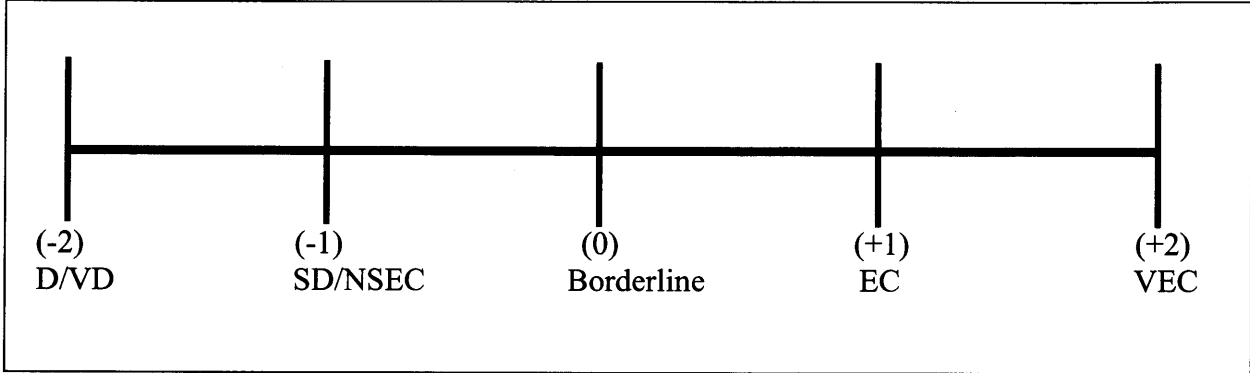
Figure 24: Displacement and force data for small size object for a few sets of values of m_1 and m_2

5.3 Experimental Results and Analyses

5.3.1 Experiment 1: System Evaluation

5.3.1.1 Results

The 5-point bipolar & equal-interval subjective rating scale designed for this experiment was as the following:



In the scale, subject's rating towards right side of the scale gives positive (+ve) weight to the evaluation and rating towards left side gives negative (-ve) weight to the evaluation of the system. Subject's rating of the system for each set of values of m_1 and m_2 for three independent objects of different sizes are shown in the following tables. Each column under 'percentile (%) distribution of subjects' indicates the percentage of the total subjects participated in the experiment responded the rating alternative (D/VD or SD/NSEC or BL or EC or VEC) of that column for different sets of values of m_1 and m_2 . There was only one subject in our current experiment. Hence, the rating alternative that was responded by the subject for a particular set of values of m_1 and m_2 got 100% and the other rating alternatives got 0% for that particular set of values of m_1 and m_2 .

Table 5: Subject's rating of the system for large size object

Values of m_1 & m_2	Percentile (%) Distribution of Subjects					Weighted Sum Score
	% of subjects responded for D/VD (-2)	% of subjects responded for SD/NSEC (-1)	% of subjects responded for Borderline (0)	% of subjects responded for EC (+1)	% of subjects responded for VEC (+2)	
$m_1=1, m_2=0.5$	0	0	0	100	0	+100
$m_1=2, m_2=0.5$	0	0	0	100	0	+100
$m_1=2, m_2=1.5$	100	0	0	0	0	-200
$m_1=1.5, m_2=1.5$	100	0	0	0	0	-200
$m_1=2, m_2=1$	0	100	0	0	0	-100
$m_1=1.5, m_2=1$	0	100	0	0	0	-100
$m_1=0.5, m_2=1.5$	100	0	0	0	0	-200
$m_1=1, m_2=1.5$	100	0	0	0	0	-200
$m_1=0.5, m_2=1$	100	0	0	0	0	-200
$m_1=1.5, m_2=0.5$	0	0	0	100	0	+100
$m_1=1, m_2=1$	0	100	0	0	0	-100
$m_1=0.5, m_2=0.5$	0	0	0	0	100	+200

Table 6: Subject's rating of the system for medium size object

Values of m_1 & m_2	Percentile (%) Distribution of Subjects					Weighted Sum Score
	% of subjects responded for D/VD (-2)	% of subjects responded for SD/NSEC (-1)	% of subjects responded for Borderline (0)	% of subjects responded for EC (+1)	% of subjects responded for VEC (+2)	
$m_1=1, m_2=1$	0	100	0	0	0	-100
$m_1=2, m_2=1$	0	100	0	0	0	-100
$m_1=0.5, m_2=0.5$	0	0	0	0	100	+200
$m_1=1, m_2=0.5$	0	0	0	100	0	+100
$m_1=1.5, m_2=0.5$	0	0	0	100	0	+100
$m_1=2, m_2=1.5$	100	0	0	0	0	-200
$m_1=0.5, m_2=1$	100	0	0	0	0	-200
$m_1=1.5, m_2=1.5$	100	0	0	0	0	-200
$m_1=0.5, m_2=1.5$	100	0	0	0	0	-200
$m_1=1, m_2=1.5$	100	0	0	0	0	-200
$m_1=1.5, m_2=1$	0	100	0	0	0	-100
$m_1=2, m_2=0.5$	0	0	0	100	0	+100

Table 7: Subject's rating of the system for small size object

Values of m_1 & m_2	Percentile (%) Distribution of Subjects					Weighted Sum Score
	% of subjects responded for D/VD (-2)	% of subjects responded for SD/NSEC (-1)	% of subjects responded for Borderline (0)	% of subjects responded for EC (+1)	% of subjects responded for VEC (+2)	
$m_1=1, m_2=1$	0	100	0	0	0	-100
$m_1=2, m_2=1$	0	100	0	0	0	-100
$m_1=0.5, m_2=0.5$	0	0	0	0	100	+200
$m_1=1, m_2=0.5$	0	0	0	100	0	+100
$m_1=1.5, m_2=0.5$	0	0	0	100	0	+100
$m_1=2, m_2=1.5$	100	0	0	0	0	-200
$m_1=0.5, m_2=1$	100	0	0	0	0	-200
$m_1=1.5, m_2=1.5$	100	0	0	0	0	-200
$m_1=0.5, m_2=1.5$	100	0	0	0	0	-200
$m_1=1, m_2=1.5$	100	0	0	0	0	-200
$m_1=1.5, m_2=1$	0	100	0	0	0	-100
$m_1=2, m_2=0.5$	0	0	0	100	0	+100

Final evaluation score (weighted sum) was calculated for each set of values of m_1 and m_2 for three independent objects of different sizes. The evaluation scores for different sets of values of m_1 and m_2 for three independent objects of different sizes were plotted as the following:

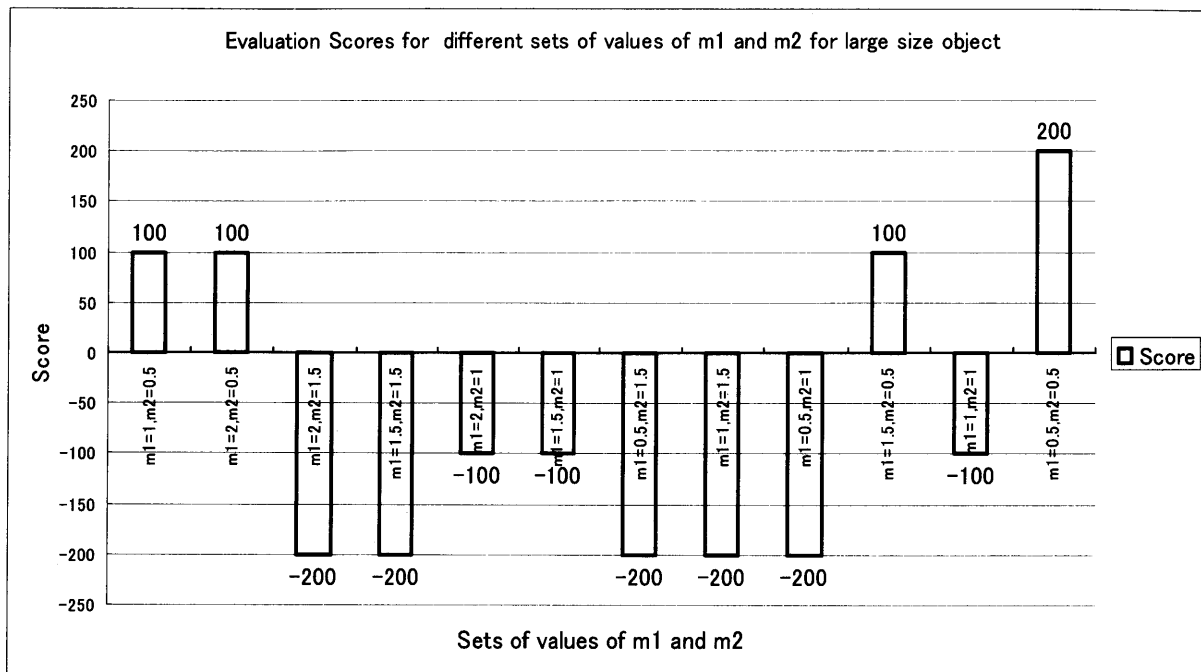


Figure 25: Evaluation scores for different sets of values of m_1 and m_2 for large size object.

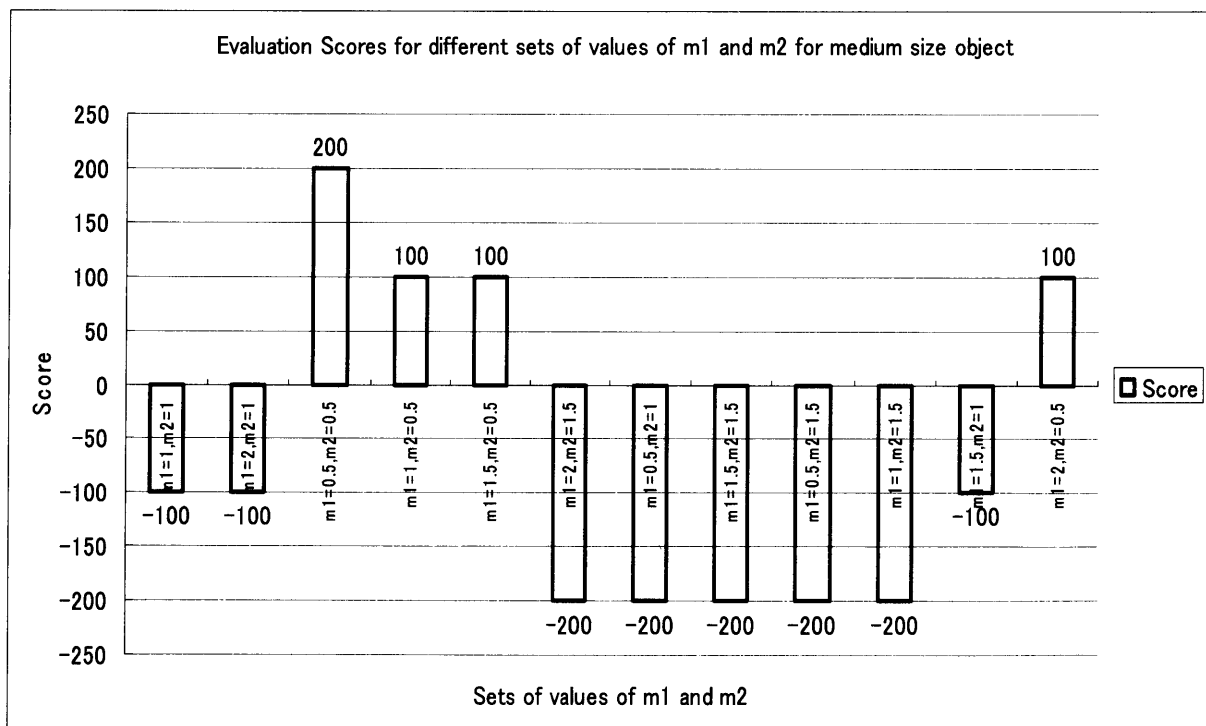


Figure 26: Evaluation scores for different sets of values of m_1 and m_2 for medium size object.

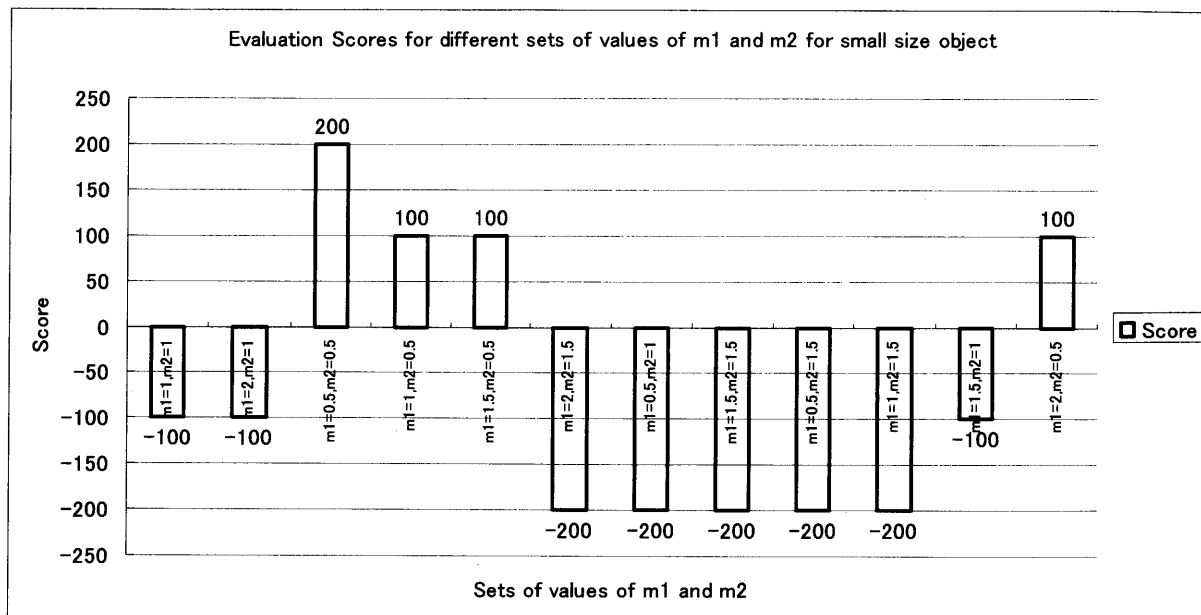


Figure 27: Evaluation scores for different sets of values of m_1 and m_2 for small size object.

It is seen from the above graphs of the system evaluation that, only the set of values of m_1 and m_2 when $m_1=0.5$ and $m_2=0.5$ got the highest scores (+200) for the objects of all sizes (small, medium and large size). It means, the subject feels very easy & comfortable to maneuver the object 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 objects of all sizes**. It is also seen from the displacement and force data for all sizes of objects for different sets of values of m_1 and m_2 in figures 22-24 that, the usual human force was comparatively very lower and the displacement was comparatively smoother for $m_1=0.5$ and $m_2=0.5$ than other sets of values of m_1 and m_2 .

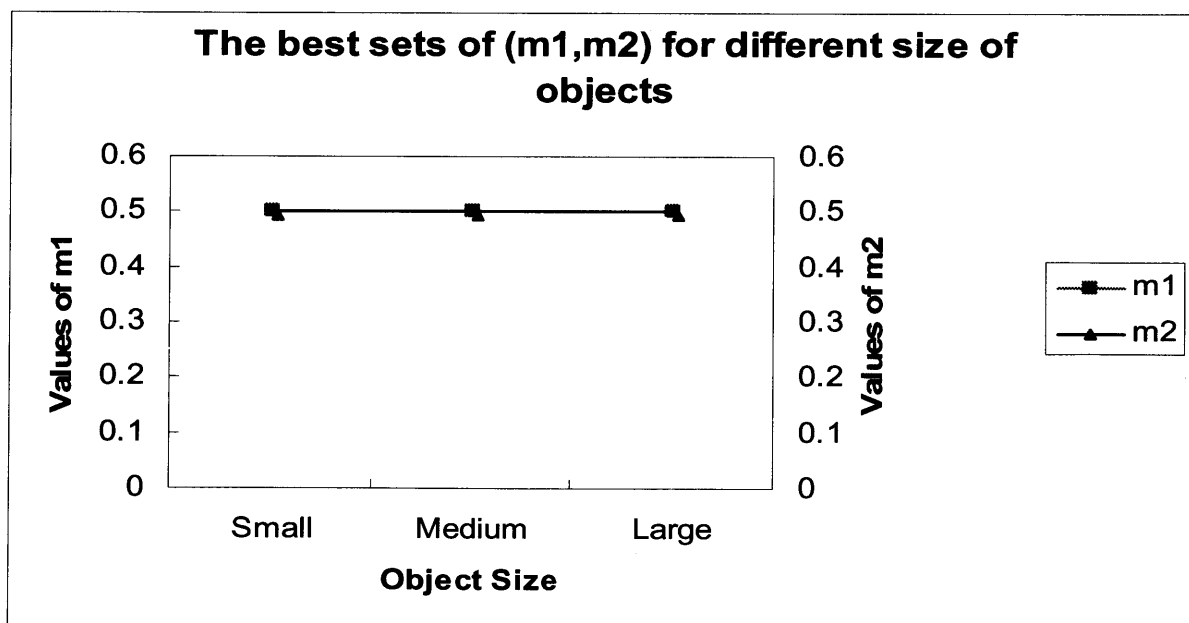


Fig.28: The best set of values of m_1 and m_2 for different sizes of objects

5.3.1.2 Analyses

The set of values of $m_1=0.5$ and $m_2=0.5$ is the best set for objects of all sizes. This set of values 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 (say, $m_1=0.2$, $m_2=0.2$), the object is supposed to be much lighter and easier, but it is still unknown whether this will be 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 and easier as it was proved by Marc O. et. al. [56] and L. Dominjon et. al. in virtual environment [67] , but it is also unknown whether this will fit human psychology or not.

It is seen from the graphs showing subject's evaluation scores for different sets of values of m_1 and m_2 for all sizes of objects that, only 33.33% sets of values of m_1 and m_2 for different sizes of objects got positive scores and were evaluated as positive by the human operator. On the other hand, the remaining 66.66% sets of values of m_1 and m_2 for different sizes of objects got negative scores and were evaluated as negative by the human operator. These findings indicate the significance of our hypothesis that, we would not be able to sort out the positive sets of values of m_1 and m_2 from the negative sets of values of m_1 and m_2 for different sizes of objects unless we thought $m_1 = m_2 \neq m$ or $m_1 \neq m_2 \neq m$ in stead of $m_1=m_2=m$.

It is still unknown whether the set of values of $m_1=0.5$ and $m_2=0.5$ will persist as the best set for all conditions in practical uses in industries or this set is best only for the particular conditions of this experiment. It means, it is yet to prove whether the best set is general and universal or not.

5.3.2 Experiment 2: Weight Comparison

5.3.2.1 Results

For objects of each size, graphs were drawn taking the gravity load (m_2) values as abscissa and the reference weight value points from where the subject starts to feel the power assisted object heavier than the reference weight as the ordinate. Here for a particular set of values of m_1 and m_2 , the reference weight point from where the subject starts to feel the power assisted object heavier than the reference weight is assumed as the perceptual weight of the power assisted object and the value of m_2 is considered as the actual weight of the power assisted object. The graphs are shown in the following pages:

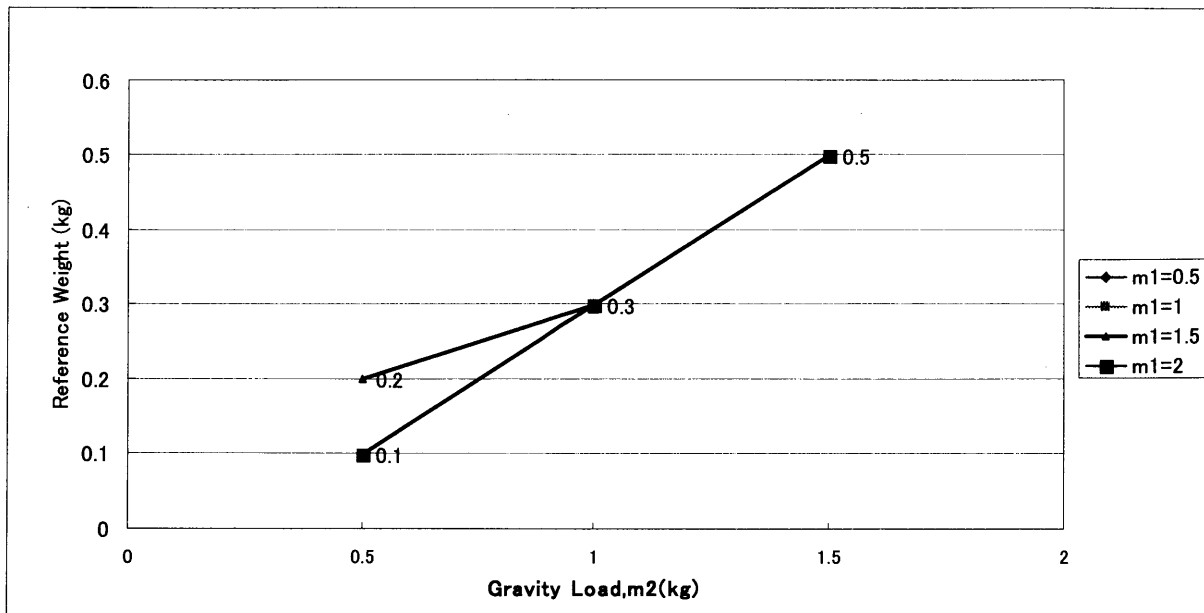


Fig.29: Relationship between perceptual weight and actual weight for large size object

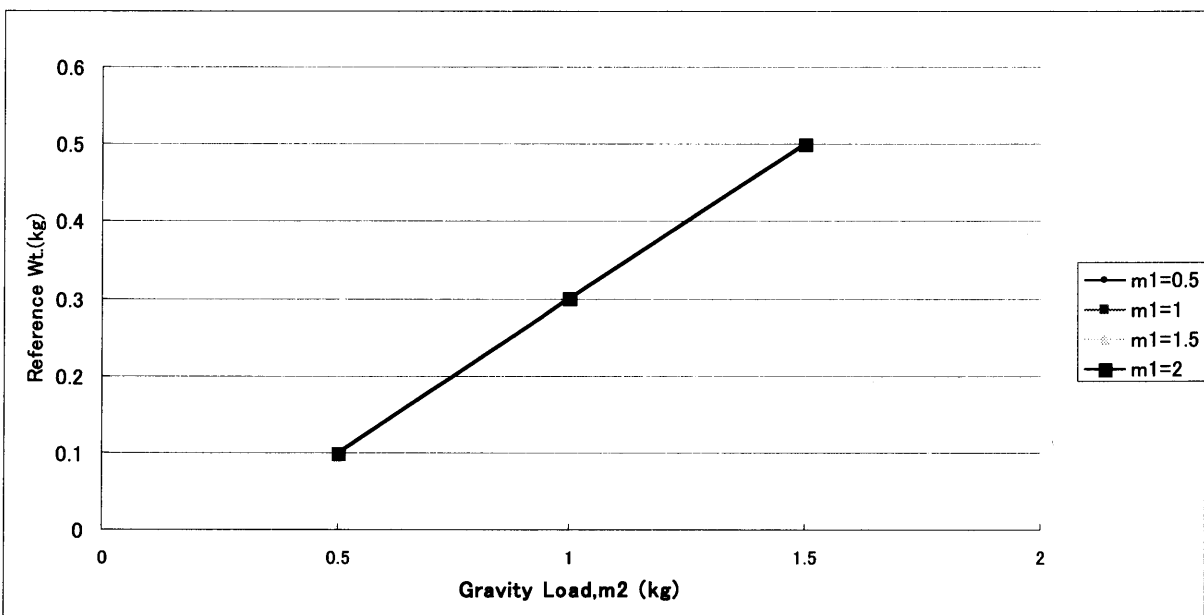


Fig.30: Relationship between perceptual weight and actual weight for medium size object

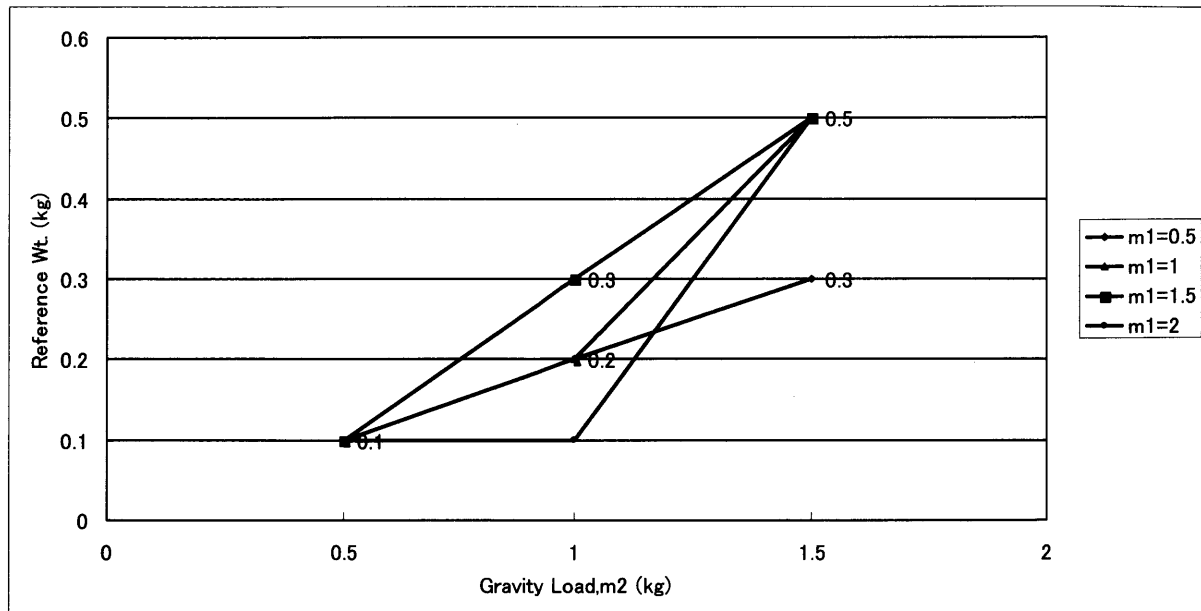


Fig.31: Relationship between perceptual weight and actual weight for small size object

5.3.2.2 Analyses

The above results show that-

1. For large and medium size object, the actual weight (m_2) and perceptual weight follow linear relationship for all values of m_1 . The relationship between the actual weight and perceptual weight for all values of m_1 for the small size object is slightly less linear. From these relationships, we can easily determine the relationship between the actual weight and perceptual weight for any set of values of m_1 and m_2 . For example, for the best set ($m_1=0.5$ and $m_2=0.5$) condition for all object sizes, the perceptual weight is 0.1 kg, where the actual weight (m_2) is 0.5 kg.

Hence, we can draw a conclusion that,

Perceptual Weight =1/5 of the Actual Weight

2. The results show that, perceived weight was proportional to object size. For this reason, the relationship between the actual weight and perceptual weight for all values of m_1 for the small size object is slightly less linear. It means, the small object was felt much lighter. But, this finding doesn't violate the well-established size-weight illusion, as in these experiments the weight comparison of objects of different sizes was independent and separated from one other.
3. Applied force by human is proportional to the perceived weight of the object. As the perceptual weight is one-fifth of the actual weight for the best set condition, the applied force by the human should also be reduced to one-fifth of the initially applied force during the initial trial of lift. If we can supply one-fifth of the initial human force to the control system of the power assist system, the initial force programming may be optimum, which will give optimum velocity to the object. Hence, we need to include this relationship to the control law.
4. We need to reduce the initial human force, f_h to its one-fifth. But, a direct reduction of f_h to its one-fifth will also affect the values of m_1 and m_2 according to the following equation:

$$m_1 \ddot{x} - m_2 g = f_h$$

Hence, we need to do further programming in the control law in order to add the relationship between perceptual and actual weight without hampering the relationship of the above equation. It is revealed from the result of the Experiment 2 that, human doesn't feel the change of m_1 . Hence, the initial human force in the above equation may be reduced to its one-fifth by further simulating the system. In this special simulation, initially a very large value of m_1 is to be set (say, $m_1=6$) and this value will gradually and automatically be reduced to 0.5 while keeping the value of $m_2=0.5$ fixed ($m_1=0.5, m_2=0.5$ for the best condition). This type of programming and simulation will give one-fifth of the usual human force to the control system during the initial trial of the lift.

5.4 Summary

This chapter deals with the experiments of this thesis research. We have conducted two experiments. The first one is the evaluation of the power assist system from the view point of operator's comfort or ease, and the second one is the comparison between perceptual and actual weight of the power assisted object.

We have also got two results from the two experiments described in this chapter. The first result is that we have identified the best set of the values of m_1 and m_2 for objects of all sizes. The second and the most expected result is the relationship between the perceptual weight and the actual weight of the power assisted object.

Hence, the results of this chapter certify that we have already reached our objective, at least for the time being, though the scope for further improvement still prevails.

Chapter 6: Conclusion

6.1 Discussions

We have obtained two 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, and the second result is that, we have established a psychophysical relationship between the actual weight and the perceptual weight of an object carried with the power assist system. Thus, our findings satisfy our objective.

The results of both the Experiment 1 and Experiment 2 are evaluated subjectively. The results are subjective instead of objective. Though the objective data and findings are always desired, it is not always possible to measure the system objectively. Especially, it is very difficult to get objective data and results for the case of human factors testing and evaluation. Though, our results are subjective, we can depend on theses. Ikeura et. al. used subjective rating method for vehicle steering based on impedance of human arms and the subjective evaluation was effective[70]. Ikeura et. al. also used subjective evaluation for maneuverability of a robot cooperating with humans where the results of subjective evaluation gave the proposed variable impedance control [71]. H. Kobayashi et. al. also used subjective evaluation method for maneuverability index for a control stick and manual tracking control where the index was proved satisfactory[72],[73]. Hence, the subjective rating of system evaluation of the power assist system presented in this thesis research is supposed to be effective.

In order to increase the accuracy and acceptability of the results, appropriate sample size may be determined for a desired sampling error of 10% at a confidence level of 80% or more. For the Experiment 1, the accuracy of the results may be further enhanced by transforming the rating scale from 5-point to 7-point. Improvement of the quality of the descriptors of the rating scale and practicability of the evaluation criteria may also increase the accuracy of the results. The rating responses may be analyzed and summarized by using chi-square test, mode statistics, squared ranks test, measure of central tendency (such as a median), variability test etc in order to achieve more accurate results. For Experiment 2, the accuracy of the results may be increased by adding more weights in the reference weight series. It means, in this experiment, the reference weights were 1.5 kg, 1.0 kg, 0.5 kg, 0.3 kg, 0.2 kg, and 0.1 kg. In order to increase the accuracy of the results, 0.7 kg, 0.6 kg, 0.4 kg, 0.35 kg, 0.25 kg, 0.15 kg, 0.05 kg etc may be added to the reference weight series.

It is seen from the force data for all sizes of objects for different sets of values of m_1 and m_2 in figures 22-24 that, force applied by the human is proportional to the object size. If we consider the best set situation($m_1=0.5$ and $m_2=0.5$), we observe that, maximum human force at the initial time of lifting for the large size object is 13.5N and the subject reduces the force to 5N after a few seconds in order to adjust with the real situation. We observe that, maximum human force at the initial time of lifting for the medium size object is 10.5N and the subject reduces the force to 5N after a few seconds in order to adjust with the real situation. We also observe that, maximum human force at the initial time of lifting for the small size object is 8.5N and the subject reduces the force to 5N after a few seconds in order to adjust with the real situation. The reason may be that, the human uses feed forward or anticipatory control methods to program the lift force on the basis of the visually perceived weight of the object and the perceived weight is proportional to the size of the object. But after a few seconds of lifting the object or for the case of repeated lifting, the human comes to understand the actual

weight of the object from haptic senses and sensorimotor feedback responses and then adjusts the force in accordance with the actual weight of the object even though their sizes may be different. The observation from our experiment supports our hypothesis that, human applies very large force to lift an object with the power assist system during the initial lifting that causes many problems and now we also see that this force is proportional to the object size. Our observation and reasoning associate the findings in [28], [30], [37], [44], [45] and [53].

6.2 Contributions

It is undoubtedly true that, the power assist systems are a boon to the humanity in the present day world and in the ensuing days. This thesis research has tried to add extra features and attributes to the existing power assist systems. In this research we have used psychophysical concepts in the domain of power assist systems. The relationship between the perceptual weight and the actual weight will certainly help develop effective power assist systems for lifting heavy objects in various types of industries. The power assist systems developed for other purposes will also get supports in incorporating human factors in the design of control systems. As a whole, this research will render an upward mobility to the global industrialization and hence the global economy.

6.3 Limitations

While conducting this research, we faced many limitations. A few of the limitations were mentioned below:

1. The author of this thesis is a very novice in the field of power assist systems. The author used most of his time in his background preparation. As the author couldn't give much time in practical experiments, the progress of the research was slightly limited.
2. Power assist system, especially psychophysical considerations with power assist system is a very recent area of research. Hence, it was difficult to obtain required textbooks and published literatures on this area that made our progress limited.
3. Required numbers of subjects were not available to conduct the experiments etc.

6.4 Future Directions

The research on power assist system contained in this thesis clearly opens a breakthrough in the fields of human-robot cooperation, especially in the field of power assist system. This is just an inception, and certainly neither the end nor even the maturity of research on this field. It is yet to address many challenges with power assist systems. Research on the following ideas can be carried out in the near future:

1. We have already established the relationship between perceptual weight and actual weight for the power assist system. In near future, it will be needed to add the relationship between perceptual and actual weight to the control law by doing further programming so that the force applied by the human operator on the object becomes optimum or nearly optimum. The optimum force applied by the human on the object will produce optimum velocity of the object carried with the power assist system. This will enhance the maneuverability, safety and stability of the system.
2. The experiments of this thesis were performed by only one subject. Findings on only one subject may not be reliable and fit for the general population in practical applications. Hence, in near future, it will be needed to do experiments for many subjects instead of

one in order to do statistical analysis and decision making so that the research findings become more reliable, general and universal.

3. We have evaluated the feelings of the subject for the power assist system by some experimental method (Experiment 1). We have also established relationships between perceptual and actual weight of the object carried with the power assist system (Experiment 2). In near future, it will be needed to search for advanced methods for system evaluation. It will also be needed to search advanced methods for the establishment of the relationships between the perceptual and actual weight of the object carried with the power assist system.
4. We have designed control law for the power assist system. The control law described in this thesis is feedback position control law. In near future, it will be needed to search for new and advanced control methods for the power assist system described in this thesis so that it is possible to obtain better performances from the system.
5. The power assist system described in this thesis is a simple 1DOF system. In near future, it will be needed to extend the power assist system from 1DOF system to MDOF (2, 3, 4,) system. In MDOF system; the object may be traveled in both vertical and horizontal directions. In horizontal direction, there exists only inertia force and there is no gravity force, hence $m_2=0$. Again, in the current project, only the translational motion of the power assist system has been considered. It is also possible to consider rotational motions of the power assist system with respect to both vertical and horizontal directions.
6. It will also be possible and beneficial to extend psychophysical considerations for other types of power assist systems or other types of human-robot cooperation.

Appendices

Appendix A

Criteria of System Evaluation

Very Easy & Comfortable (VEC)

A) Psychophysical:

- 1) The object is very light.
- 2) The object has no tendency to go downward or upward at all.
- 3) It is very easy for the operator to adjust the object to the situation or motions
- 4) The operator feels very high level of safety, sense of security, operability etc.
- 5) The operator can maintain very high level of Situation Awareness (SA)

B) Technical:

- 1) There is very less difference between the initial amplitude and usual amplitude of displacement, velocity and force.
- 2) There is no tendency or trend of voltage saturation at all.
- 3) There is no feedback error at all.

Easy & Comfortable (EC)

A) Psychophysical:

- 1) The object is light
- 2) The object has no tendency to go downward or upward.

- 3) It is easy for the operator to adjust the object to the situation or motions
- 4) The operator feels high level of safety, sense of security, operability etc.
- 5) The operator can maintain high level of Situation Awareness (SA)

B) Technical:

- 1) There is less difference between the initial amplitude and usual amplitude of displacement, velocity and force.
- 2) There is no or almost no tendency or trend of voltage saturation.
- 3) There is no or almost no feedback error.

Borderline (BL)

When it is very difficult or impossible to identify a difference between "Easy & Comfortable" and "Slightly Difficult (SD)/Not So Easy & Comfortable (NSEC)" situations.

Slightly Difficult (SD)/Not So Easy & Comfortable (NSEC)

A) Psychophysical:

- 1) The object is not so light or slightly heavy
- 2) The object has slight tendency to go downward or upward.
- 3) It is slightly difficult for the operator to adjust the object to the situation or motions
- 4) The operator feels slightly low level of safety, sense of security, operability etc.
- 5) The operator possesses slightly low level of Situation Awareness (SA)

B) Technical:

- 1) There is slightly less difference between the initial amplitude and usual amplitude of displacement, velocity and force.
- 2) There is a slight tendency or trend of voltage saturation.
- 3) There is a slight feedback error.

Difficult (D)/Very Difficult (VD)

A) Psychophysical:

- 1) The object is heavy or very heavy
- 2) The object goes downward or upward.
- 3) It is very difficult for the operator to adjust the object to the situation or motions
- 4) The operator feels very low level of safety, sense of security, operability etc.
- 5) The operator possesses very low level of Situation Awareness (SA)

C) Technical:

- 1) There is very much difference between the initial amplitude and usual amplitude of displacement, velocity and force.
- 2) There is strong tendency or trend of voltage saturation.
- 3) There is severe feedback error.

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