PSYCHOPHYSICAL AND PHYSIOLOGICAL STUDY OF
ONE-HANDED AND TWO-HANDED COMBINED TASKS

by

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ABSTRACT

Most psychophysical studies in manual material handling (MMH) have paid more attention to two-handed MMH activities than to one-handed MMH activities. Also, studies have been involved only with single MMH activities -- lifting, lowering, carrying, holding, pushing or pulling. Some studies have examined the capacities of two-handed combined MMH activities. However, the capacities for combinations of one-handed MMH activities (lifting a box, then carrying the box, and lowering the box), especially repetitive tasks, have never been examined, although these kinds of combined one-handed tasks are very common in normal life and in industry. The objective of this study was to find the psychophysical and physiological responses of human subjects from a simulated industrial task involving one-handed and two-handed combined tasks and to develop prediction models for one-handed and two-handed combined tasks.

Ten male students participated in the experiment. Capacities were determined as the maximum acceptable weight workload for a 1 hr work period for one-handed and two-handed combined tasks: lifting a box from floor-to-knuckle height, carrying the box for 4.3 m, and lowering the box from knuckle-to-floor height. Individual capacities were determined psychophysically under three frequencies: six handlings per minute, one handling per minute and one handling per five minutes. In addition to the maximum acceptable weight, heart rate, tasking time and RPE values for the whole body, the arm, and the back were also measured as responses and statistically analyzed.

The results showed that the maximum acceptable weights of a one-handed combined task were 83.0%, 75.2% and 76.3% of two-handed combined tasks at the frequency rate of 6/min, 1/min and 1/5min, respectively. Subject's strength was the important factor in determining the maximum acceptable weight during the low frequency rate tasks. During the high frequency rate tasks, the subject's physiological capability was

the important factor in determining the maximum acceptable weight. Heart rate was significantly higher at the high frequency rate tasks (6/min) than the low frequency rate tasks (1/min and 1/5min).

Prediction models for the capacity of one-handed combined tasks were developed using the capacity of two-handed combined tasks for certain frequency rates (6/min, 1/min, and 1/5min). Another prediction model for the capacity of one-handed combined tasks was developed based on the capacity of two-handed combined tasks and frequency rate.

A regression model for the capacities of both one-handed and two-handed combined tasks was developed using isometric strength of both arms and frequency rate. The advantages and disadvantages of different models were compared.

The models developed in this study provide information about the relationship between the capacities of one-handed tasks and two-handed tasks, and about the upper limit on the weight which could be handled with one hand.

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CHAPTER I

INTRODUCTION

General

In spite of advances in work automation in industry, manual materials handling (MMH) tasks continue to be an important feature of many industrial operations. Manual materials handling can be described as moving loads from place to place by lifting, lowering, pushing, pulling, or carrying (or some combination) in a work environment.

A major concern with manual materials handling tasks has been the large number of work injuries, especially musculoskeletal disorders and low-back injuries, due directly or indirectly to such tasks. According to State Labor Department reports, over 20% of the injuries in the workplace are back injuries, and 31% of the annual workers' compensation payments are the result of back injuries (National Safety Council, 1991).

Over the years, the number of overexertion injuries has continued to increase despite the use of 'safe lifting methods' (Mital, 1983). According to data from the Bureau of Labor Statistics (1988), about 31% of all disabling work injuries result from overexertions. An important strategy for reducing the extent of these injuries is to utilize ergonomics methodologies.

Three main approaches have been broadly used to determine manual materials handling capacity. First, the biomechanical approach determines the forces imposed upon the musculoskeletal system. Second, the physiological approach is concerned with the physiological stress on the body. A third approach is the psychophysical approach, which estimates an individual's capacity by quantifying his or her subjective tolerance to the stresses of manual materials handling (Ayoub, 1987). The physiological approach is restricted to frequent manual handling tasks. The biomechanical approach, on the other

hand, is mostly used for infrequent tasks. In the psychophysical approach, the performance criteria are usually based on: (1) maximum acceptable weight of lift or carry, (2) maximum acceptable frequency of lift or distance of carry, (3) maximum acceptable workload, and (4) ratings of perceived exertion (RPE) (Ayoub and Mital, 1989).

In the past, mostly two-handed handling tasks have been studied and researchers have paid more attention to them than to one-handed handling tasks due to the relative prevalence of two-handed manual handling activities in industrial settings. Much attention has been paid to establishing load limits for lifts performed with both hands either symmetrically or asymmetrically. Studies involving one-handed manual handling activities are relatively few (McConville and Hertzberg, 1968; Davis and Stubbs, 1980; Warwick *et al.*, 1980; Garg and Saxena, 1982; Garg, 1983; Mital and Asfour, 1983; Mital and Manivasagan, 1983; Mital, 1985; Fothergill *et al.*, 1991). Much less is known about the load limits for one-handed lifting and carrying tasks although one-handed lifting and carrying are still being performed routinely in industry or in our normal life (for example, carrying consumer products, tool boxes, other containers, portable television or radio sets) (Mital and Manivasagan, 1983; Mital *et al.*, 1993).

Rationale for the Study

Although musculoskeletal injuries have occurred as a result of manual materials handling and have stimulated extensive research into the capacities and limitations of humans, gaps in our knowledge still exist in many areas associated with work related activities (Fothergill *et al.*, 1991).

According to Snook and Irvine (1969), strength implies what a person can do in a singular attempt, whereas capacity implies what a person can do, repeatedly for an extended period of time without overexertion or excessive fatigue. Ayoub and Mital (1989) classified the data bases for tasks which are performed more frequently than once every 15 minutes as capacity data.

One area where data are scarce is in whole-body human strength capabilities during tasks requiring one-handed exertions. Most studies of whole-body exertion have been concerned with vertical two-handed lifting or horizontal pushing and pulling (Ayoub and McDaniel, 1974; Chaffin, 1974; Yates *et al.*, 1980), with very few reports on one-handed strengths for lifting (Davis and Stubbs, 1980; Warwick *et al.*, 1980; Fothergill *et al.*, 1991) and carrying (Mital and Manivasagan, 1983). All the strength studies for one-handed lifting tasks were just maximum isometric lifts, not realistic dynamic lifts through a given vertical distance.

Manual carriage of materials is an integral and common part of materials handling occupations (Drury *et al.*, 1982; Mital and Manivasagan, 1983b). There are some studies that examine how the rate and distance of load carriage will influence the maximum acceptable weight that people will carry (Snook, 1978; Ciriello and Snook, 1983; Mital and Okolie, 1982; Morrissey and Liou, 1988; Snook and Ciriello, 1991). The best overall reference would be the comprehensive studies by Ciriello and Snook (1983) and Snook and Ciriello (1991) in which industrial subjects walked on a treadmill at a self-paced speed while carrying a load with two hands. In a one-handed carrying study, Mital and Manivasagan (1983) investigated maximum acceptable amount of carrying for infrequent performance. The above studies indicated that most studies have been involved with single MMH activities such as lifting, lowering, carrying, pulling and pushing. Very few studies have examined the capacities of combinations of two or more activities such as lifting a box, then carrying the box and lowering the box with two hands (Jiang, 1984; Morrissey *et al.*, 1988). However, to date, no actual weight/force data are available for repetitive one-handed tasks, especially combined tasks. However, from Mital and Manivasagan's infrequent one-handed carrying study (1983), the weight that yields a heart rate of 100 beats/min was recommended for repetitive one-handed carrying tasks. Mital *et al.* (1993) recommended that if carrying were to be performed frequently, the weight should be reduced by 30% from Mital and Manivasagan's infrequent one-handed carrying data.

The significant amount of available scientific information has led to the development of a work practice guide for symmetrical manual lifting activities (NIOSH, 1981). Recently NIOSH convened a public meeting (1991) to consider updating and expanding the *Work Practice Guide* (1981). However, adequate scientific information is presently not available to develop similar guidelines for common one-handed tasks such as lifting with one hand, carrying containers in one hand by the side or combinations of the two activities. This study can provide performance ceilings and scientific information for one-handed infrequent and frequent (repetitive) combined tasks. Furthermore, developing the model to predict the capacity of one-handed combined task by using the strength variables or corresponding two-handed capacity data could make it easy to predict the maximum acceptable weight of one-handed infrequent and frequent tasks.

Objectives

The overall objective of this study was to find the psychophysical and physiological responses of human subjects from a simulated industrial task involving one-handed and two-handed combined activities and to develop mathematical models for one-handed and two-handed combined tasks. The specific objectives were as follows.

The first objective was to investigate an upper limit on the weight of industrial or military equipment which could be handled by one hand. The maximum acceptable weights of one-handed and two-handed combined tasks by males were determined by the psychophysical methodology, with high and low frequency rates. Although, the sample sizes was not large enough to establish dependable data bases, this study could provide performance ceilings for one-handed carrying tasks and might present a guide for future studies. These data could be used to develop guidelines for common one-handed combined tasks.

The second objective was to utilize the psychophysical data to develop mathematical models for the capacities of one-handed and two-handed combined tasks and

examination of the relationship between the capacities of one-handed and two-handed combined tasks.

The third objective was to investigate the effect of task variables - frequency rate and hand condition (one hand vs. two hand) on the response variables (maximum acceptable weight, heart rate, RPE value and tasking time).

CHAPTER II

REVIEW OF LITERATURE

Psychophysical Approach

To measure the maximum acceptable weights of manual material handling (lifting, lowering, pushing, pulling, and carrying), the use of the psychophysical methodology in MMH research is discussed by Snook (1978). This methodology requires subjects to adjust one of the task variables (weight of the load or frequency of lift), and the other variables are controlled by the experimenter. Studies of maximum acceptable weights of lifting have been done by Snook and Irvine (1968, 1969), Snook and Ciriello (1974, 1991), Snook *et al.* (1970), Snook (1971, 1978), Ayoub *et al.* (1978), Mital (1984a, 1984b), and Ciriello *et al.* (1990, 1991). Studies on maximum acceptable frequency of lift have been conducted by Garg and Saxena (1981, 1982), Mital and Asfour (1983), Mital (1985), and Fox (1993). The psychophysical approach for two-handed and one-handed lifting studies will be reviewed in this section.

Two-Handed Lifting

Snook and Irvin (1968,1969) used a psychophysical approach to determine the maximum acceptable frequency of lift for different combinations of height of lift and box weight. Three heights of lift were used; floor-to-knuckle height, knuckle-to-shoulder height, and shoulder-to-reach height. Two weights were used, 15.85 kg and 22.65 kg. Eight male workers from local industry performed as subjects. The final frequencies of lift selected by each worker were converted into meter-kilogram per minute to provide a comparison between the 15.85 kg and 22.65 kg weights of lift. A significant difference was found for these workloads among the three heights and two weights. The maximum workloads acceptable to male industrial workers were highest for the knuckle-to-shoulder height, followed by the shoulder-to-reach height, and then the floor-to-knuckle height.

Snook (1971) and Snook *et al.* (1970) conducted studies to determine the maximum weights and workloads acceptable to male industrial workers. The MMH activities involved lifting, lowering, pushing, pulling, walking, and carrying tasks. All tasks except walking were performed at high, medium, and low rates of work. Three height ranges were used for lifting and lowering tasks: floor-to-knuckle height, knuckle-to-shoulder height, and shoulder-to-arm reach height. Subjects were instructed to adjust their workload to the maximum amount they could perform without strain, discomfort, weakness or getting tired. The acceptable weight was higher for the lowering tasks as compared to the lifting tasks, with the exception of shoulder-to-reach height level. Subjects had a higher lifting and lowering workload for the knuckle-to-shoulder height than for the floor-to-knuckle height level or shoulder-to-reach height level.

Snook and Ciriello (1974) performed a similar study on female workers to find the maximum weight and workloads acceptable to them. Sixteen housewives and 15 industrial women were the subjects. The results of this study were very similar to the study by Snook *et al.* (1970). The lifting and lowering capacity of industrial women was higher than that of the housewives for all height levels. The acceptable workload was highest for the knuckle-to-shoulder height level, followed by the shoulder-to-reach, and then the floor-to-knuckle height level.

Ayoub *et al.* (1978) conducted a study to determine and model the lifting capacity of male and female industrial workers. Six different height levels (floor-to-knuckle, floor-to-shoulder, floor-to-reach, knuckle-to-shoulder, knuckle-to-reach, and shoulder-to-reach) and four frequencies (2, 4, 6, and 8 lifts/min) were employed. The experimental procedure was similar to the one described by Snook *et al.* (1970). The results showed that the lifting capability decreased almost linearly with the increase in the box size and frequency. The lifting capacity also decreased with the increase in height of lift and with the point of origin of the lifting task. For the same vertical height of lift, lifting capability decreased when the point of origin of lift changed from knuckle-to-shoulder.

Snook (1978) and Ciriello and Snook (1978) conducted another study in which the height of lift, frequency of lift, and size and weight of the object were studied. The psychophysical methodology was used. Three lifting heights (25, 51, 76 cm), three object lengths (36, 49, and 75 cm - in the sagittal plane), and two object widths (57, and 89 cm - in the frontal plane) were investigated. The subjects lifted weight every 5, 9, and 14 sec; every 1, 2, 5, and 30 min; and once in 8 hr. The results showed no significant weight differences in object widths. However, the differences in the weight handled for different length objects were statistically significant but only for the floor-to-knuckle height at low frequencies. The effects of lifting distances and sex on the maximum acceptable weight of lift were also significant.

Ciriello and Snook (1983) investigated task frequency. Task frequency varied from once every 5 sec to once every 8 hr. Maximum acceptable weights and forces decreased as frequency increased, particularly at the higher frequencies. It was observed that the weights and forces for the 5 min and 30 min task frequencies were overestimated in the original tables (Snook, 1978) by 10 to 15%. Female responses were also studied in relation to object size, vertical distance of lift, and height of pull/push. The results indicated that the maximum acceptable weights and forces for female subjects were significantly lower, but proportionately similar to the maximum acceptable weights and forces for male subjects.

Snook (1978) integrated the results of the previous studies (Snook and Irvine, 1967; Snook, Irvine, and Bass, 1970; Snook and Ciriello, 1974), which were conducted at the Liberty Mutual Research Center into some meaningful tables of maximum acceptable weight and force and Snook and Ciriello revised the original tables in 1991. There were a total of seven criterion tasks (two lifting, two lowering, one pushing, one pulling, and one carrying). Maximum acceptable weights for lifting tasks for males are shown in Table 2.1. From Table 2.1, if a job requires a combination of 75 cm box width, 51 cm vertical distance of lift, floor level to knuckle height of one lift every 1 min, the MAWL for males

Table 2.1
Maximum Acceptable Weight of Lift for Males (kg)
(Snook and Ciriello, 1991)

Width‡	Distance§	Percent¶	Floor level to knuckle height					Knuckle height to shoulder height					Shoulder height to arm reach					
			5	9	14	1	2	5	30	h	5	9	14	1	2	5	30	h
76		90	6	7	9	11	13	14	17	8	10	12	13	14	14	16	17	13
		75	9	11	13	16	19	20	21	24	10	14	16	18	19	21	23	17
		50	12	15	17	22	25	27	28	32	13	17	20	22	23	26	29	22
		25	15	18	21	28	31	34	35	41	16	21	24	27	28	32	35	27
75		10	18	22	33	37	40	41	48	19	24	28	31	32	37	40	31	
		90	6	8	9	12	13	15	15	17	8	11	13	15	16	18	19	15
		75	9	11	13	17	19	21	22	25	11	15	17	20	21	23	25	20
		50	13	15	18	23	26	29	30	34	14	19	21	25	26	29	32	25
25		25	14	19	22	29	33	35	42	17	23	26	30	31	32	39	30	
		10	19	22	26	34	38	42	43	50	20	26	30	35	36	41	45	35
		90	8	9	11	13	15	16	17	20	10	13	15	18	19	21	23	18
		75	11	13	15	19	22	24	24	28	13	17	20	23	24	25	30	23
76		50	15	18	21	26	29	32	33	38	17	22	25	30	30	31	35	29
		25	18	22	26	33	37	40	41	48	20	27	30	36	36	42	46	35
		10	22	26	31	38	44	47	49	57	23	31	35	42	42	44	53	41
		90	7	8	10	13	15	16	17	20	8	10	12	13	14	16	17	16
49		75	10	12	14	19	22	24	24	28	10	14	16	18	19	21	23	21
		50	14	16	19	26	29	32	33	38	13	17	20	22	23	24	26	26
		25	17	20	24	33	37	40	41	48	16	21	24	27	28	32	35	31
		10	20	24	28	38	43	47	48	57	19	24	28	31	32	37	41	36
51		90	7	9	10	14	16	17	18	20	8	11	13	15	16	18	19	18
		75	10	13	15	20	23	25	25	30	11	15	17	20	21	23	25	23
		50	14	17	20	27	30	33	34	40	14	19	21	23	24	27	29	27
		25	18	21	25	34	38	42	43	50	17	23	26	30	31	32	35	32
25		10	21	25	29	40	45	49	50	59	20	26	30	35	36	41	45	37
		90	8	10	12	16	18	19	20	23	10	13	15	18	19	21	23	21
		75	12	15	17	23	26	28	29	33	13	17	20	23	24	25	27	27
		50	16	20	23	30	34	37	38	45	17	22	25	30	31	35	38	35
76		25	21	25	29	38	43	47	48	56	20	27	30	36	36	42	46	42
		10	24	29	34	45	51	56	57	67	23	31	35	42	42	44	49	48
		90	8	10	11	15	17	19	19	23	8	11	13	15	16	18	19	18
		75	12	14	17	22	25	28	28	33	11	15	17	20	21	23	25	24
34		50	16	19	22	30	34	37	38	44	14	19	21	25	26	29	32	30
		25	20	24	28	37	42	47	47	55	17	23	26	30	31	32	36	36
		10	24	29	33	44	50	54	56	65	20	26	30	35	36	41	45	42
		90	9	10	12	16	18	20	20	24	9	12	14	17	17	18	20	20
25		75	12	15	18	23	26	28	29	34	12	16	18	22	23	23	26	26
		50	17	20	24	31	35	38	39	46	15	20	23	28	29	30	34	34
		25	21	25	30	39	44	48	49	57	18	24	27	34	35	36	40	41
		10	25	30	35	46	52	57	58	68	21	28	32	40	40	42	46	47
25		90	10	12	14	18	20	22	23	27	11	14	16	20	20	21	23	24
		75	15	18	21	26	30	32	33	38	14	18	21	26	27	28	29	31
		50	20	24	28	35	40	43	44	52	18	23	27	33	34	35	36	40
		25	26	30	35	44	50	54	55	65	21	28	32	40	41	42	47	46
10			29	35	41	52	59	64	66	76	25	33	37	47	47	49	55	

‡ Rax width (the dimension away from the body) (cm).

§ Vertical distance of lift (cm).

¶ Percentage of industrial population

Indicated values exceed 8 h physiological criteria (see text)

is 12, 17, 23, 29, 34 kg for 90%, 75%, 50%, 25%, and 10% of an industrial population, respectively.

Mital (1984 a,b) used industrial workers to determine maximum acceptable weights of lift for regular (8 hr) and extended (12 hr) work shifts. Four lifting frequencies (1, 4, 8, 12 lifts/min), three height levels (floor-to-knuckle, knuckle-to-shoulder, and shoulder-to-reach), and three box sizes were investigated. A modified psychophysical approach was used by the subjects to determine the maximum acceptable weight of lift. The subjects started with either a light or heavy load in the box and were then allowed to make adjustments by adding or removing weights from the box. They were asked to assume an 8 hr work shift and make as many adjustments as necessary to arrive at the maximum weights that they could comfortably lift, without feeling tired or exhausted. This process took approximately 20 to 25 min to complete after which an acceptable weight of lift was measured. The subjects were then asked to assume an extra 4-hr work period (4 hr of overtime, having just completed an 8 hr shift; no rest allowance was provided in between) and resumed the lifting activity. This phase also lasted approximately 20 to 25 minutes. The forty to forty-five minute work period was considered sufficient to allow individuals to determine the weight they could lift for 12 hr even if it included 4 hr of overtime about which they had no prior warning. The results of the study indicated that, in general, males were willing to lift more weight than females. The maximum acceptable weight lifted decreased with box size and frequency.

One-Handed Lifting

Unlike two-handed lifting tasks, studies dealing with one-handed lifting are relatively few. Maximum acceptable frequencies for one handed horizontal lifting were investigated by Garg and Saxena (1981, 1982), Garg (1983), and Mital and Asfour (1983).

Garg and Saxena (1981, 1982) and Garg (1983) conducted a study to determine the maximum frequencies acceptable to female workers for one-handed lifts in the

horizontal plane. Ten female college students were required to lift continuously three different loads (2.3, 4.5, and 5.7 kg for a 38 cm reach and 1.1, 2.3 and 4.5 kg for a 63.5 cm reach) to two different reach distances (38 and 63.5 cm) on a 91 cm high work table. The psychophysical approach was used and the subjects were allowed to determine the maximum frequency of lift acceptable to them for various load-reach combinations. Heart rate and RPE were measured during the last 5 minutes of the experiment to determine the physiological level of functioning and perceived exertion. The results of the study showed that both the weight of the load and reach distance had a significant effect on maximum frequency acceptable to the subjects for one-handed lifting in the horizontal plane. The average maximum acceptable frequency was 51% of the maximum frequency that the subjects could maintain for a period of 4 minutes. Although subjects selected workloads that resulted in a mean heart rate of 101 beats/min, the heart rate never stabilized over the 1-hr lifting duration. Continuous increases in heart rate were observed. Perceived exertion ratings ranged from 'fairly light' to 'somewhat hard'.

Mital and Asfour (1983) extended the work of Garg (1983) and Garg and Saxena (1981, 1982) since the specific recommendations made are applicable only if the working time does not exceed 1 hr. This was because the heart rates failed to stabilize. In order to establish permissible one-hand lift limits for the duration of the work shift, it is essential that the heart rate for a given workload stabilize, otherwise increasing muscle fatigue will force the workers to stop. The goal of Mital and Asfour's study (1983) was to determine the maximum frequency acceptable to males lifting specified weights using the preferred hand for a period of 2-hr which is a reasonable study time period, since in most work situations a break usually follows. Also the effects of training and posture on maximum acceptable frequencies were studied. Since males in general can lift heavier loads, the third load level was heavier than the three loads used by Garg (1983) and Garg and Saxena (1981, 1982). The tasks and procedures were identical to those used earlier (Garg and Saxena, 1981, 1982; Garg, 1983) except the training period of 6 weeks. In this study, two postures (sitting and standing) were examined. The results indicated that the average

maximum acceptable frequency of lift for one-handed lifting tasks for males was 51% of the 4-minutes of maximum frequency. The 4-minutes of maximum frequency was that the maximum acceptable frequency of lift the subject could maintain for a four-minute period. The acceptable frequency of lift decreased as reach and load increased. The effect of posture was not significant. Heart rate did stabilize, and showed no systematic change with time. The levels of acceptable frequency were significantly lower than for Garg and Saxena's subjects.

Part of the studies by Ayoub *et al.* (1985) was to find the maximum acceptable weight for one-handed tool box lifting from floor to workbench level (30 inch) for males and females. Subjects were required to perform a one-handed lift several times, adjusting the load in the container until they reached the maximum acceptable weight of lift for a single lift. The box measured 61 cm X 30 cm X 46 cm and was fitted with a pipe running through the 61cm length of the box at the height of 41cm from the bottom of the box. The mean and standard deviation of maximum acceptable weight of one-handed tool box lifting were 97.06 lb and 17.55 lb for males and 44.44 lb and 8.29 lb for females.

Lifting/Lowering Model Development

A number of psychophysical lifting/lowering capacity models were developed in the literature. Most models were regression models which had strength (static or dynamic) test data, epidemiological data, and/ or task variables as predictors.

Asfour (1980) proposed psychophysical lifting/lowering capacity models for two height ranges (start at floor or start at 30" height). These models were based on six subjects who conducted 48 experimental situations each. The variables incorporated in the models were subject's body weight, frequency of lift, box size, and angle of body twist.

Mital and Ayoub (1980) developed predictive models for strength (shoulder, leg, arm, back, and composite strength) of male and female industrial workers based on operator characteristics (age, sex, and anthropometric variables). They also developed

lifting capacity models to predict the amount of weight an individual can handle by using predicted isometric strengths and personal characteristics.

Garg *et al.* (1980) conducted a psychophysical study by using nine male subjects. Lifting capacity models were developed by using a single strength (static or dynamic) variable. These models are attractive because of their simple form. They showed that the static vertical lift strength measured at the origin of lift significantly underestimated the dynamic lifting capacity as determined by psychophysical methodology. When the static vertical lift strength was performed closer to the body, such a bias was eliminated. They concluded that specific static strength tests must be carefully constructed to accurately predict a person's dynamic lifting capacity.

Pytel and Kamon (1981) adapted a portable commercially available device ("Mini-Gym" model 101) to measure isokinetic dynamic strength. A lifting experiment was designed to lift a tote box (44 cm X 30 cm X 12 cm) with handles from floor to 113 cm height. Simple psychophysical models were developed. The simple strength test procedure, a concise form of the prediction models, and high R-square values are the most attractive points in this study. However, only one lifting range (floor to 113 cm height) and one lifting frequency were studied.

Kamon *et al.* (1982) employed the same test procedure as Pytel and Kamon (1981) to test 228 male steelmill workers. Two psychophysical lifting models were developed by using a single static strength measure (back extension maximum voluntary contraction) or a single dynamic strength measure (lifting strength).

Ayoub *et al.* (1982) developed a criterion with which the Air Force could reliably evaluate the compatibility of an individual's physical capacities with the physical demands of the various Air Force Specialty Codes (AFSC). Psychophysical methodology was used to determine the capacity for different MMH activities (lifting, carrying, pushing, pulling, holding). A series of one to five variable equations were developed and compared based on 571 airmen's test data. However, the single variable regression equation (isoinertial 6 foot incremental weight lifting test) performed the best except for push/pull activities. The

isoinertial 6 foot weight lift test was simple to perform. The predictability was quite satisfactory for lifting and carrying activities (R-square values ranged from 0.6443 to 0.7500).

Ayoub *et al.* (1983) stated that the psychophysical criterion is an appropriate single design criterion to use in the determination of lifting capacity. Based on two previous psychophysically determined lifting capacity data bases (Ayoub *et al.*, 1978; Snook, 1978), lifting capacity prediction models for both males and females were developed. The models can accommodate (1) a wide range of frequencies (0.1 to 12 lifts/min), (2) six ranges of lifts, (3) various container sizes (12 to 30 inch in sagittal plane), and (4) individual and different percentiles of a population. The models also allow for adjustment of lifting capacity based on the presence or absence of handles and whether or not a twist of the body occurs during lifting activity.

Jiang (1984) developed the prediction models for both individual and combined MMH activities and examined the relationship between individual and combined MMH activities. MMH capacity was defined as the maximum weight the subject was willing to handle plus his body weight for a period of 1 hr under variable task conditions. Each activity was conducted under three different frequencies: one time maximum, one handling per min, and six handlings per min. The prediction models for the capacities of individual MMH activities were developed based on the isoinertial six foot incremental weight lifting test or isometric back strength testing. The isoinertial 6 foot incremental weight lifting test proved to be the best predictor for individual MMH activities.

Carrying

The studies on the manual material handling activities of carrying are relatively infrequent compared to the studies on lifting/lowering. Drury *et al.* (1982) indicated that carrying activities were the third most common MMH activity in industry, following lifting and lowering activities. Carrying activities may be responsible for up to 15% of all

overexertion injuries caused by handling material manually (NIOSH, 1981). In this section, one-handed and two-handed carrying studies will be reviewed.

Two-Handed Carrying

Not many researchers have investigated carrying tasks compared to the lifting tasks (Snook, 1978; Ciriello and Snook, 1983; Mital and Manivasagan, 1983; Mital and Okolie, 1982; Mital, 1986; Morrissey and Liou, 1988; Snook and Ciriello, 1991). The summary of studies reported by Snook and Ciriello (1991) is the most comprehensive and includes maximum acceptable weight of carry data for male and female industrial workers as a function of carrying distance, frequency and carrying height.

Mital and Okolie (1982) investigated the effect of container shape (rectangular, cylindrical, barrel), carrying height (knuckle, elbow height), frequency of carry (once per minute, once every four minutes), distance of carry (3.05 and 9.14 m), and presence and absence of partitions in a container. The results indicated that liquid carrying capabilities could be enhanced by as much as 10% if appropriate container designs (containers with partitions) were used. The maximum acceptable amount of liquid carried might be up to 30% lower than the maximum acceptable weight of solids that could be carried. Carrying capacity also decreased with frequency and distance.

Parts of the studies by Snook *et al.* (1970), Snook and Ciriello (1974, 1991), and Ciriello *et al.* (1990) were to determine the maximum acceptable weight of carry. Subjects determined their own workloads at different walking speeds. In 1991, Snook and Ciriello revised their original manual materials handling data table (Snook, 1978). The maximum acceptable weights for carrying tasks for both males and females are shown in Table 2.2. From Table 2.2, if a job requires a carry at knuckle height (79 cm) for 4.3 meters, once every one minute, the maximum acceptable weight of carry (MAWC) for males is 18, 25, 32, 40, and 47 kg for 90%, 75%, 50%, 25%, and 10%, respectively.

Mital (1986) determined the carrying capability of male and female students for one performance every 8 hr. Twenty-seven males and 11 females carried a load through

Table 2.2

Maximum Acceptable Weight of Carry (kg)
(Snook and Ciriello, 1991)

Height	Percentile	2.1 m carry					4.3 m carry					8.5 m carry				
		6	12	s	30	h	8	10	s	16	1	2	5	min	30	h
111	90	10	14	17	17	19	21	25	9	11	15	15	17	19	22	20
	75	14	19	23	23	26	29	34	13	16	21	21	23	26	30	27
	50	19	25	30	30	33	38	44	17	20	27	27	30	34	39	35
	25	23	30	37	37	41	46	54	20	25	33	33	37	41	48	43
	10	27	35	43	43	48	54	63	24	29	38	39	43	48	57	50
79	90	13	17	21	21	23	26	31	11	14	18	19	21	23	27	26
	75	18	23	28	29	32	36	42	16	19	25	25	28	32	37	35
	50	23	30	37	37	41	46	54	20	25	32	33	36	41	48	46
	25	28	37	45	46	51	57	67	25	30	40	40	45	50	59	56
	10	33	43	53	53	59	66	78	29	35	47	47	52	59	69	65
105	90	11	12	13	13	13	13	18	9	10	13	13	13	13	18	16
	75	13	14	15	15	16	16	21	11	12	15	15	16	16	21	19
	50	15	16	18	18	18	18	25	12	13	18	18	18	18	24	22
	25	17	18	20	20	21	21	28	14	15	20	20	21	21	28	25
	10	19	20	22	22	23	23	31	16	17	22	22	23	23	31	28
72	90	13	14	16	16	16	16	22	10	11	14	14	14	14	20	19
	75	15	17	18	18	19	19	25	11	13	16	16	17	17	23	23
	50	17	19	21	21	22	22	29	13	15	19	19	20	20	26	26
	25	20	22	24	24	25	25	33	15	17	22	22	22	22	30	30
	10	22	24	27	27	28	28	37	17	19	24	24	25	25	33	33

† Vertical distance from floor to hands (cm).

§ Percentage of industrial population.

Italicized values exceed 8 h physiological criteria (see text).

open and confined spaces. The carrying distance was 7.62 m. The load was carried at knuckle and elbow heights, with and without handles, in five different boxes. Males carried 54.6% more weight, on average, than females. The carrying capability declined by 13% for both males and females, when the load was carried through confined spaces. Males carried 14.1% more weight and females 11.7% more weight at the knuckle height compared to the weight carried at the elbow height. Approximately 21% more weight was carried by subjects when boxes were held by handles. Table 2.3 shows the maximum acceptable weight of carry for occasional performance.

Morrissey and Liou (1988) examined how container width, the presence or absence of container handles, and different rates and distances of load carriage influenced the maximum acceptable weight carried by males for one hour. Conditions examined were container width, from 15.2 cm to 56 cm; rate of carriage, from one carry every 12 seconds to one carry every 60 seconds; and distance of carriage from 1 m to 6 m. All conditions were performed using containers with and without handles. The psychophysical method of load adjustment was used to determine the maximum acceptable weight carried in each condition. Results indicated that there were reductions in the maximum acceptable weight carried with increases in container width, rate of carriage, and distance of carriage.

Sharp *et al.* (1995) examined the maximum acceptable load for lifting and carrying in single and mixed-gender two person teams. Participants lifted and carried a box 7.2 meters and placed it on a 132 cm high shelf, at frequency rates of 1/min and 4/min. The means of maximum acceptable load for the frequency rates of 1/min and 4/min for males were 78 lb and 56.2 lb, respectively, and for females were 56.2 lb and 40.5 lb, respectively. The results showed that when working in pairs, team's maximum acceptable load for lifting and carrying are approximately equal to the sum of their individual maximum acceptable load for lifting and carrying.

Table 2.3

Maximum Acceptable Weight of Carry (kg)
for Occasional Performance (Mital, 1986)

Main effect	Males		Females	
	X*	S [#]	X*	S [#]
Space				
Open	28.7	5.2	18.6	4.0
Confined	24.9	4.8	16.1	3.8
Couplings				
Handles	29.6	5.1	19.1	4.1
No-Handles	24.3	4.3	15.7	3.4
Height				
Knuckle	28.6	5.2	18.3	4.2
Elbow	25.1	4.9	16.4	3.8
Box size (cm)				
30.48 x 30.48 x 25.4	27.8	5.0	18.9	4.1
45.72 x 30.48 x 25.4	27.9	5.3	17.5	3.7
60.96 x 30.48 x 25.4	26.8	5.3	16.4	3.9
30.48 x 30.48 x 30.5	26.2	5.4	17.4	4.2
-0 cm offset				
30.48 x 30.48 x 30.5	25.5	5.4	16.5	4.1
-7.61 cm offset				

X* = mean; S[#] = standard deviation

One-Handed Carrying

Mital and Manivasagan (1983) studied the maximum weight individuals are willing to carry over a certain distance in a given container. Four different shapes of containers (plastic bucket, galvanized iron bucket, tool box, and radiator can) and two different volumes were used to carry loads for three typical carrying distances in industry. The psychophysical approach was used and subjects determined the maximum amount of weight they were willing to carry comfortably in a given shape-volume container over each distance. Individuals first subjectively estimated how much weight they could carry in a given type of container for the required distance and then verified it by actually carrying it. The preferred hand was used to hold the containers. Results indicated that subjects could accurately estimate the amount of weight they could carry comfortably in one hand. Shape of the containers significantly influenced the amount of weight subjects were willing to carry in one hand. Although cross sectional area of handles laid between 2 cm² and 2.5 cm², the handle effects were not considered in this study. The acceptable amount of weight decreased with distance, but was found to increase with volume. Table 2.4 shows mean and standard deviation of response measures for males.

Physiological Approach

The physiological approach is applied to repetitive lifting where the weight of the load is presumed to be within the physical strength of the workers. During repetitive handling tasks, a worker's endurance is primarily limited by the capacity of oxygen transporting and utilization systems and not by worker's muscular strength (Astrand and Rodahl, 1986). When a person is engaged in physical work, such as MMH activities, several physiological responses are affected. These include metabolic energy cost, heart rate, blood pressure, and blood lactate. Of all these responses, metabolic energy expenditure, and/or heart rate have been widely accepted as physiological responses to repetitive handling as they are directly proportional to the workload at steady-state conditions (Aquilano, 1968; Mital, 1984 a,b; Astrand and Rodahl, 1986). Generally,

Table 2.4

Mean and Standard Deviation of Response Measures
for Males (Mital and Manivasagan, 1983)

Factor	Description		Weight carried (kg)	Pulse (bpm)	RPE (ARM)	RPE (WB)
Container shape	Plastic bucket	x	9.8	99.1	12.7	11.3
		s	2.8	8.6	1.7	1.4
	Galvanized iron bucket	x	9.3	101.1	12.3	11.1
		s	2.5	8.8	1.9	1.3
	Tool box	x	10.6	100.8	12.4	11.2
		s	3.1	10.4	1.9	1.4
	Radiator can	x	10.1	98.7	12.5	11.1
		s	3.0	11.5	1.6	1.2
Container volume (l)	8.5	x	9.7	100.5	12.3	11.1
		s	2.8	10.0	1.8	1.3
	12.3	x	10.2	99.4	12.7	11.2
		s	3.1	9.9	1.7	1.3
Distance (m)	30.48	x	11.0	100.5	12.3	11.0
		s	3.4	9.1	1.8	1.2
	60.96	x	9.7	98.8	12.4	11.0
		s	2.6	10.7	1.6	1.4
	91.44	x	9.2	100.5	12.8	11.4
		s	2.4	9.9	1.9	1.4

x = mean ; s = standard deviations

RPE (WB) : ratings of perceived exertion for whole body

RPE (ARM): ratings of perceived exertion for the arm

oxygen consumption is measured to estimate the energy expenditure required by MMH activities. When muscles become active, their increased metabolism demands an increase in the delivery of oxygen and foodstuffs if the activity is to continue. These circumstances call for an increased respiratory function and a greater amount of blood flow to the muscles. However, these respiratory and cardiovascular responses are linearly related to the amount of oxygen used by the muscles. In turn, the amount of oxygen consumption is linearly related to the amount of external work done by the muscles (NIOSH, 1981).

Muller (1953) and Bink (1962) proposed the upper limit of the energy expenditure required for daily work should be 5.0-5.2 kcal/min. Michael *et al.* (1961) conducted cycle ergometry and treadmill walking experiments. They concluded that 35% of the maximum aerobic capacity was the limit of work that could be performed without undue fatigue.

It has been generally agreed that physical jobs that require a metabolic energy expenditure rate of more than 5kcal/min (approximately 33-35% of the treadmill aerobic capacity; Micheal *et al.*, 1961) will lead to overexertion and undue fatigue. This physiological fatigue guideline was tested by Mital (1984 a,b). Mital reported that the average oxygen consumption associated with the psychophysically acceptable weight of load of male industrial workers was equivalent to 29% (3.6 kcal/min) VO_2 max for an 8-hr lifting duration and 23% (3.0 kcal/min) VO_2 max for a 12-hr lifting duration. For females, the average oxygen consumption decreased from 28% (2.3 kcal/min) VO_2 max for an 8-hr lifting duration to 24% (2.0 kcal/min) VO_2 max for a 12-hr lifting duration.

Legg and Pateman (1985) and Legg and Myles (1985) reported that since MMH activities have a combination of static and dynamic components, 21-23% of uphill treadmill aerobic capacity should be considered as the upper limit of metabolic energy expenditure that could be sustained for any load/repetition combination for 8-hr workdays. In terms of bicycle aerobic capacity, the recommendation would be approximately 28-29%. Based on Mital's work (1984 a,b), this limit should be revised downwards, to 23-24% of bicycle aerobic capacity, for 12-hr workdays.

Astrand and Rodahl (1986) reported that heart rate is a reasonable indicator of the amount of strain imposed on the cardiovascular system of an individual during muscular activity. They also indicated that the increase in the heart rate is linear with the increase in work load.

Mital and Manivasagan (1983) reported that the heart rate of males and females was not affected significantly by either the shape or volume of the container or by the carrying distance in one-handed carrying tasks. The average heart rate for males and females was 100 and 99 beats/min, respectively, and corresponds with the recommendations of Snook and Irvine (1969) for arm work.

For one-handed lifting activities, Garg and Saxena (1981, 1982) found that mean heart rate was about 101 beats/min when subjects were allowed to adjust the frequency of lift. The heart rate increased with load and reach distance, but never stabilized with time and showed continuous increase. A constantly increasing heart rate indicated increasing levels of muscle fatigue.

The average heart rate of the females who participate in the study conducted by Mital and Asfour (1983) was 88 beats per minute for identical load-reach combinations of Garg and Saxena's (1981, 1982). This value was significantly lower than that for Garg and Saxena's subjects (1981, 1982). The heart rate of the subjects also stabilized with time indicating a stable level of fatigue. As the task duration increased, subjects accepted lower levels of workloads to keep the overall level of task demand the same.

One-Handed Strength Measurement

McConville and Hertzberg (1968) examined the interaction of two variables - weight and width - of one-handled, symmetrical boxes that a sample of 30 adults males were able to lift by the preferred hand from the floor to a 30 inch table. No carrying was involved. The goal was to develop upper limits on the weight of industrial or military equipment which must be lifted by one hand. The subject sample was chosen to be a reasonable representation by height and weight of the U.S. Air Force population. A

special box was designed that permitted width variation from 6 to 32 inches. The maximum weight that 95% of the population would be able to lift, but not necessarily carry, can be expressed by a linear equation: $Y=60-X$, where Y is the weight in pounds and X is the width in inches. The numerical values of this formula provided a recommended upper limit on the design of industrial or military equipment which may be lifted under ideal conditions.

The Material Handling Research Unit of the University of Surrey (Davis and Stubbs, 1980) has recommended forces that can be exerted occasionally for one-handed lifting tasks when standing, squatting, sitting, or kneeling. These forces are for males and consider the subject's age and location of the grip. The hand (preferred) in all cases is directly in front of the body. The same forces may be applied if the arm is in a plane in line with the shoulders or it is in between the front and the side positions. If the non-preferred (weaker) hand is to be used, the values should be reduced by approximately 10%.

Warwick *et al.* (1980) used 29 healthy adult males for measuring maximum voluntary isometric strength in 120 activities representative of manual material handling tasks. Force (isometric strength) exerted by subjects, using either left or right hand, on a handle located at either 142 cm height (shoulder height) or at 60 cm height (knee height) was measured. The feet of the subject were always placed 30 cm apart, in one of the three positions; right, right posterior and left. The forces were exerted in six directions: vertically upward (lift); vertically downward (press); push forward; pull backward; push left or right parallel to the frontal plane when the body is facing the work piece.

Maximal static strength was determined for one-handed exertions in all directions in the fore and aft plane by Fothergill *et al.* (1991). Free-style manual strength, with the dominant hand, was measured on the force bar while standing. Two-handed exertions were also measured for comparison. Subjects performed steady maximal exertions in all possible directions in the fore and aft plane with the force bar set at 1.0 or 1.75 m above the ground. The ratio of mean strengths of females to that of males ranged from 0.5 to 0.83 for absolute forces and from 0.63 to 1.00 for forces normalized to body weight. The

ratio of one-handed to two-handed strengths ranged from 0.64 to 1.04. Two-handed strengths commonly exceeded one-handed strengths at the lower handle height, but showed fewer significant strength differences according to direction at 1.75 m. Both female/male and one-handed/two-handed strength ratios were found to be dependent on direction of exertion and handle height.

Factors Affecting Manual Material Handling

Frequency

Frequency, or pace, is associated with repetitive tasks. For a given task, the maximum weight of lift acceptable to an individual decreases non-linearly with an increase in pace (Garg and Saxena, 1979; Snook, 1978; Ayoub *et al.*, 1980; Ciriello and Snook, 1983; Mital and Manivasagan, 1983; Mital, 1984a). The metabolic energy expenditure rate also increases with an increase in the task pace (Ayoub, 1977; Petrofsky and Lind, 1978; Garg and Saxena, 1979; Mital, 1984a).

Ayoub *et al.* (1980) have developed various limiting combinations of load and frequency for manual lifting tasks based on subjective estimates of acceptable weight. Garg and Ayoub (1980) found that for high load (more than 15 kg), low frequency (less than 6 lifts/min), the physiological fatigue criterion (based on a limit of 5 kcal/min metabolic energy expenditure rate) appears to be more conservative than the psychophysical measure. Figure 2.1 shows that the psychophysical approach would result in more liberal standards for low frequency, high load tasks, while the physiological approach would result in more liberal standards for high frequency, low load tasks (Ayoub and Mital, 1989).

Mital and Okolie (1982) studied the effect of frequency of carry on the maximum acceptable amount of liquid carriage. In this study, they used frequency of once per minute, and once per every four minutes (0.25 carry/min). They concluded that the maximum acceptable amount of liquid carried is significantly reduced by 7.4% with an increase in frequency from 0.25 carry/min to 1 carry/min.

Figure 2.1

Psychophysical versus Physiological Fatigue Criterion
(based on Garg and Ayoub, 1980)
(From Human Factors, Vol. 22)

Morrissey and Liou (1988) used five carrying rates for the study of maximum acceptable weight in load carriage. The rates were 1 carry/min, 1.2 carries/min, 1.67 carries/min, 2.67 carries/min, and 5 carries/min. The results showed that with increases in the rate of carriage, there were reductions in the maximum acceptable weight that was carried.

Jiang *et al.* (1986) used three frequency conditions for their combined materials handling activities study. Lifting, lowering and carrying were involved in this study. The conditions were one-time maximum, one carry per minute, and six carries per minute. They mentioned that one-time maximum capacity represented a subject's maximum voluntary capacity, and one carry and six carries per minute represented an infrequent and a frequent handling in MMH activities.

Snook *et al.* (1970), Snook and Ciriello (1974), and Ciriello *et al.* (1990) determined the maximum acceptable weight of carry. Different frequencies for different distances were used in these studies. Ten carries/min, and 5 carries/min were used for 2.1 meters distance. For a 4.3 meters distance, 6 carries/min and 3.75 carries/min, and for 8.5 meters distance, 3.3 carries/min and 2.5 carries/min were used. These frequencies seem to represent frequent(repetitive) carrying activities for each distance. On the other hand, the frequencies such as one carry/min, 0.5 carry/min, 0.2 carry/min, 0.5 carry/hr, and 1 carry/8 hr were used for all three distances. These frequencies might represent infrequent carrying activities.

Frequency of handling is perhaps the most critical task characteristic that influences an individual's capability to perform MMH activities. Control of frequency is essential if the goal is to reduce fatigue and overall job strain. In general, the MMH capacity increases as the frequency of handling decreases (Mital *et al.*, 1993).

Training

Training in manual material handling has been advocated by many individuals over the years (Brown, 1974; Davies, 1978). The rationale is that worker's (subject's)

preparation will lead to the avoidance or the successful survival of injuries. It is expected that after completion of training, a worker (subject) will have learned: (i) the correct method of load handling, and (ii) to recognize and cope with the hazards due to the load, the task or the environment (Ayoub and Mital, 1989). Training is also expected to lead to improvements in physical capability of workers (subjects). The overall effects of physical training are positive and lead to enhancement in muscular strength, MMH capacity, cardiovascular capability, and endurance time (Ayoub and Mital, 1989; Genaidy, 1990).

Dehlin *et al.* (1978) reported that exercise and physical training led to decrease in perception of exertion and reduced back pain. Mital and Manivasagan (1983a) determined that experienced male industrial workers could, on the average, lift 6 kg more than their inexperienced student counterpart. Mital and Manivasagan (1983b) found that experience on the job does in fact increase the maximum acceptable weight of carry (Table 2.5). According to Asfour (1980), training can significantly increase an individual's strength and endurance. Asfour suggested that no more than 10 training sessions, 2 hrs each, were needed.

Ratings of Perceived Exertion

The perceived exertion rating scale is the most commonly used measurement instrument in psychology (Gamberale, 1985). Perceived exertion can be defined as one's subjective ratings of the intensity of work being performed. By far, the most frequently used scale for rating the degree of perceived exertion during physical work is the RPE scale (rating scales of perceived exertion) developed by Borg (1962). A 21-point graded scale was developed in 1962. In 1970, this original 21-point graded scale was changed to a 15-point graded scale. This scale consists of numbers from 6 to 20 printed in a quarto format where odd numbers are anchored with verbal descriptions ranging from 'very, very light' at 7 to 'very, very hard' at 19. This scale is shown in Table 2.6.

The RPE scale has been developed on the basis of empirical data from work on the bicycle ergometer. In fairly young to middle-aged people (25 to 45 years old), working at

Table 2.5

Comparison of Industrial and Student
Carrying Capacities (kg)
(Mital and Manivasagan, 1983b)

Carrying distance (m)	Student population		Industrial population		Level of significance (P)
	x	s	x	s	
3.05	21.70	6.51	32.96	11.68	0.01
9.14	21.47	6.98	29.96	9.34	0.01

x = mean; s = standard deviation

Table 2.6

Ratings of Perceived Exertion Scale (Borg, 1970)

<u>Ratings</u>	<u>Exertion Level</u>
6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

moderate to high intensity levels, the heart rate roughly corresponds to 10 times the RPE value. So values from 6 to 20 match the variation in heart rate for 60 to 200 beats/min.

Mital and Manivasagan (1983) used the RPE scale to estimate the perceived exertion of the arm handling the load as well as the whole body. They concluded that the ratings of perceived exertion for the arm handling the load appeared to be one-eighth of the heart rate instead of one-tenth which was the case for whole body.

This RPE scale has now been used in many different studies (Borg and Noble, 1974).

Summary

Manual material handling has been studied with three main approaches: biomechanical, physiological, and psychophysical approaches.

Snook and Irvine (1968, 1969), Snook and Ciriello (1974, 1991), Snook (1971, 1978), Ayoub *et al.* (1978), Ciriello *et al.* (1990, 1991), and Mital (1980, 1984 a,b) used the psychophysical methodology to measure the maximum acceptable weight of lift. These studies of maximum acceptable weight of lift were all for two-handed lifting tasks. The studies of one-handed lifting tasks were relatively few compared to the two-handed lifting tasks.

Psychophysical lifting/lowering capacity models were developed by many researchers (Asfour, 1980; Garg *et al.*, 1980; Mital and Ayoub, 1980; Pytel and Kamon, 1981; Ayoub *et al.*, 1982; Jiang, 1984; Jiang *et al.*, 1986). For the modeling of psychophysical lifting/lowering capacities, the predictors used in the literature were either task related variables or operator related variables. Task related variables are the ones to describe the task conditions, such as frequency, range, distance of lifting/lowering, container size or type. Operator related variables are the ones to describe an operator's physical condition, such as his/her strength and anthropometric measurements.

Garg and Saxena (1981, 1982), Garg (1983), and Mital and Asfour (1983) investigated one-handed horizontal lifting tasks. They measured maximum acceptable

frequency of lift by using the psychophysical methodology. Their findings were that the acceptable frequency of lift decreased with increasing reach and load.

Carrying tasks are one of the important manual material handling activities. However, not many studies have been conducted for carrying tasks and some studies were just a part of other studies of manual material handling tasks. (Snook, 1978; Ciriello and Snook, 1983; Snook and Ciriello, 1974, 1991).

Mital and Manivasagan (1983) studied the subjective estimates of infrequent one-handed carrying tasks. In this study, the maximum weight the subject was willing to carry over a certain distance was examined.

A maximum heart rate of 99 beats/min has been recommended for arm work by Snook and Irvine (1969). As observed by Mital and Manivasagan (1983), for infrequent one-handed carrying tasks, subjects selected a weight that resulted in an average heart rate of about 100 beats/min. The heart rate did not change significantly with distance, container volume or container shape. From these results, for repetitive one-handed carrying tasks, weights that yield a heart rate of 100 beats/min are recommended (Ayoub and Mital, 1989). For one-handed lifting tasks, the continuous work capacity should be based on a heart rate of approximately 90 beats/min (Mital and Asfour, 1983; Mital, 1985).

Studies were conducted to investigate the effects of frequency on the maximum acceptable weight of lifting or carrying (Garg and Saxena, 1979; Snook, 1978; Ayoub *et al.*, 1980; Ciriello and Snook, 1983; Mital and Manivasagan, 1983a, Mital and Okolie, 1982; Jiang *et al.*, 1986; Morrissey and Liou, 1988). They concluded that there were statistically significant differences in the load lifted or carried by the rate of lift or carriage (frequency) respectively.

A series of research projects were conducted at the Liberty Mutual Research Center to establish manual materials handling limits (Snook and Irvine, 1967; Snook *et al.*, 1970; Snook and Ciriello, 1974; Ciriello and Snook, 1983; Ciriello *et al.*, 1990, 1991). Snook and Ciriello (1991) reported comprehensive maximum acceptable weights of handling for a variety of manual material handling tasks.

The literature review above showed that lifting, especially two-handed lifting tasks have been studied by many researchers. However, the study of one-handed manual material handling tasks and the relationships between one-handed and two-handed capacities have not been established.

CHAPTER III

METHODS AND PROCEDURES

Ten male students were recruited from the student population of Texas Tech University. They participated in training sessions and were familiarized with the experimental procedures before the experimental data were collected. For describing the subject's physical condition, strength tests, anthropometric measurements, and physiological capacity tests (PWC) were conducted. The equipment used and the experimental design are presented in this chapter.

Subject

Ten student subjects were selected for the experiment. The reason for using students as subjects was the availability in terms of schedule flexibility and experimental duration. The selection of the subject population used in this study was according to the height and weight criteria. Students who had the height range of between 159.5 cm and 191.0 cm, the weight range of between 46.5 kg and 88.0 kg were considered to be selected. The subjects' ages varied between 20 and 30, with the average age being 23. The subjects ranged in height from 162.5 cm to 183.0 cm, with an average of 173.9 cm, and their weight ranged from 56.2 kg to 87.1 kg, with an average of 75.1 kg. Subjects' age, height and weight summary data are presented in Table 3.1.

Recruitment and Selection of Subject

Prospective subjects were solicited through advertisements that were posted on campus. Persons responding by telephone were given a short description of the experiment and, if still interested, were asked their height, weight, and age as a pre-screening measure. After a suitable pool of a prospective subjects had responded to the advertisement, appropriate individuals, based on a variety of heights and weights, were then called back

Table 3.1

Summary of Subject Age, Height and Weight

Subject	Age (years)	Height (cm)	Weight (kg)
S1	23	162.5	56.2
S2	30	182.3	87.1
S3	21	178.6	83.9
S4	27	170.0	75.3
S5	26	175.0	76.2
S6	20	175.7	78.4
S7	20	170.0	72.1
S8	20	170.6	70.3
S9	23	171.2	73.5
S10	20	183.0	78.0
Mean	23	173.89	75.10
S.D.	3.56	6.31	8.39

and invited to come into the lab for an explanation of the experiment and to fill out a personal data questionnaire and read and sign a consent form (Appendix A). None of the subjects had prior medical or health problems, such as back, arm or leg problems. After the subjects passed the medical screening questionnaire and consented to the experiment, they were asked to refrain from eating, smoking, and drinking carbonated or caffeinated beverages or alcohol for at least two hours prior to any experimental sessions. The subjects were also asked to avoid participating in any strenuous physical activities prior to any experimental sessions and asked to get their usual amount of rest.

The subjects were all volunteers and were paid \$5.00 per hour for their participation in the study. The subjects were informed that they could terminate their participation in the study at any time without prejudice and would be paid for all work completed. They were also informed that they could be dismissed from the study for uncooperative behavior, illness or injury in the course of the study that could alter their performance of the experimental tasks.

Anthropometric Measurements

In order to describe a subject's physical condition and to compare the present subject sample to that of past research, the following anthropometric measurements were taken from the subjects:

- stature (cm),
- weight (lbs),
- acromial height (cm),
- elbow height (cm),
- knuckle height (cm),
- knee height (cm),
- ankle height (cm),
- shoulder-elbow length (cm),
- forearm-hand length (cm),

biacromial breadth (cm),
hand length (cm),
foot length (cm),
chest depth (cm),
chest width (cm),
neck circumference (cm),
shoulder circumference (cm),
chest circumference (cm),
buttock circumference (cm),
thigh circumference (cm),
calf circumference (cm),
wrist circumference (cm),
waist circumference (cm),
biceps circumference (flexed) (cm),
forearm circumference (flexed) (cm).

The above measurements were chosen due to their use by prior researchers in MMH including the development of MMH prediction capacity models (Asfour, 1980; Mital, 1980; Jiang, 1984; Fox, 1993). The protocol for anthropometric measurement was adopted from Ayoub (1980), Asfour (1980), and Lohmann *et al.* (1991). A summary of the subjects' anthropometric data is provided in Appendix B.

Training and Familiarization Session

Asfour (1980) mentioned that the purpose of training is to provide the necessary conditioning of subjects in terms of muscular development and development of their manual material handling techniques so that they can be more representative of an industrial worker and at the same time eliminate the effect of learning on the data collected. According to Asfour (1980), at the end of ten training sessions, the subjects'

PWC increased by approximately 23%, the static strength increased about 23.5%, and maximum acceptable weight of lift increased about 50%. Legg and Myles (1981) realized that familiarization with the psychophysical methodology and optimal subject cooperation were important in order to obtain reproducible psychophysical data.

Jiang *et al.* (1986) summarized the purposes of familiarization sessions as:

1. The subjects could become familiar with the experimental environment and activities conducted.
2. The subjects could become familiar with the experimental procedures and psychophysical methodology.
3. The subjects could utilize muscle groups that would be used during the experimental sessions in order to have natural responses as the data collection began.
4. The experimenter could become familiar with the subjects (and vice versa) in order to have better cooperation.

Although training was not a major variable in this study, training and familiarization sessions were conducted for subjects to represent the industrial workers more closely and to get more representative data for industry.

Some studies (Fox *et al.*, 1973, 1974; Sidney *et al.*, 1972) using interval training showed that 2 or 3 days-per week training resulted in changes in max VO_2 similar to those observed with 5 days-per week training. So, typical training programs are conducted 2 to 3 days a week with a rest day spaced between 2 workout days (McArdle *et al.*, 1991). Although, Asfour (1980) found that the results of ten training sessions (five sessions per week for two weeks) showed significant increment in the subjects' PWC, the static strength, and maximum acceptable weight of lift, according to Fox *et al.* (1974) and Sidney *et al.* (1972), three training sessions per week may be enough for reasonable training results. So, in this study, each subject was given three training and familiarization sessions per week for two weeks, for a total of six sessions. The training programs that the subjects performed for this study were as follows:

1. Cardiovascular Endurance: Training for cardiovascular endurance was conducted every training session. As a general rule, aerobic capacity improves if exercise is of sufficient intensity to increase heart rate to about 70% of maximum, and an exercise heart rate of 70% maximum represents moderate exercise that can be continued for a long time with little or no discomfort (McArdle *et al.*, 1991). In this study, the bicycle ergometer was used for training. Each subject was trained for 25 minutes on the bicycle. For the first 5 minutes, the subject warmed up at a load that elicited a heart rate of 100 beats/min. Then for the following 20 minutes, the subject exercised with the intensity of 70% of each subject's maximum heart rate. Heart rate was monitored continuously for the entire 25 minutes.

The cooling down period can prevent muscle cramps and stiffness and facilitates the recovery process. The optimal level of recovery exercise (cooling down) is between 29% and 45% of maximum VO_2 (equivalent to about 50% and 60% of maximum heart rate) for bicycle exercise (McLellan and Skinner, 1982). After 25 minutes bicycle training, five minutes of cooling down period with 50% of maximum heart rate intensity was conducted.

2. Practicing tasks: During the six training and familiarization sessions, each subject was asked to perform all combinations of carrying activities. Table 3.2 shows the list of experimental conditions. For each session, each subject was asked to conduct one of six different conditions. The order was randomly chosen by each subject. At the end of six sessions, all conditions were exposed to each subject.

3. Muscle strength: Training for muscle strength was held during five training sessions. Asfour (1980) conducted this training every other training session during ten training sessions to allow for muscle recovery. In this study, every training session was at least every other day, so there was enough time for the muscle recovery. DeLorme and Watkins (1948) established the idea of a "repetition maximum" (RM). A repetition maximum is the maximal load that a muscle group can 'lift' over a given number of repetitions before fatiguing. Although, in this study, the subjects were asked to perform a

Table 3.2
Experimental Conditions for Familiarization Session

Conditions	Task *	Distance (meters)	Frequency (task/min)
1	one-handed	4.3	6/min
2	one-handed	4.3	1/min
3	one-handed	4.3	1/5min
4	two-handed	4.3	6/min
5	two-handed	4.3	1/min
6	two-handed	4.3	1/5min

* for one-handed task -- using tool box
for two-handed task -- using container

combined task (lifting, carrying, and lowering), lifting and lowering were important parts of the task, so the idea of an "RM" applied in this study. According to Berger (1962 a,b,c), the greatest improvement in strength was obtained from 3 sets, each with a 6 RM load. Three sets, of six repetitions each, were used from floor to knuckle height. The subjects were asked to determine the maximal load that they could lift and lower in a box (46 cm X 30 cm X 30 cm) six consecutive times without resting between the lifts. The three sets, of six repetitions each, were as follows:

Set 1: 6 repetitions at a load of 1/2 the 6 RM load

Set 2: 6 repetitions at a load of 3/4 the 6 RM load

Set 3: 6 repetitions at a load equal to the 6 RM load.

Strength Test

A series of static or isometric strength measurements were taken for each subject. The isometric strengths for the arm, back, shoulder, leg, and composite were measured based on the equipment and protocol used by Asfour (1980). Since, this study was for one-handed carrying tasks, subjects' task arm strength was also measured. In conducting a strength test, the subjects were instructed to sustain the maximum static strength, not to jerk on the handle, for each trial for three to five seconds. At least three trials were taken of each test until three maximum values were within 15 percent of each other. The maximum values were averaged to yield a strength value for that particular test. The subject was allowed a short rest (10 to 15 seconds) between each trial and given at least two minutes of rest between each test (Aghazadeh, 1982; Jiang, 1984; Fox, 1993). A summary of subjects' strength data is provided in Appendix C. The description of the measurement procedure of the isometric strength test is provided in Appendix D.

All strengths were measured before and after the training session to see the effect of the training. Also, isometric strength testing data were compared with the other studies in Table 3.3.

Table 3.3

The Comparison of Strength Data *
for the Present study and Previous studies

Strength	Present (N=10)	Ayoub (1978) (N=73)	Jiang (1984) (N=12)	Fox (1993) (N=12)
Arm	73.3 (10.0)**	81.5 (21.3)	83.8 (19.4)	68.8 (21.2)
Back	157.3 (40.3)	159.5 (34.4)	127.8 (46.5)	129.5 (57.7)
Composite	223.2 (40.5)	249.1 (59.8)	235.7 (77.4)	246.1 (72.9)
Shoulder	132.8 (17.3)	110.2 (28.1)	132.7 (43.3)	103.6 (44.3)
Leg	265.3 (41.3)		274.5 (79.3)	235.2 (85.4)

* all units in lbs

** The values in parentheses are standard deviations

Physical Work Capacity Measurement (PWC)

The PWC (VO_2 max) was determined for each subject on a bicycle ergometer using submaximal techniques. The resting heart rate of the subject was measured after five minutes of resting in a sitting position. This is known as the Resting Heart Rate (RHR). The Maximum Heart Rate was estimated from the empirical equation; $\text{MHR} = 205 - 1/2 \text{ Age}$. The subject rode a bicycle ergometer for four minutes at each of three different workload. Oxygen consumption and heart rate data were collected during the fourth minute of each workload. The oxygen consumption (in liters/minute) and heart rate data for each of the workloads were then used in a least squares regression to estimate VO_2 max, using the subject's predicted maximum heart rate. The bicycle ergometry PWC assessment was adapted from the protocols of Fernandez (1986), Kim (1990), and Fox (1993).

According to deVries (1986), oxygen consumption is assumed to be directly proportional to percent of Heart Rate Range (HRR). Heart rate range was determined as follows:

$$\text{HRR} = \text{MHR} - \text{RHR},$$

where MHR was the maximum heart rate ($205 - 1/2 \text{ Age}$) and RHR was the resting heart rate. The percentage of the HRR during exercise was computed as:

$$\text{percent HRR} = ((\text{EHR} - \text{RHR}) / \text{HRR}) \times 100,$$

where EHR was the exercise heart rate at a given workload.

The first workload used for all subjects was 400 kpm/min at 55 rpm, and the second and third workload were one to achieve 50 and 65 percent of HRR, respectively (Fernandez, 1986; Fox, 1993). The PWC measurements were taken before and after the training session for the comparison. Although, during the experiment, subjects' oxygen consumption was not the response variable, subjects' PWC would be a good reference for the effect of training sessions and for the subject data. A summary of subject PWC data is provided in Appendix E.

Experimental Apparatus

The equipment used in this study included static strength measuring equipment, metabolic energy expenditure measurement equipment, a heart rate monitoring device, anthropometric measurement equipment, timing device, bicycle ergometer, containers, and different weights of load (lead shots). All the necessary equipment and apparatus was available in the Ergonomics Lab of the Industrial Engineering Department of Texas Tech University. Details of the equipment and apparatus are provided below.

Anthropometric Measurements

An anthropometric tool kit manufactured by GPM of Switzerland was used to take the height, length, breadth, and circumference anthropometric measurements. The kit is shown in Figure 3.1. A standard medical scale was used to measure subject's body weight.

Static Strength Test

For the static strength test, an AmetekTM model HSC-11 load cell manufactured by Alphatron, Inc. was used with the laboratory apparatus. This equipment was used by other researchers (Asfour, 1980; Jiang, 1984; Fox, 1993) for the measurement of back, shoulder, arm, leg and composite strength. Weights were used to periodically verify the accuracy of the load cell.

PWC Measurement

A bicycle ergometer (Fitron Cycle-Ergometer) manufactured by Lumex, Inc. was used for the measurement of PWC. A Metabolic Measurement Cart (MMC) manufactured by a Sensormedics Inc. of Yorba Linda, CA, Model 2900 MMC, that included the headgear and mouthpiece was used for the collection of oxygen consumption data. Heart rate was monitored using Polar Pacer Heart Rate Monitor manufactured by Polar CIC Inc. The heart rate monitor consisted of a wristwatch style receiver and a

Figure 3.1
Anthropometric Tools

sensor/transmitter which mounted on an elastic belt and was fastened around the subject's chest with the sensor located under the breasts. The sensor/transmitter unit transmitted the heart rate via a radio signal to a wristwatch style receiver that displayed the heart rate in beats per minute (bpm). The transmitter had an effective range of about three feet. The heart rate monitor is shown in Figure 3.2. A subject performing the bicycle ergometry PWC test while connected to the MMC is shown in Figure 3.3.

Experimental Task

A rectangular tool box with a pipe as a handle running through the length of the box at a height of 30 cm from the bottom of the box was used for one handed tasks. The diameter of pipe for a handle was 2.5 cm. So, the sectional area of the handle was 4.9 cm^2 . The size of the tool box container was 49 cm X 16 cm X 20 cm, which represented a typical tool box size. For two-handed tasks, a container which had a dimension of 46 cm X 30 cm X 30 cm and was constructed with 1.3 cm thick plywood. The container had 15.2 cm high handles midway in the width dimension. Figures 3.4 and 3.5 show the one-handed task tool box and two-handed task container.

The Polar Heart Rate monitor that was described above was used to record heart rate for this study. The beeper/metronome consisted of a model 355 Shawnee II TM digital setting solid state timer manufactured by automatic Timing & Control, Inc. in a circuit with a Sonalert TM model SC110N solid state signaler manufactured by Newark Corp. which was used to control the frequency. The face of the beeper/metronome is shown in Figure 3.6.

Experimental Design

A randomized block factorial design was utilized. Each subject was considered as a random block. The experimental variables for the experiment are:

Figure 3.2
Heart Rate Monitor

Figure 3.3

Subject's Bicycle Ergometry PWC Testing
While Connected to MMC

Figure 3.4

One-handed Task Tool Box

Figure 3.5

Two-handed Task Container

Figure 3.6

Beeper/Metronome

Independent Variables

1. Frequency rates : Three different frequencies were studied. Table 3.4 summarizes previous research efforts and their frequencies for carrying tasks. According to this table, previous research considered more than one carry per minute as frequent carrying tasks, and one carry or below per minute as infrequent carrying tasks. So, six carries/min for 4.3 m was considered as a frequent carrying task, one carry/min was considered borderline for frequent and infrequent tasks, and one carry/5 min (0.2 carry/min) was considered as an infrequent carrying task for this study.
2. Hand condition: One-handed tasks and two-handed tasks were performed by each subject. For one-handed tasks, all subjects used their “right hand” as their preferred hand.
3. Replication: Two of each combination were conducted to increase the statistical power of the experiment and to provide a check on the validity of the psychophysical approach. If two measurements under a certain test condition were found to have a difference of 15% or more (Ciriello and Snook, 1983), another test was supposed to be conducted until the difference of two values were within 15%. However, more than 15% of the difference did not occur in this experiment. The average of these two measurements was taken as the capacity for that subject under a certain task condition.

Dependent Variables

1. Maximum acceptable weight: Each subject determined the amount of weight they could handle comfortably for their preferred hand tasks and two-handed tasks for an actual one-hour period using the psychophysical methodology.
2. Heart rate: Heart rate was monitored continuously during the experiment, however, minute heart rate was recorded for four full minutes at the end of one

Table 3.4

Major Studies with their Carrying Frequencies

Researcher	Frequency (carry/min)
Jiang <i>et al.</i> (1986)	1/min, 6/min, one-time maximum
Morrissey and Liou (1988)	1/min, 1.2/min, 1.67/min 2.67/min, 5/min
Snook (1978) Snook and Ciriello (1991)	5/min, 10/min (2.1m) 3.75/min, 6/min (4.3m) 2.5/min, 3.3/min (8.5m) 1/min, 0.2/min, 0.5/hr, 1/8hr : for all three distances
Mital and Manivasagan (1983)	one-time maximum
Present study	6/min, 1/min, 1/5min

hour (57th to 60th minute) for the frequency of 1/min and 6/min. If the subject adjusted the load during the last ten minutes at the end of one hour, the subject was supposed to be asked to handle that adjusted load for fifteen more minutes from the time of the last adjustment and the minute heart rate would be recorded at the end of that fifteen minutes for four full minutes (12th to 15th minute).

However, in this experiment, none of the subjects adjusted the load during the last ten minutes at the end of one hour. For the frequency of 1/5min, the 55th and 60th minute of heart rate were recorded.

3. Ratings of perceived exertion (RPE): At the end of each different combination, the subjects were asked to rate the degree of perceived exertion for the arm holding the container, RPE(A), for the whole body, RPE(WB), and for the back, RPE(BK).
4. Tasking Time: Tasking time was recorded every ten minutes and the average was used as the tasking time for a certain task.

Controlled Variables

1. Container: For one-handed tasks, a rectangular tool box measuring 49 cm X 16 cm X 20 cm with a pipe handle running through the length of the box at a height of 30 cm from the bottom of the box was used. For two-handed tasks, a container (46 cm X 30 cm X 30 cm) with two handles at both side was used.
2. Carrying distance: 4.3 m (14 ft) was selected according to the previous studies (Snook, 1978; Snook and Ciriello, 1991; Ayoub *et al.*, 1982; Jiang *et al.*, 1986). This represents a medium carrying distance in industry.
3. Task duration: One hour.
4. Laboratory environment: Temperature was maintained at 70 to 75 degrees F with a 45 to 60 percent relative humidity.

The experimental design resulted in 120 data points (1 distance X 2 hand conditions X 3 frequencies X 10 subjects X 2 replicates).

The model for the experiment was as follows:

$$Y_{ijkl} = \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + \delta_l + (\alpha\delta)_{il} + (\beta\delta)_{jl} + (\gamma\delta)_{kl} \\ + (\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)_{ijl} + (\alpha\gamma\delta)_{ikl} + (\beta\gamma\delta)_{jkl} + \epsilon_{ijkl} \\ (i = 1 \text{ to } 3 ; j = 1 \text{ to } 2 ; k = 1 \text{ to } 10 ; l = 1 \text{ to } 2)$$

where α_i , β_j , γ_k and δ_l represent the treatment effect and correspond to frequency rate (FREQ), hand condition (HAND), subject (SUBJ), and replication (REP), respectively. Subject (SUBJ) and replication (REP) were considered random factors. The $(\alpha\beta)_{ij}$ term represents the fixed interaction effect and corresponds to the FREQ*HAND, while $(\alpha\gamma)_{ik}$, $(\alpha\delta)_{il}$, $(\beta\gamma)_{jk}$, $(\beta\delta)_{jl}$, $(\gamma\delta)_{kl}$, $(\alpha\beta\gamma)_{ijk}$, $(\alpha\beta\delta)_{ijl}$, $(\alpha\gamma\delta)_{ikl}$, and $(\beta\gamma\delta)_{jkl}$ represent the independent random variables and correspond to the FREQ*SUBJ, FREQ*REP, HAND*SUBJ, HAND*REP, SUBJ*REP, FREQ*HAND*SUBJ, FREQ*HAND*REP, FREQ*SUBJ*REP, and HAND*SUBJ*REP interactions, respectively. ϵ_{ijkl} is the random error term which is assumed to $N(0, \sigma^2)$.

To analyze the frequency rate and hand condition effect on the response variables, the full model was first applied to remove any insignificant random interaction effects to increase the power for the main effect tests. After elimination of all the nonsignificant random interaction terms, the final reduced model was examined.

From the reduced model, if there was nonsignificant interaction effects between the frequency rate and hand condition, the explanation of frequency rate and hand condition tests were meaningful and Tukey's multiple comparison tests were conducted to classify the frequency rate and hand condition level, respectively.

From the reduced model, if there was a significant interaction effect between the frequency rate and hand condition, the interaction plot was drawn and the interaction effect was investigated. To statistically investigate the interaction effect on the response variables, frequency and hand condition made a new variable 'task', and this variable had six different levels. Task 1 represented the frequency of 6/min with one hand, task 2 represented the frequency of 6/min with two hands, task 3 represented the frequency of

1/min with one hand, task 4 represented the frequency of 1/min with two hands, task 5 represented the frequency of 1/5min with one hand, and task 6 represented the frequency of 1/5min with two hands. The subject and replication were considered random variables, and task was used as a fixed variable. The analysis with task variable was conducted and if there was a significant main effect (task) on the response variables, multiple comparison tests were performed to classify the six different tasks.

Procedures

Using the psychophysical methodology, subjects were asked to determine the amount of weight they could lift, carry, and lower comfortably with their preferred (strong) one hand or two hands for an actual one-hour work period. The one-hour period was selected rather than an eight-hour work shift because it more closely approximates an intermittent work schedule that would be encountered when carrying activities occur (Jiang *et al.*, 1986). A copy of instructions that were read to the subjects before each familiarization and data collect session is provided in Appendix F.

Each subject determined the maximum amount of weight they were willing to lift, carry, and lower for one-hour with their preferred hand or two hands at various task variable combinations. The order of tasks was randomly selected. The initial weight in the tool box was selected randomly, either very light or very heavy, with weights concealed in a false bottom of the container (up to 26 lb and 16 lb for two-handed tasks and one-handed tasks, respectively). Then, frequency was identified, and subjects were instructed to walk through the distance of 4.3 m with the identified frequency for several cycles with their box at their normal rate of walking. Subjects were encouraged to make adjustments to this initial weight by adding or removing some weights, in order to arrive at the maximum acceptable weight for that task without getting tired or exhausted. The walking speed was not controlled. Adjustment of the weight was allowed throughout an hour, and heart rate was monitored continuously during the experiment, however, minute heart rate was recorded only during the last few minutes of the session, as previously

described. The final weight at the end of the period was considered as the maximum acceptable weight of the combined task for that particular frequency. The actual tasking time for each task was recorded over the one hour period. After finishing each combination, the RPE value for the whole body, RPE(WB), for the arm handling the container, RPE(A), and for the back, RPE(BK), were recorded. Each experimental condition was completed twice by each subject (one replication) and the order in which the subject performed the condition was randomized for each set of experiment. One of two experiments for each condition started with either heavy or light loads for each subject.

A subject performing the one-handed task and two-handed task are shown in Figure 3.7 and Figure 3.8.

Figure 3.7
Subject Performing One-handed Task

Figure 3.8
Subject Performing Two-handed Task

CHAPTER IV

RESULTS AND DISCUSSION

The results and discussion of the study together with the relevant statistical analysis will be presented in the following order:

1. The effects of training;
2. Analysis-of-variance of the results of one-handed and two-handed task experiment;
3. Development of prediction equations for the capacities of combined tasks.

Effects of Training

Although training was neither a major variable nor an important factor in this study, the results of the training programs used in this study could be compared with the results of Asfour (1980) even though the number of training sessions was different with this study. Both the means of strengths and endurance of the 10 subjects after the training showed some incremental changes.

Effects of Training on Cardiovascular Endurance

The mean maximal oxygen uptake ($\text{VO}_2 \text{ max}$) of the nine subjects before training was 42.48 ml/kg-min. After the six training sessions, the mean maximal oxygen uptake increased to 44.17 ml/kg-min or by approximately 4 percent. The reason for using the mean of nine subjects' $\text{VO}_2 \text{ max}$ instead of 10 was that one of the subjects could not finish the PWC test before the cardiovascular endurance training. However, after six sessions of training, that subject could finish the PWC test successfully. To compare the data before and after the training sessions, that subject's data was not used. The increment of 4 percent compared to the 23 percent increase of Asfour's study (1980) might be small, however, statistically the difference was marginally significant ($p < 0.05$). In Asfour's

study, there were four more training sessions to reach that increment and some of the subjects in this study showed more than 10 percent increments of VO_2 max.

The mean maximal oxygen uptake of 44.17 ml/kg-min after the training compared well with 46.78 ml/kg-min for Fox's (1993) and 46.21 ml/kg-min for Jiang's (1984).

Effects of Training on Muscle Strength

After the training, one arm strength increased by 3.1%, two arm strength by 4.2%, back strength by 5.2%, composite strength by 2.9%, leg strength by 3.2%, and shoulder strength by 2%, and the "overall" strength by 3.4%. The "overall" strength is the sum of the all six strengths mentioned above. The percentage of increase was almost the same as the cardiovascular endurance result. Among the muscle strengths, only back strength was significantly increased after the training ($p < 0.01$). Asfour's study (1980) also showed that after 10 training sessions, the "overall" strength increased by 23.5 % which was almost the same as the increment of cardiovascular endurance improvement of his study.

Combined Task

To investigate the difference of the tasks on the dependent variables, the analysis-of-variance test was performed using SAS (SAS 6.11, SAS Institute, Inc.). The GLM procedure was run using the random variables: subjects and replication, and fixed variables: frequency rates (6/min, 1/min, 1/5min) and hand condition (one hand, two-hands). Dependent variables used were maximum acceptable weight, heart rate, ratings of perceived exertion (RPE) and tasking time.

Maximum Acceptable Weight

The maximum acceptable weight was determined for the combined task by the subject. The average of the two repetitions corresponding to each task condition is shown and compared with Jiang's study (1984) in Table 4.1. The present study showed similar results with Jiang's study.

Table 4.1

Comparison of Maximum Acceptable Weight *
for the Combined Task with Previous Study

Frequency	Present (N=10)		Jiang (1984) *** (N=10)
	one-handed	two-handed	two-handed
6/min	30.58 (5.98) **	36.83 (5.13)	42.73 (7.50)
1/min	59.48 (12.20)	79.13 (17.44)	71.56 (13.49)
1/5min	71.5 (16.48)	93.73 (21.34)	

* Units are lb.

** The value in parentheses are standard deviations.

*** Jiang's one time maximum acceptable weight was 141.73 lb (s.d=44.8).

**** Box width of Jiang's study was 29.2 cm, present study was 30 cm.

The maximum acceptable weight of combined tasks with one hand were 83.0%, 75.2%, and 76.3% of two-handed tasks at frequency rates of 6/min, 1/min, and 1/5min, respectively. This study showed that the capacity of one-handed tasks could be over 75% of the capacity of two-handed tasks at the same frequency rate.

To investigate the frequency and hand condition effect on the maximum acceptable weight, the full model was first applied to remove any insignificant random interaction effects to increase the power for the main effect tests. In the full model, only the third-order interaction terms were examined. The ANOVA summary for the third-order random interaction effects for the full model is shown in Table 4.2. Among the third-order variable interactions, only SUBJ*FREQ*HAND interaction effect was significant with a p-value of 0.0068. So the other nonsignificant third-order interaction terms were removed from the full model and pooled with the error term. The ANOVA test for the reduced model was performed and the results are shown in Table 4.3. According to the ANOVA test results (Table 4.3) for the reduced model, FREQ was a dominant factor for the model, so even though the REP showed a nonsignificant effect on the maximum acceptable weight, the FREQ*REP term showed a marginally significant effect on the maximum acceptable weight. Also, since the SUBJ random term was not an important factor in this study, the analysis of SUBJ related random interaction terms was not of concern in this study.

For the fixed terms, the interaction effect (FREQ*HAND) was investigated because of its significance to the maximum acceptable weight (p-value=0.0002). The interaction plot was drawn and is shown in Figure 4.1. From Figure 4.1, maximum acceptable weight clearly decreased as the frequency rate increased for one-handed tasks and two-handed tasks. The difference of maximum acceptable weight between one-handed tasks and two-handed tasks decreased with increasing frequency rate. In the case of the frequent task (6/min), the difference of the maximum acceptable weight between one-handed tasks and two-handed tasks was smaller than for infrequent tasks. With this

Table 4.2.

ANOVA Summary for Third-Order Interaction Effects
for Maximum Acceptable Weight, Full model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ*HAND	MSE	18	3.3614	0.0068
SUBJ*FREQ*REP	MSE	18	0.5834	0.8688
SUBJ*HAND*REP	MSE	18	0.6994	0.7018
FREQ*HAND*REP	MSE	18	0.1722	0.8432

Table 4.3

ANOVA Summary for Maximum Acceptable Weight
Reduced model

SOURCE	ERROR	DF	F VALUE	P-VALUE
FREQ	MS (SUBJ*FREQ) + MS (FREQ*REP) - MSE	2	60.5337	0.0001
HAND	MS (SUBJ*FREQ*HAND)	1	126.6960	0.0001
FREQ*HAND	MS (SUBJ*FREQ*HAND)	2	11.7812	0.0002
SUBJ	MS (SUBJ*FREQ)	9	3.8151	0.0075
SUBJ*FREQ	MS (SUBJ*FREQ*HAND)	18	6.4422	0.0001
REP	MS (FREQ*REP)	1	0.5576	0.5331
FREQ*REP	MSE	2	3.5850	0.0342
SUBJ*FREQ*HAND	MSE	27	6.0027	0.0001

Figure 4.1

Interaction plot of FREQ*HAND
for Maximum Acceptable Weight

interaction effect, there would be no meaningful interpretation for the main effects. To statistically investigate the interaction effect on the maximum acceptable weight, the analysis with task variable, mentioned earlier, was performed. The subject and replication were considered random variables, and task was used as a fixed variable. The ANOVA summary for random interaction effects for the full model is shown in Table 4.4. From the full model, random interaction terms, SUBJ*REP (p-value=0.43390) and TASK*REP (P-VALUE=0.2169), were removed because of the nonsignificance and the ANOVA table for the reduced model is shown in Table 4.5. From Table 4.5, the main effect (task) was found to be highly significant for maximum acceptable weight with a p-value of 0.0001. So, multiple comparison tests were performed to classify the six different tasks. Table 4.6 presents Tukey's test for maximum acceptable weight by task.

From Table 4.6, the mean of maximum acceptable weight for each frequency was significantly different from each other with one-handed and two-handed tasks, respectively. Given the same frequency rate, two-handed task capacity was significantly greater than one-handed task capacity except at the high frequency rate (6/min). These results agreed with the interaction plot of Figure 4.1. For the low frequencies of 1/5min or 1/min, the subject's strength is the important factor because of the complete physiological recovery obtained from the long resting period. However, because of the nature of the combined task (pick up the load, carry the load, lower the load), during the high frequency task (6/min), subjects had almost no time to rest between the tasks, and the repetitive bending of the back in a short period (every 10 seconds) made it difficult for the subject to take advantage of using two hands to handle more weight compared to one hand. Also, because of the short resting time, there was very little time for physiological recovery from muscle fatigue. Jiang (1984) also found similar results and mentioned the physiological restrictions for the high frequency task. The results indicated that as the frequency becomes faster, the physiological capacity is more important for deciding the maximum acceptable weight.

Table 4.4

ANOVA Summary for Interaction Effects
for Maximum Acceptable Weight
with Task variable, Full model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*TASK	MSE	45	18.3108	0.0001
SUBJ*REP	MSE	9	1.0268	0.4339
TASK*REP	MSE	5	1.4748	0.2169

Table 4.5

ANOVA Summary for Maximum Acceptable Weight
with Task variable, Reduced model

SOURCE	ERROR	DF	F VALUE	P-VALUE
TASK	MS (SUBJ*TASK)	5	61.8428	0.0001
SUBJ	MS (SUBJ*TASK)	9	7.7365	0.0001
SUBJ*TASK	MSE	45	17.5335	0.0001
REP	MSE	1	1.8380	0.1804

Table 4.6

Tukey's Studentized Range (HSD) Test
for Maximum Acceptable Weight by Task

Tukey Grouping *	Mean **	Task
A	93.73	1/5min with two-handed
B	79.08	1/min with two-handed
B	71.50	1/5min with one-handed
C	59.48	1/min with one-handed
D	36.83	6/min with two-handed
D	30.58	6/min with one-handed

* Means with same letter are not significantly different

** Units are lb.

Heart Rate

Heart rate was recorded for four minutes at the end of one hour for the frequency rate of 1/min and 6/min, and the 55th and 60th minute for 1/5 min during the experiment. The average was taken as heart rate of that task. The mean heart rate is shown and compared with Jiang's data (1984) in Table 4.7. The heart rate of this study was a little higher compared to Jiang's study. In Jiang's study, each subject was given approximately 20 min to determine the maximum load he was willing to handle for 1 hour and then he handled that load for 10 min to record the heart rate. However, in this study, each subject did an actual 1 hour task to determine the maximum load and at the end of 1 hour, heart rate was recorded. That difference of actual tasking time might lead to a little higher heart rate than Jiang's study.

For the analysis-of-variance of heart rate, the full model was applied to find random interaction effects and the third-order interaction terms are shown in Table 4.8. All the third-order interactions could be removed from the full model because of the nonsignificance to the heart rate. The ANOVA table for the first reduced model with random interaction terms is shown in Table 4.9. From this ANOVA test result (Table 4.9), the nonsignificant interaction terms, HAND*REP (p -value=0.5364) and SUBJ*REP (p -value=0.5373), were removed. The ANOVA table for the second reduced model is shown in Table 4.10. For the fixed term, the interaction of FREQ*HAND needed to be investigated because the p -value was significant (p -value=0.0001) to the heart rate. The interaction plot of FREQ*HAND for heart rate was drawn and is shown in Figure 4.2. The difference of heart rate between a one-handed task and a two-handed task increased during the high frequency rate (6/min). However, the difference was almost the same between the frequencies of 1/5min and 1/min (9.2 bpm for 1/5min and 10.3 bpm for 1/min).

To investigate the interaction effect on the heart rate, an analysis-of-variance test with task variable was performed and the ANOVA summary for random interaction effects for the full model is shown in Table 4.11. From the full model, the nonsignificant

Table 4.7

Comparison of Heart Rate Data with Data from Jiang (1984)

Frequency	Present		Jiang (1984)
	One-handed	Two-handed	Two-handed
6/min	120.0 * (11.0) **	147.2 (16.0)	133.7 (13.5)
1/min	100.1 (6.6)	110.4 (9.1)	101.7 (11.1)
1/5min	105.6 (6.4)	116.8 (8.7)	

* Unit of heart rate is bpm (beat per min.).

** The value in parentheses are standard deviations.

Table 4.8

ANOVA Summary for Third-Order Interaction Effects
for Heart Rate, Full model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ*HAND	MSE	18	1.2644	0.3120
SUBJ*FREQ*REP	MSE	18	0.6069	0.8507
SUBJ*HAND*REP	MSE	18	0.9171	0.5324
FREQ*HAND*REP	MSE	18	0.2814	0.7580

Table 4.9.

ANOVA Summary for Heart Rate, Reduced model I

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ	MSE	18	4.5036	0.0001
SUBJ*HAND	MSE	9	4.8913	0.0001
SUBJ*REP	MSE	9	0.8921	0.5373
FREQ*REP	MSE	2	1.7804	0.1767
HAND*REP	MSE	1	0.3864	0.5364

Table 4.10

ANOVA Summary for Heart Rate, Reduced model II

SOURCE	ERROR	DF	F VALUE	P-VALUE
FREQ	MS (SUBJ*FREQ) + MS (FREQ*REP) - MSE	2	48.9578	0.0001
HAND	MS (SUBJ*HAND)	1	46.8395	0.0001
FREQ*HAND	MSE	2	26.7648	0.0001
SUBJ	MS (SUBJ*FREQ) + MS (SUBJ*HAND) - MSE	9	2.2913	0.0623
SUBJ*FREQ	MSE	18	4.6008	0.0001
SUBJ*HAND	MSE	9	4.9970	0.0001
REP	MS (FREQ*REP)	1	0.0917	0.7906
FREQ*REP	MSE	2	1.8188	0.1693

random interaction terms, SUBJ*REP (p-value=0.4502) and TASK*REP (p-value=0.4141), were removed and the ANOVA table for the reduced model is shown in Table 4.12. A Multiple comparison test for the heart rate was performed and Table 4.13 presents Tukey's test for heart rate by task. The mean of heart rate for each frequency was significantly different between the frequent task (6/min) and other tasks (5/min and 1/min) on the same hand condition. However, there was no significant difference between the frequency rate of 1/5min and the frequency rate of 1/min on the same hand condition. The interaction plot Figure 4.2 showed the same results.

Figure 4.2

Interaction plot of FREQ*HAND for
Heart Rate

Table 4.11

ANOVA Summary for Interaction Effects
for Heart Rate with Task variable, Full model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*TASK	MSE	45	3.7439	0.0001
SUBJ*REP	MSE	9	1.0050	0.4502
TASK*REP	MSE	5	1.0256	0.4141

Table 4.12

ANOVA Summary for Heart Rate
with Task variable, Reduced model

SOURCE	ERROR	DF	F VALUE	P-VALUE
TASK	MS (SUBJ*TASK)	5	48.2054	0.0001
SUBJ	MS (SUBJ*TASK)	9	5.8029	0.0001
SUBJ*TASK	MSE	45	3.73295	0.0001
REP	MSE	1	0.1834	0.6700

Table 4.13

Tukey's Studentized Range (HSD) Test for Heart Rate by Task

Tukey Grouping *		Mean **	Task
	A	147.2	6/min with two-handed
	B	120.0	6/min with one-handed
	B	116.8	1/5min with two-handed
C	B	110.4	1/min with two-handed
C	D	105.6	1/5min with one-handed
	D	100.1	1/min with one-handed

* Means with same letter are not significantly different.

** Units are bpm.

Interestingly, even though there was no significant heart rate difference between the frequency rate of 1/5min and the frequency rate of 1/min, the heart rate of the frequency rate of 1/5min, which was the lower frequency rate between the two, was a little higher than that of the frequency rate of 1/min. During these two frequencies tasks, the subject had enough time for physiological recovery during the resting period between the tasks, so physiological limitation was not a dominant factor. Psychologically, since the frequency rate of 1/5min is the lower frequency than the frequency rate of 1/min, subjects seemed to feel that they could handle more weight for 1/5min frequency rate than 1/min frequency rate, so heart rate for the frequency rate of 1/5min was higher than that of 1/min. For the same frequency rate, the heart rate for the two-handed task was significantly higher than that for the one-handed task.

Ratings of Perceived Exertion

The level of physical exertion perceived by the subjects in determining the maximum weight for the comfortable combined task was determined by the Ratings of Perceived Exertion Scale (Borg, 1962). This scale ranges from 6 to 20, 7 being very, very light and 19 being very, very hard. The average perceived exertion ratings by frequency and hand condition for the whole body (RPE[WB]), arm (RPE[A]), and back (RPE[BK]) are shown in Table 4.14. For one-handed tasks, the level of perceived exertion for the arm handling the load was the highest and back and whole body followed in order on each of the three frequency rates. On the other hand, for the two-handed task, subjects felt the lowest level of exertion on the arm among the three body parts for each of the three frequency rates. During the one-handed tasks, subject handled the load with just one hand, so the weight of the load could not be broken up with the other hand. However, during the two-handed tasks, the weight of the load could be balanced with two hands and this could explain why subjects perceived strong exertion on the arm handling the load during the one-handed tasks. Also, since the one-handed task was a kind of asymmetric work, subjects expressed the feelings of more exertion on the lower back, especially the preferred hand side of the external oblique muscle areas, rather than on the whole body.

Table 4.15 shows the average perceived exertion ratings and heart rate by hand condition for RPE(WB), RPE(A), and RPE(BK). There was some correlation between heart rate and RPE(WB), RPE(A) and RPE(BK), respectively. From Table 4.15, during the one-handed tasks, each RPE(WB), RPE(A) and RPE(BK) value was about one-eighth of the heart rate. Mital and Manivasagan's (1983) findings for one-handed carrying tasks and Garg and Saxena's (1981) study for one-handed lifting tasks showed similar results.

Perceived Exertion Ratings of the Whole Body, RPE (WB)

For the analysis of RPE (WB), the full model was applied to find random interaction effects and Table 4.16 shows the third-order interaction terms for the full model. All the third-order variable interactions, SUBJ*FREQ*HAND (p-value=0.2733),

Table 4.14

Mean Values of Ratings of Perceived Exertion
by each Task

Fre- quency	One-handed			Two-handed		
	Whole body	Arm	Back	Whole body	Arm	Back
6/min	14 (0.8) *	15.3 (1.36)	15.2 (1.6)	15.4 (1.2)	14.2 (2.0)	16.4 (1.1)
1/min	12.3 (0.8)	13 (1.2)	12.3 (1.2)	12.8 (0.7)	12.3 (1.1)	13.1 (1.0)
1/5min	11.8 (1.1)	12.8 (1.1)	12.3 (1.0)	12.4 (0.7)	12.3 (0.9)	12.6 (1.1)

* The value in parentheses are standard deviations.

Table 4.15

Mean Values of Ratings of Perceived Exertion
by Hand Condition and HR

Hand Condition	RPE(WB)	RPE(A)	RPE(BK)	HR *
one-handed	12.67 (1.39) **	13.68 (1.88)	13.23 (2.04)	108.6 (12.15)
two-handed	13.48 (1.74)	13.00 (1.77)	14.02 (2.19)	124.8 (20.16)
total mean	13.07 (1.62)	13.34 (1.85)	13.62 (2.14)	116.7 (18.47)

* Unit of heart rate is bpm (beat per min.).

** The value in parentheses are standard deviations.

SUBJ*FREQ*REP (p-value=0.4155), SUBJ*HAND*REP (p-value=0.7718), and FREQ*HAND*REP (p-value=0.7962), could be removed because of their nonsignificance. The ANOVA summary with random interaction terms for the first reduced model is shown in Table 4.17. Some of the second-order interaction terms, SUBJ*HAND (P-value=0.3693), FREQ*REP (p-value=0.2543), and HAND*REP (p-value=0.7593), were removed from the model and the result of the second reduced model is shown in Table 4.18.

For the fixed terms, the interaction effect (FREQ*HAND) was marginally significant (p-value=0.0466), so the interaction plot for RPE(WB) was drawn and shown in Figure 4.3. The exertion level of two-handed tasks was higher than that of one-handed tasks at the same frequency rate. With same hand condition, the frequency rate of 6/min had the highest exertion level, followed by the frequencies of 1/min and 1/5min. The difference of the exertion level between one-handed tasks and two-handed tasks increased at the high frequency rate (6/min).

To statistically investigate the fixed interaction effect, FREQ*HAND, on the RPE(WB), the ANOVA summary for random interaction terms for the full model with the task variable is shown in Table 4.19. From Table 4.19, the TASK*REP (p-value=0.6106) was removed because of the nonsignificance and the reduced model is shown in Table 4.20. Tukey's multiple comparison test for RPE(WB) by the task is presented in Table 4.21. The RPE(WB) level was significantly different between one-handed tasks and two-handed tasks during the high frequency task (6/min). However, there was no significant difference between one-handed tasks and two-handed tasks during the frequency rates of 1/min and 1/5min. With the same hand condition, the perceived exertion during the task at a frequency rate of 6/min was significantly higher than the other two tasks at frequency rates of 1/min and 1/5min. No significant difference was found between the frequency rate of 1/min and 1/5min for one-handed tasks and two-handed tasks.

Table 4.16

Ratings of Perceived Exertion for ANOVA Summary
for Third-Order Interaction Effects for RPE(WB), Full model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ*HAND	MSE	18	1.3346	0.2733
SUBJ*FREQ*REP	MSE	18	1.1074	0.4155
SUBJ*HAND*REP	MSE	18	0.6177	0.7718
FREQ*HAND*REP	MSE	18	0.2308	0.7962

Table 4.17

ANOVA Summary for Random Interaction Effects
for RPE(WB), Reduced model I

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ	MSE	18	1.8847	0.0332
SUBJ*HAND	MSE	9	1.1089	0.3693
SUBJ*REP	MSE	9	2.0343	0.0492
FREQ*REP	MSE	2	1.3986	0.2543
HAND*REP	MSE	1	0.0946	0.7539

Table 4.18

ANOVA Summary for RPE(WB), Reduced Model II

SOURCE	ERROR	DF	F VALUE	P-VALUE
FREQ	MS (SUBJ*FREQ)	2	51.0372	0.0001
HAND	MSE	1	24.9665	0.0001
FREQ*HAND	MSE	2	3.1923	0.0466
SUBJ	MS (SUBJ*FREQ) + MS (SUBJ*REP) - MSE	9	1.5065	0.2455
SUBJ*FREQ	MSE	18	1.8636	0.0321
SUBJ*REP	MSE	9	2.0115	0.0491
REP	MS (SUBJ*REP)	1	0.2533	0.6268

Figure 4.3

Interaction plot of FREQ*HAND for RPE(WB)

Table 4.19

ANOVA Summary for Interaction Effects
for RPE(WB) with Task Variable, Full model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*TASK	MSE	45	1.6092	0.0571
SUBJ*REP	MSE	9	2.2021	0.0396
TASK*REP	MSE	5	0.7217	0.6106

Table 4.20

ANOVA Summary for RPE(WB) with Task Variable, Reduced Model

SOURCE	ERROR	DF	F VALUE	P-VALUE
TASK	MS (SUBJ*TASK)	5	30.1495	0.0001
SUBJ	MS (SUBJ*TASK) + MS (SUBJ*REP) - MSE	9	1.6702	0.1933
SUBJ*TASK	MSE	45	1.6552	0.0419
REP	MS (SUBJ*REP)	1	0.2533	0.6268
SUBJ*REP	MSE	9	2.2652	0.0325

Table 4.21

Tukey's Studentized Range (HSD) Test for RPE(WB) by Task

Tukey Grouping *	Mean	Task
A	15.4	6/min with two-handed
B	14.0	6/min with one-handed
C	12.8	1/min with two-handed
C	12.4	1/5min with two-handed
C	12.3	1/min with one-handed
C	11.8	1/5min with one-handed

* Means with same letter are not significantly different.

The means of RPE level for the whole body with a frequency rate of 6/min were 15.4 and 14.0 on two-handed tasks and one-handed tasks, respectively. On the scale 13 is 'somewhat hard' and 15 is 'hard'. Thus, in terms of the exertion to the whole body, tasks performed two-handed were perceived as hard and tasks with one-handed were perceived less than hard but more than somewhat hard. The means of RPE(WB) for the other four tasks (two-handed at 1/min, two-handed at 1/5min, one-handed at 1/min and one-handed at 1/5min) ranged between 11.8 to 12.8. These tasks were perceived as between fairly light to somewhat hard.

Perceived Exertion Ratings of the Back, RPE (BK)

To study the perceived exertion of the back, the full model was also applied to find the random interaction effects and the third-order interaction terms are shown in Table 4.22. The third-order level interaction variables, SUBJ*FREQ*HAND (p-value=0.6737), SUBJ*FREQ*REP (p-value=0.7434), SUBJ*HAND*REP (p-value=0.5774), and

Table 4.22

ANOVA Summary for Third-Order Interaction Effects
for RPE(BK), Full model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ*HAND	MSE	18	0.8062	0.6737
SUBJ*FREQ*REP	MSE	18	0.7311	0.7434
SUBJ*HAND*REP	MSE	18	0.8569	0.5774
FREQ*HAND*REP	MSE	18	0.2237	0.8017

FREQ*HAND*REP (p-value=0.8017), could be removed from the model because of their nonsignificance. The ANOVA table with random interaction terms for the first reduced model is shown in Table 4.23. All the second-order random interaction terms, SUBJ*FREQ (p-value=0.3421), SUBJ*HAND (p-value=0.5878), SUBJ*REP (p-value=0.4054), FREQ*REP (p-value=0.3399), and HAND*REP (p-value=0.4170), were nonsignificant and could be removed from the model. The result of the second reduced model is shown in Table 4.24. For the fixed terms, the interaction of FREQ*HAND was not found to be significant with p-value of 0.2334. Since there was no significant interaction effect, the explanation of main effect tests was meaningful and Tukey's multiple comparison tests were available to classify the main treatment levels. Table 4.25 and Table 4.26 show Tukey's test results for RPE (BK) by frequency and hand condition. Table 4.25 showed that the level of the perceived exertion was significantly higher at the frequency rate of 6/min than at the frequency rates of 1/min and 1/5 min. However, between the frequency rates of 1/min and 1/5min, there was no significant difference of the level of the perceived exertion. For the high frequency tasks (6/min), subjects felt the

Table 4.23

ANOVA Summary for Random Interaction Effects
for RPE(BK), Reduced Model I

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ	MSE	18	1.1340	0.3421
SUBJ*HAND	MSE	9	0.8338	0.5878
SUBJ*REP	MSE	9	1.5092	0.4045
FREQ*REP	MSE	2	1.0972	0.3399
HAND*REP	MSE	1	0.6671	0.4170

Table 4.24

ANOVA Summary for RPE(BK), Reduced Model II

SOURCE	ERROR	DF	F VALUE	P-VALUE
FREQ	MSE	2	91.1987	0.0001
HAND	MSE	1	12.0281	0.0008
FREQ*HAND	MSE	2	1.4756	0.2334
SUBJ	MSE	9	5.5638	0.0001
REP	MSE	1	3.7369	0.0657

Table 4.25

Tukey's Studentized Range (HSD) Test for RPE(BK) by Frequency

Tukey Grouping	Mean *	Frequency
A	15.8	6/min
B	12.7	1/min
B	12.4	1/5min

* Means with same letter are not significantly different.

Table 4.26

Tukey's Studentized Range (HSD) Test for RPE(BK) by Hand Condition

Tukey Grouping	Mean *	Hand Condition
A	14.0	two-handed
B	13.2	one-handed

* Means with same letter are not significantly different.

exertion on the back more than “hard,” and for the low frequency tasks (1/min and 1/5min), the perception of the exertion on the back was around “somewhat hard.” For the hand condition, two-handed tasks were perceived as requiring greater exertion than one-handed tasks.

Perceived Exertion Ratings of the Arm, RPE(A)

To analyze the perceived exertion of the arm handling the load, the full model was investigated to find random interaction effects and the third-order interaction terms are shown in Table 4.27. The third-order level interaction variables, SUBJ*FREQ*HAND (p-value=0.3021), SUBJ*FREQ*REP (p-value=0.5775), SUBJ*HAND*REP (p-value=0.8170), and FREQ*HAND*REP (p-value=0.5748), were nonsignificant enough to be eliminated from the model. The ANOVA summary with random interaction terms for the first reduced model is shown in Table 4.28. The second-order random interaction terms, SUBJ*FREQ (p-value=0.3027), SUBJ*HAND (p-value=0.7328), SUBJ*REP (p-value=0.5801), FREQ*REP (p-value=0.3251), and HAND*REP (p-value=0.3825), were nonsignificant and removed from the model. The result of the second reduced model is shown in Table 4.29. For the fixed terms, the interaction of FREQ*HAND was not significant to the RPE(A) with p-value of 0.4236. Since there was no significant interaction effect, the explanation of the main effect tests was meaningful and Tukey’s multiple comparison tests were performed to classify the main treatment levels. Table 4.30 and Table 4.31 show the results of Tukey’s test for RPE (A) by frequency and hand condition. Table 4.30 shows that the level of perceived exertion was significantly higher at the frequency rate of 6/min than at the frequency rates of 1/min and 1/5 min. However, between the frequency rate of 1/min and 1/5min, there was no significant difference of the level of the perceived exertion. For the high frequency tasks (6/min), subjects perceived “hard” exertion on the arm, and for the low frequency tasks (1/min and 1/5min), the perceived exertion on the arm was “somewhat hard.” For the hand condition, as discussed

Table 4.27

ANOVA Summary for Third-Order Interaction Effects
for RPE(A), Full Model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ*HAND	MSE	18	1.2816	0.3021
SUBJ*FREQ*REP	MSE	18	0.9108	0.5775
SUBJ*HAND*REP	MSE	18	0.5531	0.8170
FREQ*HAND*REP	MSE	18	0.5712	0.5748

Table 4.28

ANOVA Summary for Random Interaction Effects
for RPE(A), Reduced Model I

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ	MSE	18	1.1903	0.3027
SUBJ*HAND	MSE	9	0.6700	0.7328
SUBJ*REP	MSE	9	0.8729	0.5801
FREQ*REP	MSE	2	1.0653	0.3251
HAND*REP	MSE	1	0.9702	0.3825

Table 4.29

ANOVA Summary for RPE(A), Reduced Model II

SOURCE	ERROR	DF	F VALUE	P-VALUE
FREQ	MSE	2	38.2641	0.0001
HAND	MSE	1	8.9324	0.0035
FREQ*HAND	MSE	2	0.8661	0.4236
SUBJ	MSE	9	7.2792	0.0001
REP	MSE	1	2.8110	0.0966

Table 4.30

Tukey's Studentized Range (HSD) Test for RPE(A) by Frequency

Tukey Grouping	Mean *	Frequency
A	14.8	6/min
B	12.8	1/min
B	12.5	1/5min

* Means with same letter are not significantly different.

Table 4.31

Tukey's Studentized Range (HSD) Test for RPE(A) by Hand Condition

Tukey Grouping	Mean *	Hand Condition
A	13.7	one-handed
B	13.0	two-handed

* Means with same letter are not significantly different

earlier, one-handed tasks were perceived as requiring more exertion on the arm handling the load than two-handed tasks.

Tasking Time

The tasking time was measured during the experiment. The starting point was the time the subject was ready to lift the box after the beep sound and the finishing point was the time the box touched on the floor. Tasking time was recorded every ten minutes and the average was used as the tasking time for a certain task. Since walking speed was not controlled in this study, measuring the tasking time might help to analyze the subject's tasking patterns between the frequency rates and the hand conditions. The summary of the tasking time is presented in Table 4.32.

For more analysis of tasking time, the full model was examined and the result with the third-order interaction terms is shown in Table 4.33. Some of the third-order variable interactions, SUBJ*FREQ*REP (p-value=0.5935) and FREQ*HAND*REP (p-value=0.3229), were removed because of their nonsignificance and the results for the first reduced model is shown in Table 4.34. Some of the insignificant second-order interaction terms, SUBJ*REP (p-value=0.7898), FREQ*REP (p-value=0.3066), HAND*REP (p-value=0.7367) were also removed from the model. The second reduced model is shown in Table 4.35.

Table 4.32

The Summary of Tasking Time

Frequency	Tasking Time *	
	One-handed	Two-handed
6/min	5.02 (0.43) **	5.55 (0.45)
1/min	5.25 (0.46)	6.26 (0.68)
1/5min	6.00 (0.70)	7.15 (1.52)

* Units are sec.

** The value in parentheses are standard deviations.

Table 4.33

ANOVA Summary for Third-Order Interaction Effects
on Tasking Time, Full Model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ*HAND	MSE	18	2.6839	0.0214
SUBJ*FREQ*REP	MSE	18	0.8930	0.5935
SUBJ*HAND*REP	MSE	18	2.1756	0.0767
FREQ*HAND*REP	MSE	18	1.3899	0.3229

Table 4.34

ANOVA Summary for Random Interaction Effects
for Tasking Time, Reduced Model I

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*FREQ	MS (SUBJ*FREQ*HAND)	18	2.5688	0.0262
SUBJ*HAND	MS (SUBJ*HAND*REP) + MS (SUBJ*FREQ*HAND) - MSE	9	1.7370	0.1616
SUBJ*REP	MS (SUBJ*HAND*REP)	9	0.5737	0.7898
FREQ*REP	MSE	2	1.6441	0.3066
HAND*REP	MS (SUBJ*HAND*REP)	1	0.1202	0.7367
SUBJ*HAND*REP	MSE	9	2.2140	0.0427
SUBJ*FREQ*HAND	MSE	18	2.7312	0.0045

Table 4.35

ANOVA Summary for Tasking Time, Reduced Model II

SOURCE	ERROR	DF	F VALUE	P-VALUE
FREQ	MS (SUBJ*FREQ)	2	18.0981	0.0001
HAND	MS (SUBJ*HAND)	1	26.3871	0.0006
FREQ*HAND	MS (FREQ*SUBJ*HAND)	2	3.5538	0.0521
SUBJ	MS (SUBJ*FREQ) + MS (SUBJ*HAND) - MSE	9	2.7828	0.0392
SUBJ*FREQ	MS (SUBJ*FREQ*HAND)	18	2.5688	0.0262
SUBJ*HAND	MS (SUBJ*HAND*REP) + MS (SUBJ*FREQ*HAND) - MSE	9	2.0375	0.0909
REP	MS (SUBJ*HAND*REP)	1	3.7112	0.0623
SUBJ*HAND*REP	MSE	19	1.6125	0.1006
SUBJ*FREQ*HAND	MSE	18	2.6460	0.0052

Table 4.36

ANOVA Summary for Interaction Effects
for Tasking Time with Task variable, Full Model

SOURCE	ERROR	DF	F VALUE	P-VALUE
SUBJ*TASK	MSE	45	4.3429	0.0001
SUBJ*REP	MSE	9	1.0469	0.4193
TASK*REP	MSE	5	1.1338	0.3565

For the fixed terms, HAND*FREQ was marginally significant (p -value=0.0521), so the interaction plot for tasking time was drawn and shown in Figure 4.4. The tasking time decreased as the frequency rate increased. Two-handed tasking time was longer than one-handed tasking time at the same frequency rate.

To statistically investigate the interaction effect on the tasking time, an analysis-of variance test with task variable was performed and the ANOVA summary for the random interaction effects for the full model is shown in Table 4.36. From the full model, random interaction terms, SUBJ*REP (p -value=0.4193) and TASK*REP (p -value=0.3565), were removed because of their nonsignificance and the ANOVA table for the reduced model is shown in Table 4.37. A multiple comparison test was performed to classify the six different task levels and Table 4.38 shows Turkey's test results for the tasking time by task.

For the two-handed task, tasking time for the frequency rate of 1/5min was significantly different from the tasking time for the other two frequency rates (1/min and 6/min). However, between the frequency rate of 1/min and 6/min, tasking time was not significantly different. For the one-handed task, tasking time for the frequency rates of 1/5min and 1/min showed no significant difference, and tasking time for frequency rates of 1/min and 6/min also showed no significant difference, however, between the frequency

Figure 4.4

Interaction plot of FREQ*HAND for Tasking Time

Table 4.37

ANOVA Summary for Tasking Time
with Task variable, Reduced Model

SOURCE	ERROR	DF	F VALUE	P- VALUE
TASK	MS (SUBJ*TASK)	5	17.1351	0.0001
SUBJ	MS (SUBJ*TASK)	9	5.8817	0.0001
SUBJ*TASK	MSE	45	4.2640	0.0001
REP	MS (SUBJ*REP)	1	3.4152	0.0742

Table 4.38

Tukey's Studentized Range (HSD) Test
for Tasking Time by Task

Tukey Grouping			Mean*	Task
A			7.15	1/5min with two-handed
B			6.26	1/min with two-handed
C	B		6.00	1/5min with one-handed
C	B	D	5.55	6/min with two-handed
C	D		5.25	1/min with one-handed
		D	5.02	6/min with one-handed

* Means with same letter are not significantly different.

rates of 1/5min and 6/min, tasking time was significantly different. For the same frequency rate, tasking time at the frequency rates of 1/5min and 1/min for two-handed tasks was significantly different from one-handed tasks. However, for the tasking time at the frequency rate of 6/min, the difference between two-handed tasks and one-handed tasks was not significantly different.

During the high frequency rate task (6/min), subjects had very little time between the tasks (10 sec/task) and their physiological capability was a dominant factor to maintain the pace of the work, so the subjects tried to shorten the tasking time to have a little more resting time between the tasks by carrying the load as quickly as possible with a small load relative to the load handled during the other frequency rates. On the other hand, during the low frequency rate task, subjects did not have to hurry because of the enough time to rest between the tasks and also their selected load, which was relatively heavier than the high frequency rate load, made them take a longer time to complete the task.

The Development of the Model

One of the purposes of this study was to develop prediction models for the capacity of combined tasks and to examine the relationship between two-handed tasks and one-handed tasks. Statistical models were developed to predict the performance on combined tasks with one-handed and two-handed task performances by using strength variables, frequency rate and hand condition. Also, a prediction model for the capacity of the one-handed combined tasks was developed by using the capacity of two-handed combined tasks. The SAS package (SAS 6.11), especially the PROC STEPWISE and the PROC REG, were used to develop regression models and residual plots.

For developing the models, determination of final models was made based on the following criteria.

1. Simplicity: Determine the most appropriate model based on the principles of simplicity. The simple model was preferred if it could describe the data well and if it could predict well. And also, a simple model could be easy to apply.

2. R^2 : The comparison of R^2 for the different models was made. The R^2 is a descriptive measure of the strength of the regression relationship, a measure of how well the regression line fits the data. However, the R^2 value could be increased with the inclusion of additional variables in the model. Too many variables in the model may cause the model to lose its prediction ability.
3. Meaningful coefficient: The sign of the coefficient of a predictor variable should be in agreement with the direction of the partial effect of that predictor variable. For example, if a predictor variable has a positive correlation with the response variable, it should cause a positive sign for that predictor.
4. PRESS statistic: The main purpose of regression analysis in this study is to predict Y for a future set of X's. However, due to the small sample size, there is a problem that we have only present Y's and X's to use for developing models. So, the PRESS statistic could be applied to evaluate the model by how well it estimates Y's with new X's. In the PRESS statistic, each observation is 'predicted' using the other n-1 observations. 'PRESS' stands for Prediction Error Sum of Squares and is defined as followed (Allen, 1974) :

$$PRESS = \sum_{i=1}^n (Y_i - Y_{h_i})^2$$

where Y_i = observed value for the i-th observation,

Y_{h_i} = the estimator of $E(Y_i)$ excluding the i-th observation.

The PRESS value indicates the amount of prediction sum of squares error.

Comparison of the residual sum of squares and PRESS statistic could provide information of predictability in the present sample and the simulated sample having the same sample size.

5. Testing or validation of models: Models were validated by residual plots, by the PRESS statistic, and by testing the models on other study's data.

Modeling for One-handed Combined Task Capacities using Two-handed Combined Task Capacities as a Predictor

As mentioned earlier in this chapter, the capacity of a one-handed combined tasks was generally over 75% of the capacity of a corresponding two-handed combined tasks at the same frequency rate. Therefore, the simplest model (which would also be conservative) would be to simply say that one-handed task capacity (lift, 4.3m carry, and lower) could be estimated as 75% of the corresponding two-handed task capacity. Table 4.39 shows the correlation between the capacities of one-handed tasks and two-handed tasks. From Table 4.39, there was some correlation between one-handed and two-handed task capacities at the same frequency rate, so, there might be a positive, linear relationship between the capacities of one-handed and two-handed tasks. The prediction models for the capacity of one-handed combined tasks were developed by using the capacity of the two-handed combined task as a predictor for each frequency.

Table 4.40 shows the developed model for each frequency using the capacity of the two-handed combined task as a predictor and corresponding R^2 values, PRESS statistic and Residual SS. Each model showed a high R^2 value (0.9361 for 6/min, 0.7019 for 1/min, and 0.8330 for 1/5min) and had just one predictor (the capacity of two-handed task) for simplicity. However, each model in Table 4.40 had a limit that it was restricted to use only for a certain frequency rate.

To overcome the fixed frequency limit of the models in Table 4.40, another model was developed for one-handed combined tasks capacity using two-handed combined task capacity and frequency rate as predictors (Table 4.41). In this model, the proportional frequency rate (PFR) was used. For example, if the frequency rate was 6/min, 6 was used as PFR and for the 1/5min frequency rate, 0.2 was used as PFR. Table 4.41 shows the prediction model for the one-handed combined task capacity using two-handed combined task capacity and frequency rate. The corresponding R^2 value, PRESS statistic and Residual SS are also shown in Table 4.41. Figure 4.5 through 4.8 shows the plot of the predicted value and observed value for each of the models 1 through 4.

Table 4.39

Correlation between the Capacities of One-handed Task
and Two-handed Task

		one-handed task		
		6/min	1/min	1/5min
two- handed task	6/min	0.9495 ^a (0.0001) ^b	0.5403 (0.1069)	0.2297 (0.5233)
	1/min	0.3304 (0.3512)	0.8387 (0.0024)	0.7054 (0.0227)
	1/5min	0.3856 (0.2711)	0.7366 (0.0151)	0.9132 (0.0002)

^a Pearson correlation coefficient.

^b Prob > |R| under Ho: Rho = 0.

Table 4.40

Prediction Models for the Capacity of One-handed Combined Task
using the Capacity of Two-handed Combined Task for Each Frequency

Frequency	Model	R ²	PRESS	Residual SS
6/min	C1 = - 11.622 + 1.1412 x C2 (Model 1)	0.9361	31.186	20.539
1/min	C1 = 13.129 + 0.5861 x C2 (Model 2)	0.7019	596.79	399.37
1/5min	C1 = 5.337 + 0.7055 x C2 (Model 3)	0.8330	530.82	408.46

where : C1 = capacity of one-handed combined task for each frequency rate (lb),
C2 = capacity of two-handed combined task for each frequency rate (lb).

Table 4.41

Prediction Model for the Capacity of One-handed Combined Task
using the Capacity of Two-handed Combined Task and Frequency rate

Model 4	R ²	PRESS	Residual SS
Ln(C1) = (3.105 + 0.012 x C2 - 0.0257 x PFR)	0.9233	0.4935	0.4135

where: C1 = capacity of one-handed combined task (lb),
C2 = capacity of two-handed combined task (lb),
PFR = 6 when frequency rate is 6/min
1 when frequency rate is 1/min
0.2 when frequency rate is 1/5 min,
Ln = natural log.

Figure 4.5

Predicted versus Observed values
for Model 1 (Frequency rate of 6/min)

Figure 4.6

Predicted versus Observed Values
for Model 2 (Frequency rate of 1/min)

Figure 4.7

Predicted versus Observed Values
for Model 3 (Frequency rate of 1/5min)

Figure 4.8

Predicted versus Observed Values for Model 4

Modeling for Combined Tasks Capacities

An objective of this section was to develop a model to predict both one-handed and two-handed combined task capacities. The correlation between combined task and isometric strengths is shown in Table 4.42. From the Table 4.42, the isometric strength of two arms had positive correlation with frequency rate of 1/min and 1/5min. Also, one arm isometric strength had some correlation with the capacity of one-handed tasks, especially at the frequency rate of 1/5min. This result indicated that arm strength was an important factor for the combined tasks, especially for the low frequency rate task. In the present study, carrying a load was an important part of the combined task and arm strength might have an important role during the carrying activity.

The PROC STEPWISE program on the SAS package was applied for developing the statistical model to predict combined task capacity by using all isometric strengths, frequency rates, and hand condition. For the general prediction model, the proportional frequency rate (PFR) mentioned earlier was applied. The hand condition was an indicator variable. For one-handed task, hand condition was 1 and for two-handed task, hand condition was 0. Interestingly, as mentioned earlier about correlation between strengths and capacities, strength generated by both arms among the all the strengths was the first variable entering the model and the other isometric strengths failed to show any significant contribution to the model. This result agreed with the analysis of correlation shown in Table 4.42. Also, the proportional frequency rate and hand condition entered in the model. Hence, following model was developed for the capacity of both one-handed and two-handed combined tasks.

Model 5 :

$$\text{Ln}(C) = (3.5156 - 0.1472 \times \text{PFR} - 0.2485 \times \text{hand condition} + 0.0135 \times A)$$

$$R^2 = 0.8303 \quad \text{PRESS} = 4.6387 \quad \text{Residual SS} = 4.2797$$

where : C = capacity of combined tasks,

Table 4.42

Correlation between Capacities of Combined Tasks
and Isometric Strengths

	one arm strength	two arms strength	back strength	comp. strength	leg strength	shoulder strength
ONE A	0.4585 ^a (0.183) ^b	0.2151 (0.551)	0.1784 (0.622)	0.2895 (0.417)	-0.2393 (0.505)	0.0647 (0.853)
TWO A	0.2381 (0.508)	0.0745 (0.838)	0.0844 (0.817)	0.2754 (0.442)	-0.2707 (0.449)	0.1095 (0.763)
ONE B	0.4885 (0.152)	0.6297 (0.051)	0.3067 (0.389)	0.6054 (0.064)	0.2539 (0.479)	0.3965 (0.257)
TWO B	0.4582 (0.183)	0.6947 (0.026)	0.3406 (0.336)	0.3745 (0.286)	0.2952 (0.408)	0.4391 (0.204)
ONE C	0.8234 (0.003)	0.6054 (0.063)	0.2058 (0.568)	0.1572 (0.665)	0.2706 (0.449)	0.2630 (0.463)
TWO C	0.6156 (0.058)	0.6645 (0.036)	0.1568 (0.665)	0.3105 (0.383)	0.4425 (0.200)	0.3580 (0.310)

^a pearson correlation coefficient

^b Prob > |R| under Ho: Rho = 0

ONE : one-handed task

TWO: two-handed task

A: frequency rate of 6/min

B: frequency rate of 1/min

C: frequency rate of 1/5min

$PFR = 6$ when frequency rate is 6/min
 1 when frequency rate is 1/min
 0.2 when frequency rate is 1/5min,
 hand condition = 1 when task is one-handed task
 0 when task is two hand task,
 A = isometric strength of both arms,
 Ln = natural log.

Comparison of Developed Models

Five models were developed for the combined task capacities. These were:

1. To predict the one-handed combined task capacities from two-handed combined task capacities for each frequency rate (model 1,2,3).
2. To predict the one-handed combined task capacities from two-handed combined task capacities and frequency rate (model 4).
3. To predict both one-handed and two-handed combined task capacities from the isometric strength of both arms and frequency rate and hand conditions (model 5).

The advantage of the models 1 through 3 was that these models were very simple to use because of just one predictor. Also, in spite of their simplicity, these models represented a good fit to the current data set and simulated future data set in terms of R^2 values, Residual SS, and PRESS values. If the two-handed combined task capacity is known, the one-handed combined task capacity could be predicted for the same frequency rate. However, these models were limited to use only their own frequency rate (either 6 handlings/min, 1 handling/min or 1 handling/5min).

Model 4 overcame the shortcomings of the models 1 through 3 by adding frequency rate as a predictor to avoid using different models for different frequency rates. Model 4 showed high R^2 value and Residual SS and PRESS values were also impressive. However, since a small sample size (10 subjects) was used for the model development in this study, for the best predicted results, this model should be applied within the range of

independent variables of present study. The best ranges for the two-handed task capacities for this model is from 30 lb to 114 lb, and ranges for the frequency rates is from 6/min to 1/5min.

The big advantage of model 5 compared to the models 1 through 4 was that in model 5, both one-handed and two-handed combined capacities could be predicted. Also, combined task capacities could be predicted by simple isometric strength testing for both arms, which could take less than five minutes. Another advantage of model 5 was that the frequency rate was incorporated into the model, rather than requiring a different model for each frequency rate (as in models 1-3). So, from the generalization point of view, this model improved a lot compared to models 1 through 4. Also, R^2 value, PRESS value and Residual SS showed a good fit to the current data set and could provide a good predictive model. The disadvantage of model 5 was similar to that of model 4. In another words, since a small sample size was used for developing the model, the application of this model should be used with caution outside of the range of isometric strength values of both arms (50-85 lb) and frequency rates (6/min - 1/5 min) of the present study. Also, the testing procedure for isometric strength of both arms in this study should be followed to measure the isometric strength of both arms.

The residual plots for models 1 through 5 are shown in Appendix G.

Validation and Testing of Model

Because of the lack of the past references for one-handed tasks, model 1 through model 4 could not be validated with another study's actual data set; however, model 5 could be tested and validated with a data set studied in the past (Jiang, 1984).

Part of Jiang's study was conducted to examine the effects of combinations of lifting, carrying and lowering activities. Jiang measured the capacities of two-handed combined tasks (lift a load from floor-to-knuckle height, carry the load for 4.3 meters, and lower the load from knuckle height to floor) at frequency rates of 6/min, 1/min and one time maximum. Table 4.43 shows the comparison of the measured and predicted

Table 4.43

Comparison of Predicted Value and Measured Value
with Model 5 using Jiang's Data

sub- ject	frequency rate	two arm strength	predicted value	measured value	error	absolute error (%)
1	6/min	58	30.43	33.85	-3.42	10.11
	1/min		63.52	68.95	-5.43	7.87
2	6/min	52.3	28.18	30.8	-2.62	8.52
	1/min		58.82	44.5	14.32	32.18
3	6/min	74	37.77	43.55	-5.78	13.28
	1/min		78.84	74.5	4.34	5.82
4	6/min	72	36.76	49.6	-12.84	25.89
	1/min		76.74	84.75	-8.01	9.45
5	6/min	83.5	42.93	37.7	5.23	13.88
	1/min		89.63	74.4	15.23	20.47
6	6/min	84.3	43.40	40.75	2.65	6.50
	1/min		90.60	57.8	32.80	56.75
7	6/min	73.3	37.41	43.65	-6.24	14.29
	1/min		78.10	66.8	11.30	16.91

* All the tasks are two-handed combined tasks.

* The unit of predicted, measured value and two arm strength are lb.

* Error = (predicted value - measured value).

* Absolute error = | measured value - predicted value | / measured value x 100.

capacities for the subjects used in Jiang's study. As mentioned earlier, this model was developed using a small sample size, so some of the Jiang's subjects who had strength of both arms within the range of present study (50-85 lb) were evaluated. The box size in Jiang's study was 44.5 cm (frontal) x 29.2 cm (sagittal) x 24.8 cm (vertical).

Figure 4.9 shows the plot of predicted values and measured values of Jiang's data. The correlation between the measured and the predicted values was 0.8468. The paired T-test was conducted to examine the difference of the measured values and predicted values. The result showed that there was no significant difference between the measured values and predicted values ($P > |T| = 0.3779$).

Figure 4.9

Validation of Model 5 using Jiang's (1984) Data Values.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The objectives of this study were the:

1. development of prediction models for one-handed and two-handed combined tasks and examination of the relationship between the capacities of one-handed and two-handed combined tasks.
2. development of an upper limit on the capacity of one-handed tasks using the psychophysical methodology.
3. investigation of the effect of the independent variables (frequency rate and hand condition) on the dependent variables (maximum acceptable weight, heart rate, RPE value, and tasking time).

The prediction models for the capacity of one-handed combined tasks were developed based on the two-handed combined task capacities for each frequency rate (model 1 for 6/min, model 2 for 1/min, model 3 for 1/5 min). The average R^2 for models 1 through 3 was 0.8237 and the average PRESS statistic and Residual SS were 386.27 and 276.12, respectively. Even though there was a restriction for models 1 through 3 that each model could be used just for a certain frequency, the attraction for the models 1 through 3 was their simplicity of use. Another prediction model for the one-handed task capacities was developed using frequency rate and two-handed task capacities as predictors (model 4). The advantage of model 4 compared to the models 1 through 3 was that this model could be used without restriction of frequency rate. Model 5 can be used to predict both one-handed and two-handed combined task capacities. Model 5 was tested and validated with a previous study's data. The disadvantage of all five models above was that these models were developed based on a small sample size, so the

application of these models should be used with caution. At the simplest level, one-handed task capacity can be estimated as 75% of two-handed capacity.

The effects of frequency rate and hand condition (one hand vs. two hands) on the dependent variables were analyzed using the analysis-of-variance technique. The dependent variables used in this study were maximum acceptable weight, heart rate, tasking time and RPE values for the whole body, the arm handling the load and the back.

Using the psychophysical methodology, the maximum acceptable weights of combined tasks were determined. The maximum acceptable weight of combined tasks with one hand were 83.0%, 75.2% and 76.3% of two-handed tasks at the frequency rates of 6/min, 1/min and 1/5min, respectively. For the low frequency rates such as 1/5min or 1/min, the subject's strength was the important factor in determining the maximum acceptable weight. However, as the frequency became faster, the physiological capability of the subject was the dominant factor in determining the maximum acceptable weight.

Heart rate was recorded during the experiment. The average heart rate on the tasks with the high frequency rate (6/min) was significantly higher than that of the low frequency rates (1/5min and 1/min) for the same hand condition. However, there was no significant difference of mean heart rate between the tasks of 1/5min frequency rate and 1/min frequency rate, which is not surprising since the subjects had ample time between experimental trials to physiologically recover.

The level of physical exertion perceived on the whole body, the arm handling the load, and the back in determining the maximum acceptable weight was asked of the subjects using the Ratings of Perceived Exertion (RPE) Scale (Borg, 1962). For one-handed tasks, the level of perceived exertion for the arm handling the load was the highest, with the back and whole body following in order. For two-handed tasks, back perceived exertion was the highest and arm perceived exertion was the lowest.

The tasking time was measured during the experiment. During the high frequency rate task (6/min), subjects tried to shorten the tasking time by carrying the load as quickly as possible with a smaller load.

Conclusions

The following conclusions were drawn from the results of this study.

1. In the high frequency rate (6/min), the capacity of two-handed combined task was not significantly different from one-handed combined task capacity. However, in the low frequency rates (1/5min and 1/min), the maximum acceptable weight of two-handed combined tasks was significantly heavier than that of one-handed combined tasks.
2. During the low frequency rate tasks, the subject's strength is the important factor in determining the maximum acceptable weight.
3. As the frequency becomes faster, the physiological capability of the subject is the dominant factor in determining the maximum acceptable weight.
4. For the heart rate, there was no significant difference between the frequency rate of 1/min and the frequency rate of 1/5min for the same hand condition. However, there was a significant difference between the frequent task (6/min) and the other tasks (1/min and 1/5min) for the same hand condition.
5. For the same frequency rate, the heart rate for the two-handed task was significantly higher than that for the one-handed task, reflecting the physiological demand of more muscle involvement and the handling of more weight.
6. The ratings of perceived exertion scale can be used to estimate the physiological demands of combined tasks with reasonable accuracy.
7. For one-handed tasks, the level of perceived exertion for the arm handling the load was the highest among the three body parts, however, for the two-handed task, the level of perceived exertion for the arm handling the load was the lowest.
8. During the high frequency rate task (6/min), the physiological capability of the subject was a dominant factor to maintain the pace of the work, so the subjects tried to shorten the tasking time to have a little more resting time between the tasks.

9. The one-handed combined task capacities for the frequency rate of 6/min, 1/min and 1/5min can be predicted by using two-handed combined task capacities as a predictor.
10. The one-handed combination task capacities can be predicted without restriction of frequency rates by using two-handed combined task capacities and frequency rate as predictors.
11. Both one-handed and two-handed combined task capacities can be predicted by using simple isometric strength test for both arms, frequency rate and hand condition.

Recommendations for Future Study

The current study was the first to examine the capacities of repetitive one-handed combined tasks which included lifting, carrying and lowering activities and to investigate the relationship between the capacities of one-handed and two-handed combined tasks. Based on the results of this study, the following suggestions are offered for future study.

1. Investigation of the capacities of one-handed tasks and two-handed tasks for female subjects, as well as increased sample sizes of both male and female subjects. Such data would allow combined male/female models to be developed.
2. Investigation of other frequency rates tasks such as one task every 15 sec, 2 min and 30 min.
3. Investigation of the combined tasks with different carrying distances.
4. Investigation of the relationship between lifting task capacities and combined task capacities.
5. Investigation of the relationship between dynamic strengths and combined task capacities.

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APPENDIX A

PERSONAL DATA AND CONSENT FORM

PERSONAL DATA AND CONSENT FORM

Institute for Ergonomics Research
Texas Tech University

**Psychophysical and Physiological Study of
One-handed and Two-handed Combined Tasks**

Date _____

Name _____ Age _____

Local Address

Telephone # _____

SS# _____

Date of birth _____

Sex _____

Height (ft in) _____

Weight (lb) _____

Name of physician _____ Telephone # _____

Name of individual to contact in case of emergency

Telephone # _____

Check if susceptible to: shortness of breath ____ dizziness ____ headache ____ Fatigue ____

Pain in hand, wrist, elbow, arm, shoulder, Knee or chest ____

If you checked any of the above, please explain:

Have you ever had a heart attack?

If so, give history:

Are you currently taking any type of medication?

If so, please explain:

Have you ever had any problems with blood pressure?

If so, please explain:

Have you had any surgery or serious illness? _____

If so, please explain:

Have you had any back injury or pain? _____

If so, please explain:

Have you had, or do you now have a hernia?

If so, corrective date:

Have you had, or do you now have any knee problems?

If so, please explain:

Please read carefully and sign the following consent form.

CONSENT FORM

Institute for Ergonomics Research

I have truthfully answered the personal data questions attached to this form to the best of my knowledge. I hereby give my consent for my participation in the research project entitled: Psychophysical and Physiological Study of One-handed and Two-handed Combined Tasks. I understand that the person responsible for this research project is Dr. J.L. Smith (806)742-3543. He or his authorized representative, Hoonyong Yoon, (806)743-2870 has explained to me that this study has the following objectives: to find the maximum weight I can safely carry with one hand and two hands. I will be asked to determine this maximum weight at one carry per minute, six carries per minute, and a one time only carry. Dr. Smith or his authorized representative have agreed to answer any inquiries I may have concerning the procedures of the project and have informed me that I may contact the Texas Tech University Institutional Review Board for the Protection of Human Subjects by writing them in care of the Office of Research Services, Texas Tech University, Lubbock, TX 79409 or by calling (806)742-3884.

Information concerning payment for my participation in this study has been explained to me as follows: (a) hourly wage is \$5 per hour; (b) payment will be made to me at the end of my participation in the study; (c) method of disbursement of my wages will be a check or cash from the experimenter presented directly to me; (d) in the event of my withdrawal from the experiment I will be paid for the work completed to date; and (e) the researchers for this study have the right to terminate my participation if I am not cooperative or have conflicting schedule problems.

He or his authorized representative has (1) explained the procedures to be followed and identified those which are experimental and (2) described the attendant risks and discomforts.

Briefly, these procedures involve the following: (a) measurement of various body segment dimensions, especially height, weight, and segment length; (b) measurement of static and dynamic strength; (c) measurement of physiological responses (oxygen consumption rate and heart rate) for static bicycling and carrying tasks; (d) Determination of maximum acceptable weight of carrying for three frequencies - 6/min, 1/min, 1/5min - with one hand and two hand at 4.3 m; (e) Determination of RPE (Ratings of Perceived Exertion) value for a given specific task parameters. To measure body segment dimension, I will be asked to hold my limbs in certain position while calipers or tape measures are used for measuring. To measure static strength I will be asked to exert a static force against an anchored load cell. I will be asked to give my maximum voluntary strength on all tests. To measure oxygen consumption rate, I will be asked to wear a noseclip and place a mouthpiece in my mouth through which the exhaled air will be collected and analyzed. To measure heart rate, I will be asked to attach a sensor to my chest. I will be asked to conduct six training and familiarization sessions before the

experiments. Each session consists of three programs - for increasing cardiovascular endurance, for practicing tasks, and for increasing muscle strength. To measure the amount of maximum weight that I can handle, I will be asked to lift, then carry for 4.3 m and lower a container that contains weight which I will adjust based on my own judgement for one hour. I am allowed to adjust the weight any time by adding or removing the weight to determine that a particular weight is the maximum that I can safely handle for one hour at a specific frequency. During the experimental sessions I will be asked to determine maximum acceptable weight for one-handed and two handed combined tasks at three different frequency rates. Each task will have a replication. To determine the RPE (Ratings of Perceived Exertion) value at the end of different task combination, I will be asked to rate the degree of perceived exertion - how hard the work feels in terms of physical difficulty - for the arm holding the container, for the whole body and for the back. The risks have been explained to me as follows: muscle strains and sprains, pulled tendons, back pain or strain, hernia bruises, or broken bones if the container is dropped. There are also possible changes such as abnormalities of blood pressure or heart rate, I understand that I will most likely experience muscle soreness, especially if I am not used to using muscle groups that they will be utilizing during the study.

If this research project causes any physical injury to me, treatment is not necessarily available at Texas Tech University or the Student Health Center, nor is there necessarily any insurance carried by the University or its personnel applicable to cover any such injury. Financial compensation for any such injury must be provided through my own insurance program. Further information about these matters may be obtained from the Office of Research services, (806)742-3884, Room 203 Holden Hall, Texas Tech University, Lubbock, TX 79409.

I understand that I will not derive any therapeutic treatment from participation in this study. I understand that I may discontinue participation in this project at any time without prejudice. I understand that all data will be kept confidential and that my name will not be used in any reports, written or unwritten.

Signature of Subject _____ Date _____

Signature of Project Director or Authorized Representative

Signature of Witness to Oral Presentation

APPENDIX B

SUBJECT ANTHROPOMETRIC DATA

Table B.1
Subject Anthropometric Data

<u>Measurement</u>	<u>S1</u>	<u>S2</u>	<u>S3</u>	<u>S4</u>
weight (lbs)	124.0	192.0	185.0	166.0
below in cm :				
height	162.5	182.3	178.6	170.0
acromial ht.	134.0	154.2	146.4	138.3
ankle ht.	7.4	8.6	8.2	6.0
elbow ht.	100.8	119.1	108.5	104.1
knuckle ht.	71.0	82.1	77.0	72.5
iliac crest ht.	98.7	103.0	100.5	97.2
knee ht.	48.3	52.2	51.5	45.5
shoulder-elbow len.	34.4	36.1	36.5	31.5
forearm-hand len.	46.9	50.5	45.5	46.7
biacromial breadth	40.0	43.6	45.0	42.5
hand len.	18.4	19.2	17.8	18.1
foot len.	25.9	26.9	25.5	25.1
neck circum.	33.0	41.0	43.0	38.0
shoulder circum.	103.2	122.0	123.3	118.0
chest circum.	86.0	103.0	99.2	98.5
waist circum.	72.0	96.5	91.0	89.5
buttock circum.	88.2	106.0	107.0	103.5
thigh circum,	47.0	59.0	61.5	58.0
calf circum.	32.5	36.0	40.6	36.0
wrist circum,	16.0	17.0	17.5	18.0
biceps circum. (flexed)	28.5	31.0	35.9	35.7
forearm circum. (flexed)	26.5	28.8	29.9	28.0

Table B.1 Continued

<u>Measurement</u>	<u>S5</u>	<u>S6</u>	<u>S7</u>	<u>S8</u>
weight (lbs)	168.0	172.5	159.0	155.0
below in cm :				
height	175.0	175.7	170.0	170.6
acromial ht.	144.8	146.0	141.0	139.2
ankle ht.	6.7	8.4	7.1	7.8
elbow ht.	107.4	113.9	107.3	106.0
knuckle ht.	73.8	77.0	75.8	75.9
iliac crest ht.	103.8	99.3	94.9	96.5
knee ht.	52.2	55.0	47.6	48.5
shoulder-elbow len.	37.2	36.8	36.7	32.2
forearm-hand len.	49.9	49.7	49.8	43.5
biacromial breadth	41.9	44.3	43.3	40.8
hand len.	19.8	20.4	18.2	15.5
foot len.	27.1	27.1	27.2	22.0
neck circum.	41.0	38.5	37.0	38.0
shoulder circum.	117.5	114.3	110.5	116.0
chest circum.	99.0	94.3	94.0	96.0
waist circum.	84.0	84.1	75.0	74.8
buttock circum.	96.0	100.0	100.2	97.0
thigh circum,	55.3	60.0	56.8	56.0
calf circum.	38.5	39.0	40.5	34.0
wrist circum,	18.2	17.5	16.5	16.5
biceps circum. (flexed)	35.1	32.5	32.2	34.7
forearm circum. (flexed)	31.0	29.5	29.2	27.7

Table B.1 Continued

<u>Measurement</u>	<u>S9</u>	<u>S10</u>
weight (lbs)	162.0	172.0
below in cm :		
height	171.2	183.0
acromial ht.	140.4	152.0
ankle ht.	6.8	8.4
elbow ht.	106.5	116.7
knuckle ht.	71.0	82.4
iliac crest ht.	94.1	106.0
knee ht.	46.6	52.5
shoulder-elbow len.	33.3	36.5
forearm-hand len.	48.6	49.0
biacromial breadth	38.8	41.0
hand len.	15.4	16.0
foot len.	23.7	23.2
neck circum.	41.0	40.0
shoulder circum.	109.8	118.0
chest circum.	91.0	95.0
waist circum.	76.0	77.0
buttock circum.	96.8	96.0
thigh circum,	55.7	56.2
calf circum.	37.3	36.5
wrist circum,	17.0	17.3
biceps circum. (flexed)	32.4	35.0
forearm circum. (flexed)	30.1	28.5

APPENDIX C

SUBJECT STRENGTH SUMMARY

Table C.1
Subject Strength Summary *

<u>SUBJECT</u>	<u>BACK</u>		<u>COMPOSITE</u>	
	<u>TRAINING BEFORE</u>	<u>TRAINING AFTER</u>	<u>TRAINING BEFORE</u>	<u>TRAINING AFTER</u>
S1	163.3	160.0	181.0	190.0
S2	166.0	170.7	199.0	202.0
S3	110.0	118.3	253.0	244.7
S4	189.3	207.3	262.0	270.3
S5	118.3	124.0	229.3	234.3
S6	163.7	171.7	257.0	289.3
S7	71.7	81.7	148.7	146.3
S8	197.0	211.0	225.3	223.0
S9	151.0	149.7	191.0	214.0
S10	165.0	178.7	223.7	218.0
MEAN	149.53	157.30	217.00	223.20
S.D.	38.50	40.33	36.75	40.49

* Units are lb

Table C.1 Continued

<u>SUBJECT</u>	<u>ARM (ONE HAND)</u>		<u>ARM (TWO HAND)</u>	
	<u>TRAINING BEFORE</u>	<u>AFTER</u>	<u>TRAINING BEFORE</u>	<u>AFTER</u>
S1	52.3	55.0	70.0	76.7
S2	47.3	48.7	64.0	70.0
S3	49.3	47.7	77.0	76.3
S4	55.7	59.0	80.3	85.0
S5	50.7	51.3	68.7	68.7
S6	41.7	39.3	76.3	78.3
S7	30.7	33.3	51.7	50.3
S8	40.3	43.3	56.3	66.3
S9	46.7	49.0	77.3	80.3
S10	44.0	46.0	81.3	80.7
MEAN	45.87	47.27	70.30	73.27
S.D.	7.14	7.40	10.21	9.97

Table C.1 Continued

<u>SUBJECT</u>	<u>LEG</u>		<u>SHOULDER</u>	
	<u>TRAINING BEFORE</u>	<u>AFTER</u>	<u>TRAINING BEFORE</u>	<u>AFTER</u>
S1	273.7	285.3	123.3	125.0
S2	184.0	189.3	132.3	131.3
S3	301.7	292.3	109.7	128.7
S4	280.0	263.7	135.3	132.7
S5	215.3	252.3	128.0	132.7
S6	303.3	308.3	143.3	143.0
S7	213.7	214.3	97.3	96.7
S8	230.0	244.3	149.3	152.0
S9	248.3	278.7	127.0	125.3
S10	317.3	321.7	156.3	160.7
MEAN	256.73	265.03	130.20	132.80
S.D.	45.14	41.26	17.69	17.29

APPENDIX D*

ISOMETRIC STRENGTH MEASUREMENT

* Adapted from Asfour, S.S., 1980, Energy cost prediction models for manual lifting and lowering, Ph.D. dissertation, Texas Tech University, Lubbock, TX.

Static Arm Strength Measurement (Figure D.1):

The measurement requires that the long handle be adjusted such that the forearms are flexed 90° , i.e., perpendicular to the subject's torso, and the arms are vertical, i.e., parallel and adjacent to the torso. The subject stands erect, with legs and back straight and the feet flat. A load cell and a chain connect the handle to the platform on which the subject is standing. The erected force is to be upward, vertical and generated by only the arm muscles. The subject is instructed avoid any shoulder movement, or other body movement.

Figure D.1

Subject Posture for Arm Strength Measurement.

Static Back Strength Measurement (Figure D.2):

The long handle is located at 75 % of the knee height (tibiale height) and approximately 15 inches in front of the medial malleous. The height measurement is from the platform to the lower horizontal plane of the handle.

The subject's feet are separated at shoulder width. Both feet are kept at an equal distance from the chain anchor point. The subject flexes the torso in order to grip the handle.

The upward, vertical force is exerted by torso extension. The elbow and knee are fully extended and the eyes are looking straight ahead.

Figure D.2

Subject Posture for Back Strength Measurement.

Static Composite Strength Measurement (Figure D.3):

The short handle is adjusted to the height of 15 inches above the platform (the height is measured from the platform to the lower horizontal plane of the handle). The subject is to take a semi-squat position, such that the handle is between the legs. The subject's elbows are extended. Contact between the upper and lower extremities is not permitted. The heads of the first metatarsal are to be placed opposite one another and intersect the vertical plane of the chain and the load cell. The feet are to remain flat on the platform. The subject is to exert an upward, vertical force by extending the knees and simultaneously extending the torso.

Figure D.3

Subject Posture for Composite Strength Measurement.

Static Shoulder Strength Measurement (Figure D.4):

The subject stands erect and supports, with both arms, a bar with two straps. The straps are positioned over the distal end of the humerus by inserting the arms outside-in. The arms are flexed to a posture such that the arms are perpendicular to the subject's torso, i.e., at the shoulder level, and the forearms are vertical, i.e., parallel to the torso. The subject's feet are to remain flat, the legs straight, and the back erect. A load cell and a vertical, link chain connect the bar to the platform on which the subject is standing. The exerted force is to be upward, vertical and generated by only the shoulder muscles.

Figure D.4

Subject Posture for Shoulder Strength Measurement.

Static Leg Strength Measurement (Figure D.5):

The height of the bar is based on the subject's stature:

- a. For subject heights equal to or below 169.5 cm, the bar is placed at the height of 66 cm.
- b. For subject heights between 169.5 cm and 179 cm, the bar is placed at a height of 72 cm.
- c. For subject heights equal to or greater than 179 cm, the bar is placed at a height of 79 cm.

The horizontal bar is gripped with the palm of the hands (finger grasping is not permitted) such that the dorsal surfaces of the hands are facing outward (visible to the experimenter). The subject exerts an upward, vertical force on the bar, by extending the knees, while keeping the scapulae, the buttocks, and the heels against a common vertical plane, such as a wall. The feet are to be kept flat.

Figure D.5
Subject Posture for Leg Strength Measurement.

APPENDIX E

SUBJECT PWC SUMMARY

Table E.1
Subject PWC Summary

<u>SUBJECT</u>	<u>Before Training</u>		<u>After Training</u>	
	<u>PWC</u> (ml/min)	<u>PWC</u> (ml/kg-min)	<u>PWC</u> (ml/min)	<u>PWC</u> (ml/kg-min)
S1			2214	39.40
S2	2855	32.78	2632	30.22
S3	2919	34.79	3090	36.83
S4	3677	48.83	4047	53.75
S5	3408	44.72	3756	49.29
S6	3461	44.15	3366	42.93
S7	3204	44.44	3551	49.25
S8	2853	40.58	2978	42.36
S9	3272	44.52	3222	43.84
S10	3706	47.51	3830	49.10
Mean	3262.0	42.48	3269.0	44.17
S.D.	332.5	5.46	556.0	7.26

APPENDIX F
INSTRUCTIONS TO SUBJECT

Instructions to Subject

The object of this study is to determine the weight handling ability of individuals in a representative work situation. This is an experiment to find reasonable quantities that normal healthy person can handle under the combined activities at one and six handlings per minutes, and one handling per 5 minutes. Also to find the relationship between one-handed and two-handed combined tasks capacities. The combined activities for this study are one and two-handed lifting, carrying and lowering with different frequencies.

THIS IS NOT A TEST TO DETERMINE YOUR MAXIMUM WEIGHT LIFTING OR CARRYING CAPACITY. I repeat, **THIS IS NOT A TEST TO DETERMINE YOUR MAXIMUM WEIGHT LIFTING OR CARRYING CAPACITY.** Rather, this is a study to find reasonable quantities -- I repeat, reasonable quantities that individuals can handle without injury, strain, or undue exhaustion repetitively under the specified conditions. From this quantities, the relationship between one and two-handed combined capacities could be found.

We want you to imagine that you are on a one hour job, getting paid for the amount of work that you do. In other words, the more weight you handle the more money you make. You are expected to work continuously at least 1 hour, as hard as you can, without straining yourself or without becoming unusually tired, weakened, overheated, or out of breath. You are to determine the amount of weight you can handle comfortably in your preferred (strong) hand and two hand for an actual one-hour work period. You are asked to perform manual materials combined tasks that require to pick up the load, carry the load, and put the load down. You are encouraged to make adjustments by adding or removing some weights, in order to arrive at the maximum acceptable weight (MAW) without getting tired or exhausted. Adjustment of the weight will be allowed

throughout an hour. After finishing each task, the RPE value for the whole body, RPE(WB), for the arm handling the container, RPE(A), and for the back RPE(BK) will be asked.. Each experimental condition will be completed twice by you (one replication).

ONLY YOU WILL ADJUST THE WORKLOAD. You will work only when the sound is on. If you feel that you can work harder without getting overloaded, add more weight to the box. If you feel you are working too hard and could not keep up the rate for an hour period, you should remove some weight from the box. Remember, only you will adjust this workload.

DO NOT BE AFRAID TO MAKE ADJUSTMENTS. You have to make enough adjustments so that you get a good feeling for what is too heavy and what is too light. You can never make too many adjustments, but you can make too few.
REMEMBER THIS IS NOT A CONTEST.

EVERYONE IS NOT EXPECTED TO DO THE SAME AMOUNT OF WORK.

WE WANT YOUR JUDGMENT ON HOW HARD YOU CAN WORK WITHOUT BECOMING UNUSUALLY TIRED.

TAKE IT EASY.

Remember to adjust the weight, when necessary, so that the box represents the maximum weight that you would be willing to handle at this pace, and distance.

**Instructions
For
Training and Familiarization session**

You will have total of 6 training and familiarization sessions three days a week for 2 weeks. There are three different training methods for this session.

1. Cardiovascular Endurance: You will be trained for 25 minutes on the bicycle.

a. For the first 5 min., you will be warmed up at a load that elicits a heart rate of 100 beats/min. b. Then for the 20 min, you will exercise with the intensity of 70% of your maximum heart rate. c. After 20 min. of training, you will have 5 minutes of cooling down period with 50% of maximum heart rate intensity.

2. Practicing tasks: You will practice six different tasks during the training sessions, one task per one session. The conducting order will be randomly chosen by you.

3. Muscle strength: You will be asked to determine the maximal load you can lift and lower in a box 6 consecutive times without resting between lifts. Three sets, of 6 repetition each, will be as follows.

set1: 6 repetitions at a load of $1/2$ the 6 RM load.

set2: 6 repetitions at a load of $3/4$ the 6 RM load.

set3: 6 repetitions at a load equal to the 6 RM load.

APPENDIX G
RESIDUAL PLOTS

Figure G.1 Residual plot for Model 1

Figure G.2 Residual plot for Model 2

Figure G.3 Residual plot for Model 3

Figure G.4 Residual plot for Model 4

Figure G.5 Residual plot for Model 5

APPENDIX H
SUBJECT RAW DATA

Table H.1
Subject Raw Data

Subject	Responses	Frequency Rate		
		6/min	1/min	1/5min
<u>S1</u>	MAW (1)	31.75	50.55	91
	MAW (2)	34.55	77.25	113.50
	HR (1)	138	101	104
	HR (2)	175	121	135
	TT (1)	5.31	5.61	6.90
	TT (2)	5.85	7.16	10.71
<u>S2</u>	MAW (1)	37.75	61.50	74.00
	MAW (2)	42.75	94	97.25
	HR (1)	117	97	104.00
	HR (2)	144	108	116.00
	TT (1)	5.05	5.95	6.82
	TT (2)	5.25	6.91	7.76
<u>S3</u>	MAW (1)	22.75	60.50	78.25
	MAW (2)	30	84.25	105.50
	HR (1)	126	109	109
	HR (2)	163	120	117
	TT (1)	5.66	5.33	5.90
	TT (2)	6.00	6.90	7.39
<u>S4</u>	MAW (1)	33.50	62.25	72.25
	MAW (2)	37.25	72.50	81.25
	HR (1)	109	87	91
	HR (2)	143	103	103
	TT (1)	5.01	4.97	6.52
	TT (2)	5.68	5.83	6.96

Table H.1 Continued

Subject	Responses	Frequency Rate		
		6/min	1/min	1/5min
<u>S5</u>	MAW (1)	40.50	72	86
	MAW (2)	46.75	78.5	110
	HR (1)	123	97	114
	HR (2)	142	114	120
	TT (1)	4.71	5.09	6.27
	TT (2)	5.42	6.04	6.79
<u>S6</u>	MAW (1)	33.75	63.75	53.25
	MAW (2)	40.25	81	90.75
	HR (1)	113	98	105
	HR (2)	146	99	116
	TT (1)	5.26	4.95	5.41
	TT (2)	5.84	6.30	7.38
<u>S7</u>	MAW (1)	24	33.25	37
	MAW (2)	32.5	40	42.25
	HR (1)	131	99	105
	HR (2)	139	99	105
	TT (1)	4.86	4.57	4.88
	TT (2)	5.87	5.78	5.88
<u>S8</u>	MAW (1)	25.25	56.75	63.50
	MAW (2)	33.25	71.50	78.50
	HR (1)	102	97	107
	HR (2)	117	104	117
	TT (1)	5.43	5.65	6.30
	TT (2)	5.93	6.96	7.64

Table H.1 Continued

Subject	Responses	Frequency Rate		
		6/min	1/min	1/5min
<u>S9</u>	MAW (1)	30.25	78.5	86
	MAW (2)	37	107.8	116.50
	HR (1)	114	107	114
	HR (2)	161	123	123
	TT (1)	4.13	4.69	5.08
	TT (2)	4.80	5.39	5.21
<u>S10</u>	MAW (1)	26.25	55.75	73.75
	MAW (2)	34.25	84.5	98.75
	HR (1)	126	108	106
	HR (2)	142	112	115
	TT (1)	4.85	5.67	5.91
	TT (2)	4.83	5.38	5.83

MAW (1) : maximum acceptable weight with one-handed task (lb)

MAW (2) : maximum acceptable weight with two-handed task (lb)

HR (1) : heart rate with one-handed task (bpm)

HR (2) : heart rate with two-handed task (bpm)

TT (1) : tasking time for one-handed task (sec)

TT(2) : tasking time for one-handed task (sec)