Modelling the Additivity of Perceived Exertion in Symmetric, Mid-Sagittal Lifting

by

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(ABSTRACT)

Two hypotheses were formulated to examine the additivity of perceived exertion in repetitive, symmetric, mid-sagittal lifting. "Additivity" has been defined as the means by which a whole-body rating of perceived exertion is composed of a weighted combination of component ratings of perceived exertion. The "task additivity" hypothesis asserts that a perceived exertion rating for the whole body in a floor-to-overhead lifting task can be modelled by the perceived exertion ratings of the component motions, i.e., floor-to-knuckle height lifting and knuckle height-to-overhead lifting. This is an inter-task (subtask) additivity paradigm. The "body-segment additivity" hypothesis asserts that the perceived exertion rating for the whole body in a floor-to-overhead lifting task can be modelled by a combination of the ratings of perceived effort from the arms, legs, torso, and central (cardio-respiratory) body functions. This is an intra-task (regional) additivity paradigm.

Two lifting posture conditions (squat and stoop) were examined by generating separate models to determine if posture affected the means of integrating the whole-body perceived exertion rating. Two work load levels were included in the models to obtain a better regression fit to the data. The work loads were established relative to each subject's maximum single lift capability, thus the relative workloads were identical

among subjects. The Borg CR-10 (category-ratio) scale was used as the psychophysical response metric. Heart rate was recorded as a measure of physiological stress.

Linear regression techniques were used to model the whole-body ratings of perceived exertion by the independent variables (regional perceived exertion ratings or subtask, whole-body perceived exertion ratings). The task additivity models both resulted in a significant ($p<0.05$) regression relation with coefficients of multiple determination (r^2) of 0.562 for the stoop posture condition and $r^2=0.693$ for the squat posture condition. The stoop posture, whole-body rating was best modelled by only the knuckle-to-overhead, whole-body rating. The squat posture, whole-body rating was best modelled by both the floor-to-knuckle and knuckle-to-overhead lift . This suggests that initial lifting posture affects the perceptual relations of the component lifting motions to the floor-to-overhead perceived exertion rating.

The body-segment additivity models were also significant ($p<0.05$) regression relations. The stoop posture, whole-body rating was best modelled by the ratings from the arms, torso, and central effort signals. The high r^2 (0.810) for the stoop posture model indicates that much of the variance in the whole-body rating can be attributed to the differentiated (regional and central) ratings. The squat posture, whole-body rating was modelled by only the rating from the legs. The r^2 of 0.621 was not appreciably increased by inclusion of the other differentiated signals.

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Dedicated to my parents David and Geraldine Lowe

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1. INTRODUCTION

Subjective assessments of the perception of physical exertion arise from a gestalt of many sensations (Borg and Noble, 1974). The term "undifferentiated" perceived exertion applies to the perception and psychophysical rating of an overall, whole-body exertion that is perceived as an integration of sensory cues. Numerous factors appear to contribute to the perception of physical effort, originating from both physiological and psychological processes. Pandolf (1978) presented a model of perceived exertion which included factors such as physical exertion, motivation, task aversion, and general exertion.

The term "differentiated" perceived exertion refers to more specific sensations of physiological processes which contribute to the overall, undifferentiated perception and corresponding psychophysical rating. Everyday experience demonstrates that humans can distinguish among different "types" of exertion, or at least, possess the ability to distinguish regional differences in effort sensation. Ekblom and Goldbarg (1971) dichotomized perceived exertion into a model including differentiated sensations from the circulatory system (central signals) and sensations from the working muscle groups (local, or regional/peripheral signals).

Undifferentiated ratings of perceived exertion are formed by an integration of the differentiated, local and central effort sensations. The perceptual integration of these differentiated signals is believed to be dependent upon the type of activity and muscle mass involved. Several studies (Cafarelli, 1977; Gamberale, 1972; Pandolf, 1978; Pandolf, 1982; Pandolf, Burse, and Goldman, 1975) have analyzed psychophysical ratings of differentiated perceived exertion, mostly in correlation with quantifiable physiological processes. However, the means by which differentiated

ratings of regional sensations are integrated to form the undifferentiated psychophysical rating of perceived exertion remains speculative in the literature.

Robertson, Gillespie, McCarthy, and Rose (1979a), examining differentiated perceived exertion in bicycle ergometer pedalling, found that the overall, undifferentiated rating of exertion was slightly, but significantly, lower than the average of differentiated ratings of the legs and chest (local and central). The mean of the legs plus chest rating showed a high correlation with the overall, undifferentiated rating (r^2= .82, .85, .81 at pedal cadences of 40, 60, 80 rpm). The researchers concluded that a weighted average procedure was employed by the subjects in perceptually integrating the differentiated signals into the overall, undifferentiated rating.

The "weighted average" procedure proposed by Robertson et al. (1979a) is an important concept which serves as the focal point of this project. Their study concerned ergometer pedalling which involves relatively localized muscular activity. A similar weighted average integration procedure might exist for whole-body tasks in which multiple muscle groups and body segments elicit regional signals of exertion.

This study tested two weighted-average hypotheses by examining ratings of perceived exertion in an activity stressing multiple muscle groups. An "additivity" concept has been hypothesized as the mechanism by which psychophysical ratings of perceived exertion are perceptually integrated to reflect the intensities of the sensory processes which they represent. The first hypothesis relates to additivity among differentiated ratings of perceived exertion. This additivity hypothesis asserts that the undifferentiated rating of exertion can be modelled by a weighted linear combination of the differentiated ratings. The perceptual weightings of these differentiated ratings were believed to be dependent upon the work characteristics of initial lift posture and work load.

If an additive property existed between regional, differentiated ratings and the undifferentiated rating of perceived exertion within a task, the concept might also be applicable to the perceived exertion among tasks which are physically additive components of a larger, more complex task. Therefore, the second hypothesis related to the perceptual weighting of "subtasks" in relation to an overall, whole-body task. This hypothesis asserts that the perceived exertion in a whole-body activity could be modelled by a weighted linear combination of the perceived exertion ratings given to the component motions of the activity.

2. LITERATURE REVIEW

This chapter summarizes the perceived exertion literature related to the experiment. The literature encompasses knowledge in the fields of exercise/work physiology and psychophysical scaling. The scaling literature (specific to perceived exertion) has been dominated by the work of Gunnar Borg at the University of Stockholm. The physiology literature has numerous contributors, mostly from the field of exercise and sport science.

2.1 Background

The first studies in perceived exertion of muscular work began with short-duration, isometric, force sensations (Borg and Dahlstrom, 1960; Stevens and Mack, 1959). These investigations determined that the perception of muscular effort followed a power function with an exponent of roughly 1.6 to 1.7. Perceived exertion studies of dynamic activities of longer duration were first conducted by Borg in the early sixties (Borg, 1962). This topic has since aroused the interests of both physiologists and psychologists, in a quest to determine the underlying physiological and psychological processes in the perception of exertion.

In the mid-seventies Borg proposed the term "ergology" to encompass the general study of physical activities (Borg, 1974). Borg and Noble (1974) stated that, "In human factors studies, one main objective is to discover methods to improve productivity, i.e., to decrease the work time and number of errors, but often an understanding of the subjective 'costs' behind the performance is neglected" (p. 133).

Borg believed that just as physiological measures are important to quantify mental effort so should subjective measures be critical in quantifying physical effort. The study of dynamic muscular work provides good examples of the need for both physiological and psychological methods. Borg believed that a physically stressful task could be studied with regard to perceptual, performance, and physiological responses. Figure 2.1 shows Borg's measures of physical stress and their relationship within the psychophysiological domain. The stimulus situation (S) experienced by the observer (O) can be examined with perceptual, performance, and physiological measures.

2.2 Psychophysical Scaling

2.2.1 Scaling Classification

Psychophysical scaling is a means of determining the relationship between perceptual responses and physical stimulus intensity. Stevens (1961) classified psychophysical rating methods into three groups: ratio methods, interval methods, and rank order methods. Borg (1982a) proposed another classification scheme for rating methods - those designed for functional determinations and those constructed for direct level determinations. Ratio scaling methods are used in making functional determinations, while category rating scales are effective in making direct level determinations.

In studies of perceived exertion, category and ratio scales have been popular techniques for quantifying the subjective assessment of effort. Category scales are advantageous in making direct interindividual comparisons of subjective intensity levels (Borg, 1973). Ratio scales allow intensity levels to be compared on a relative

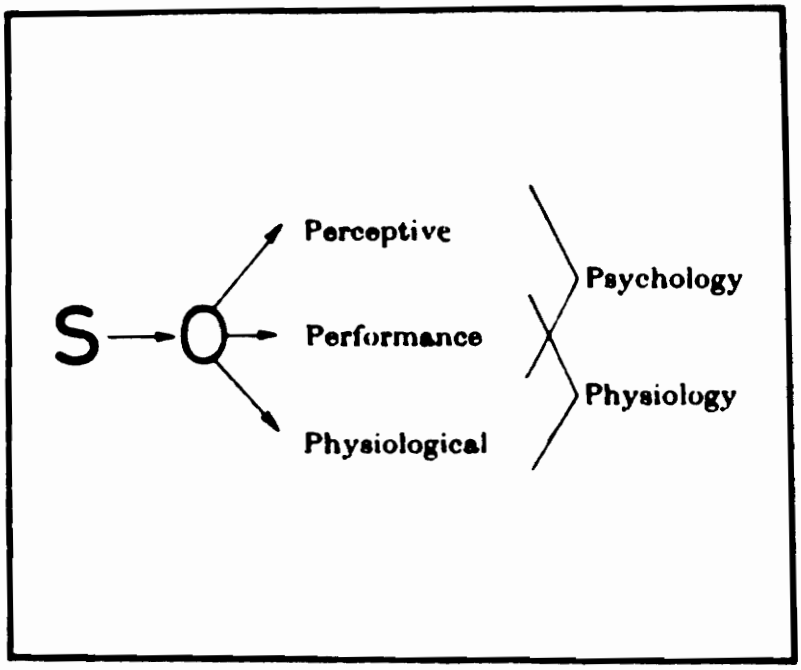


Figure 2.1 Model of Psychophysiological Responses Proposed by Borg (1971a).

"intra-individual" basis, but not between individuals. Borg (1982b) cited the major disadvantage of ratio scaling methods as a lack of "subjective 'levels' for immediate interindividual or intermodal comparisons" (p. 25).

The analysis of psychophysical data is dependent upon the scaling method used in obtaining the ratings. The method of assigning "scores" or ratings to observations must be isomorphic to the numerical structure which includes the desired operations (Siegel and Castellan, 1988). For example, ordinal scales preserve only the order of a rating system. Therefore, the numerical values assigned to each observation hold no meaning beyond the rank ordering of the ratings. It is thus inappropriate to use a statistic in conjunction with ordinal data which is dependent upon the differences in magnitude between the observations (e.g. mean, standard deviation).

In the perceived exertion literature category scales have been classified as those which allow for direct level comparisons. Rating scales with verbal, anchor expressions "categorize" the levels of exertion based on the intensities associated with the semantic expressions. However, these "category" scales possess ordinal scale properties in the corresponding numeric ratings. Thus, some confusion results from the nomenclature in the literature between the terms "categorical" and what would be formally considered "ordinal".

Interval scales are constructed on the assumption that the absolute differences between scale values, as well as their ordering are meaningful. The zero point on an interval scale is arbitrary and does not imply zero intensity, hence, ratios between scale values are not preserved. Absolute, interval distances are meaningful, so that an arithmetic mean and standard deviation are appropriate statistics.

Ratio scales provide for more powerful analyses by preserving the ratio between two scale values. A ratio scale contains a true zero point as its origin and can be transformed by the scalar multiplication property. The unit of measurement in a ratio

scale is thus arbitrary. Parametric statistical tests are supported by ratio scale measurement, provided that the assumptions concerning the distribution are met (Siegel and Castellan, 1988). In this protocol, subjects rated four differentiated sensations of effort simultaneously. It was expected that these ratings would be made by relative comparison of the perceived intensities. Thus, a ratio scaling technique was sought.

2.2.2 Perceived Exertion Rating Scales

2.2.2.1 The Borg RPE Scale

Studies on subjective rating scales specific to perceived exertion have been dominated by the work of Borg and his colleagues at Stockholm University. Perhaps the most noted work in quantifying the subjective perception of effort has been Borg's (1962) RPE (Rating of Perceived Exertion) scale. This scale was designed to parallel the linear increase in heart rate associated with increasing work load during bicycle ergometer pedalling (see Figure 2.2).

The perception of physical effort has been shown to be a positively accelerating function of physical work load (Borg and Dahlstrom, 1960). That is, the perception of exertion increases exponentially with physical work intensity. Heart rate, however, increases linearly with work load along most of the effort continuum. The RPE-heart rate correlation has been shown to be high for a variety of activities. Thus, RPE scaling is advantageous because it is an absolute scale, permitting inter-individual comparisons while paralleling a physiological event. Borg (1962) constructed the RPE scale using numeric values from six to twenty with semantic anchors at the odd numeric values. The scale values were selected to approximate heart rate divided by ten. The RPE scale

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	

Figure 2.2 Borg RPE (Rating of Perceived Exertion) Scale.

has become so popular in exercise/stress testing that "RPE" has become synonymous with any psychophysical rating of perceived exertion. In this paper, however, the term RPE will be reserved for perceived exertion ratings using the 15-point, Borg RPE scale.

The RPE scale is practical in making direct perceived exertion comparisons between individuals. While Borg refers to RPE as a "category" scale, it exhibits interval scale properties. The high correlation coefficients reported between RPE and heart rate support the notion that subjects can make at least interval judgments of perceived exertion, since heart rate increases linearly with increasing work load. However, ratio scale properties are necessary if it is desired to make relative comparisons among intensity levels. Different categorical, or interval, ratings tell nothing about how much greater one effort is relative to another. Unfortunately, classical ratio scaling techniques do not allow for absolute comparisons between individuals with different perceptual frames of reference. For these reasons, Borg constructed a "ratio category scale", based on the RPE scale, which allows for both ratio calculations and absolute inter-subject comparisons (Borg, 1973).

2.2.2.2 The Borg CR-10 Scale

The first of Borg's category scales with ratio properties was developed in 1973. Knowledge of physical intensities behind the RPE verbal expressions was integrated with results from the general psychophysical function to determine placement of the semantic anchors along the numeric continuum (Borg, 1973). The scale contained numerical values from 0 to 20 with verbal expressions placed at scale values to semantically match subjective intensities. Borg and his colleagues tested this ratio-

category scale for ergometer work and obtained an exponent of approximately 1.6, which was similar to previously obtained results (Borg, 1973).

The 0-to-20 scale had a tendency towards a ceiling effect, thus warranting a revision in the scaling method. In 1982 Borg developed a new category scale with ratio properties. He called this the CR-10 scale (C-category, R-ratio). Borg's CR-10 scale was constructed with respect to simplicity in the range of numeric values. The visible scale values range from 0 to 10 with the word "maximal" placed outside of the scale. The CR-10 scale instructions emphasize that any number exceeding 10 can be assigned to the stimulus if it is perceived as exceeding a maximal exertion from earlier experiences. This modification was intended to reduce the ceiling affect demonstrated by the 21-point ratio scale. The new CR-10 scale also encouraged use of fractional ratings should this be appropriate; 0.5 is shown as a scale value corresponding to the expression "extremely weak". Borg (1982a) tested the CR-10 scale for ergometer work and obtained the power function:

$$R = 0.4 + 0.00003 \times S^{1.65}$$

(goodness of fit $r_{xy} = 0.999$).

The CR-10 scale is shown in Figure 2.3. Instructions for the scale (G.A. Borg, personal communication, September, 1992) were incorporated into the rating scale instructions shown in Appendix B.

The RPE scale has clearly been the most popular scale in the perceived exertion literature. However, the author has noticed an increasing trend towards use of the CR-10 scale in the literature, perhaps owing to its ratio properties. This scale is still relatively young and lacks much of the testing which RPE has received. The 1992 Human Factors Society Annual Conference contained several presentations in which the

0	Nothing at all	
0.5	Extremely weak	(just noticeable)
1	Very Weak	
2	Weak	(light)
3	Moderate	
4		
5	Strong	(heavy)
6		
7	Very strong	
8		
9		
10	Extremely strong	(almost max)
●	Maximal	

Figure 2.3 Borg CR-10 Scale.

Borg CR-10 scale was used to obtain psychophysical, perceived exertion ratings (Deeb and Drury, 1992; Resnick and Chaffin, 1992). Unfortunately, some researchers misused the RPE scale, typically in conjunction with processes for which it was not designed to be sensitive.

R.J. Robertson, who has used the Borg scales extensively at the University of Pittsburgh, Human Energy Laboratory, made some recommendations regarding their use (R.J. Robertson, personal communication, November, 1992). Dr. Robertson believes RPE to be an interval scale and feels it is also well suited to inter-individual comparisons. He believes that the CR-10 scale possesses "weak" ratio properties and noted that CR-10 scaling was useful for comparing ratios between ratings provided by a single subject. Since this investigation involved both intra-individual and inter-individual comparisons among perceived exertion ratings, it was appropriate to use the CR-10 rating scale in the experimental procedure.

2.3 Physiological Factors in the Perception of Exertion

Carton and Rhodes (1985) and Mihevic (1981) provided excellent summaries of the perceived exertion literature and many of its underlying assumptions and theories to date. It was proposed by Edwards, Melcher, Hesser, Wigertz, and Eklund (1972) that a physiological response to exercise is unlikely to act as a sensory cue for the perception of exertion unless it is subject to conscious monitoring during the exercise. This concept seems to contradict the notion of perception as defined in the psychology domain as a sensory process dissociated from conscious awareness (Mihevic, 1981). In view of our everyday experiences, it appears that individuals can perceive physiological events resulting from physical exertion and are capable of consciously monitoring these

responses. Walking several flights of steps typically makes one suddenly aware of an increase in cardiovascular activity. Some individuals may actively monitor somatic responses during exercise, however, important sensory cues are likely to indirectly and unconsciously influence the perception of effort (Morgan and Pollock, 1977).

Ekblom and Goldbarg (1971) were the first formal advocates of a two-factor, differentiated model of perceived exertion. They differentiated perceived exertion into two distinct categories: strain in the working muscles (local factors) and sensations from the cardiopulmonary system (central factors). Ekblom and Goldbarg (1971) proposed that the dominance among the differentiated signals (local or central) was dependent upon the size of the muscle groups involved in the task (i.e., the "active" muscle mass).

A consensus in the literature supports the notion that the perception of exertion can be divided between local signals and central signals of physical effort. These differentiated "cues" are believed to be distinctly perceptible and of unequal contribution to the overall effort sense. While a conscious awareness of certain discrete physiological cues may affect the assessment of perceived exertion, an integration of both conscious and unconscious responses is more likely indicative of the perception of effort (Mihevic, 1981). Differentiated, local and central cues are likely to be the principal conscious responses to the integration of effort signals into an undifferentiated perception of exertion.

2.3.1 Central Physiological Factors

Central signals of perceived exertion are typically described as feelings of exertion stemming from the cardiopulmonary system. Heart rate (HR), oxygen

consumption ($\dot{V}O_2$), ventilatory minute volume ($\dot{V}E$), and respiration rate (RR) are the principal physiological events associated with the central effort signal (Mihevic 1981). These events relate to the circulatory, ventilatory, and metabolic demand of a work activity.

Robertson (1982) suggested that heart rate has been inappropriately associated with perceived exertion, particularly with RPE. Manipulation of HR by both temperature increases and neurological drugs have resulted in nonlinear HR relations to RPE. Robertson cited hemodynamic mechanisms such as cardiac output, stroke volume, and blood pressure as being contributors to the centrally-perceived exertion. This does not invalidate the use of RPE; Borg never suggested that the RPE-HR relation was causal. It does imply that the correlation between HR and RPE is facilitated by other physiological mechanisms.

Respiratory resistance appears to be a contributing variable to centrally-perceived effort (Robertson, 1982). Chemoreceptor activity controls ventilation at rest, however, afferent impulses from the mechanoreceptors in the chest wall, lungs, and airways have been identified at elevated ventilatory stress. These mechanoreceptor signals may be consciously monitored by exercising individuals. Robertson (1982) also noted that RPE has been shown to begin a parallel relation to $\dot{V}E$ at exercise intensities exceeding 50% $\dot{V}O_{2max}$, approximately the same metabolic rate as the peak tidal volume. It appears that respiratory events may drive the central effort sense despite the correlational support for heart rate as the mediator.

2.3.2 Local Physiological Factors

Local signals (also known as regional or peripheral signals) of perceived exertion are defined as "feelings of strain in the working muscles" (Ekblom and Goldbarg, 1971). The principal physiological events in relation to strain in the working muscles have been defined as: muscle lactate accumulation, Golgi tendon activity, and general muscle sensations (Mihevic, 1981).

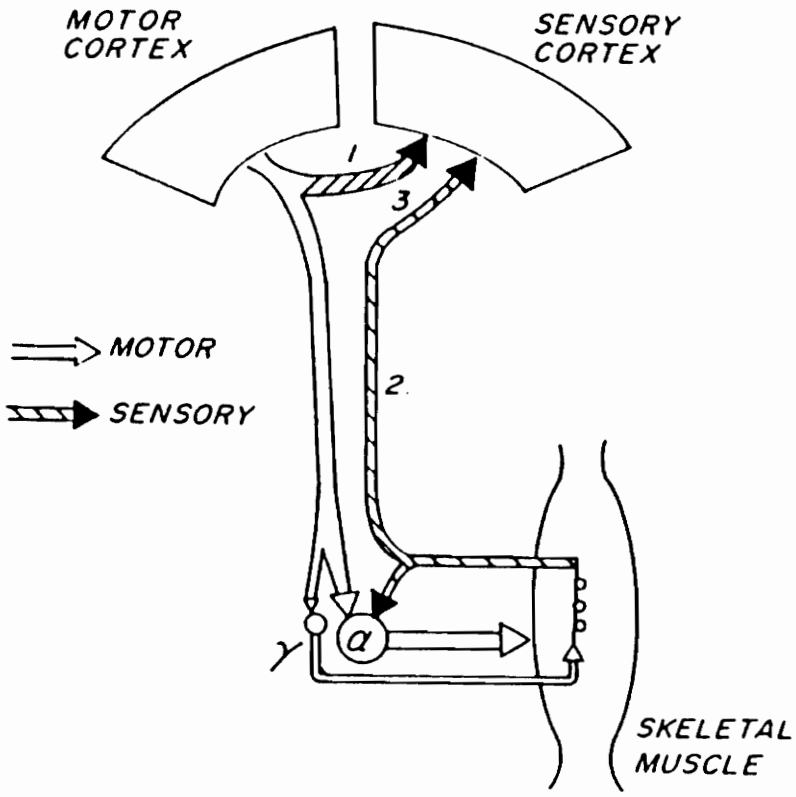
Cafarelli (1982) proposed that sensory responses to all forms of muscular exercise are a function of the neuromuscular system. He cited three mechanisms by which both static and dynamic, kinesthetic information is transmitted to the sensorium:

1. **Feedforward -** A copy of the efferent signal leaving the motor cortex is transmitted simultaneously to the sensory cortex.

2. **Feedback -** An afferent inflow from joint, tendon, and muscle receptors transmits contraction information to the sensory cortex.

3. **Feedforward + feedback -** The afferent inflow from the peripheral receptors is compared to a copy of the feedforward motor outflow. Any misalignment between the two signals initiates a correction in the movement.

The sensations of effort at the beginning of exercise are mediated entirely by local muscle feedback (Cafarelli, 1982; Robertson, 1982). Figure 2.4 depicts the mechanisms of the kinesthetic mediation of effort. Initially, these sensations are perceived as force, and are independent of frequency (Cafarelli, 1977). Central signals



1. Feedforward
2. Feedback
3. Feedforward + feedback

Figure 2.4 Mechanisms of the Neuromuscular Mediation of Effort (from Cafarelli, 1982).

to the effort sense begin a potentiating input approximately 30-180 s after the onset of exercise (Robertson, 1982).

2.4 Dominance of Local Versus Central Factors

A study by Michael and Hackett (1972) shed some skepticism on the relationship between central physiologic events and perceived exertion. Subjects were asked to equate subjective efforts by manipulating the workloads they felt would "tire" them in 15 minutes. The subjects performed this *magnitude production* task for both treadmill running and ergometer pedalling. Heart rate, $\dot{V}O_2$, and ventilation rate were all significantly lower for the bicycle work at equivalent RPE levels. The researchers concluded that these central variables were not good predictors of the perceived effort between the tasks.

Cafarelli (1977) examined peripheral and central inputs to the effort sense during bicycle ergometer work at various pedalling frequencies. His results indicated that pedalling at 30 rpm was perceived as more difficult than 60 rpm at the same work output. This result had been achieved in earlier studies, however, Cafarelli found that the central processes (heart rate, $\dot{V}O_2$) remained relatively constant at equivalent work outputs while the perceived exertion was greater at the slower pedalling rate. He concluded that the peripheral signals (from the leg exertion) were dominant in their contribution to the effort sense.

Cafarelli (1977) also proposed that during rhythmic exercise "the primary signal for effort relates to the force of contraction which, along with the rate of contraction, determine the metabolic demand. Thus, the central input appears to function as an amplifier that potentiates the peripheral signal in proportion to the metabolic demand

for oxygen" (p. 188). He also speculated that the more forceful contractions resulted in a greater sensation of effort as a result of blood flow impedance reducing the available substrate and the accumulation of metabolites in the working muscles. Cafarelli (1977) proposed a model of the relationship between rate and force of contraction which may drive the effort sense (see Figure 2.5).

Several investigators have proposed that the dominance of local or regional signals of perceived exertion is dependent upon the volume of muscle mass contributing to the activity (Cafarelli, 1977; Cafarelli and Noble, 1976; Ekblom and Goldbarg, 1971). Using integrated electromyography, Cafarelli (1977) measured muscle fiber activity during bicycle ergometer work. He concluded that the peripheral effort signal (leg rating) was not related to the amount of fiber activity per unit time, but to the amount of fiber activity per contraction. This supported the findings of Ekblom and Goldbarg (1971): the peripheral signals to the perception of exertion are related to the volume of muscle mass utilized per repetition (contraction) of the activity.

Much of the literature in support of either central or local signals as dominating perceived exertion ignores the relationship between the underlying physiological processes contributing to these sensations. Pandolf (1978), however, has suggested that RPE is not a function of a single physiological parameter, but of inputs from several "levels" of subjective reporting. Pandolf's model of perceived exertion consists of a perceptual integration of both psychological and physiological sensations (see Figure 2.6).

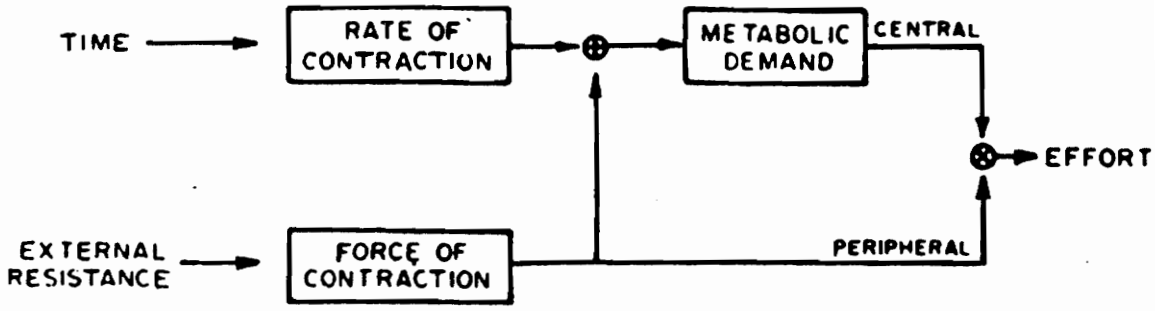


Figure 2.5 Model of Exertion Proposed by Cafarelli (1977).

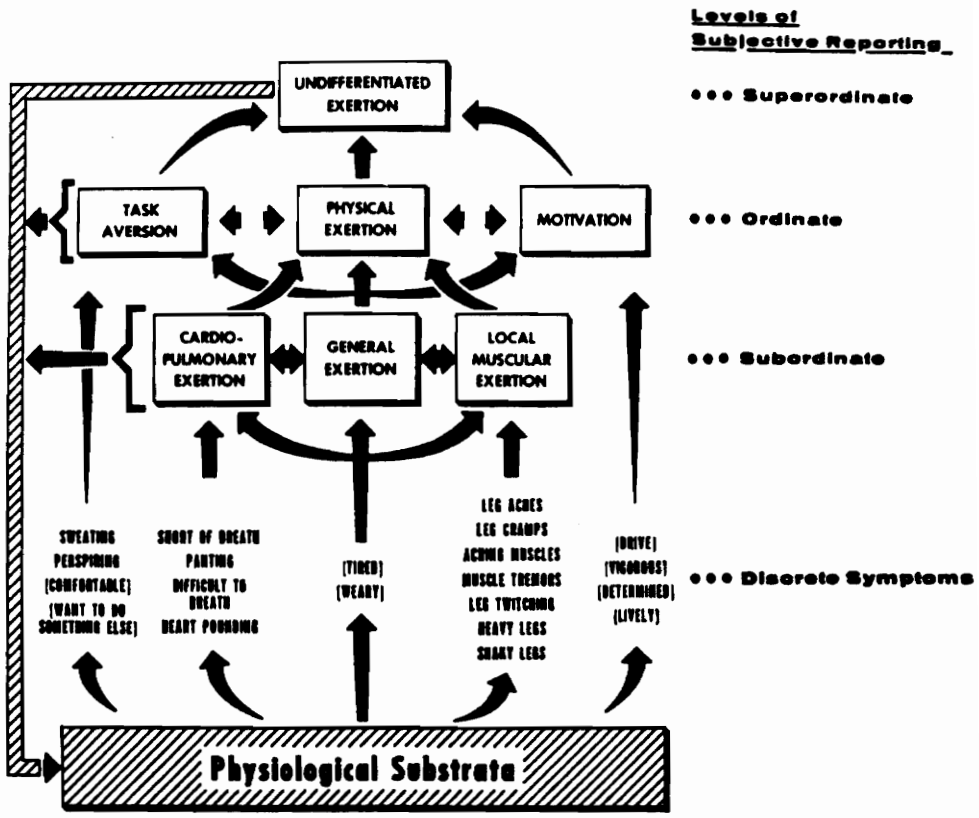


Figure 2.6 Hierarchical Model of Exertion Proposed by Pandolf (1978).

2.5 Interaction of Central and Local Factors

Relationships between central factors, local factors and subjective measures of exertion have been investigated and dominate much of the perceived exertion literature. Gamberale (1972) examined the relation between blood lactate concentration, $\dot{V}O_2$, heart rate, and RPE in three different work operations. She found that higher blood lactate concentrations as compared to $\dot{V}O_2$ were associated with higher RPEs as compared to heart rate. Lower blood lactate concentrations compared to $\dot{V}O_2$ yielded a lower RPE as compared to heart rate. Thus, Gamberale concluded that Borg's RPE scale had limitations in its relation between perceived exertion and heart rate, owing to the type of muscular activity and the oxygen demand involved. Higher blood lactate concentrations as compared to $\dot{V}O_2$ yielded a higher differentiated perceived exertion rating from the most involved "local" muscle groups as compared to the overall, undifferentiated RPE. When small muscle masses are anaerobically stressed and lactic acid concentrations rise, metabolic processes in the peripheral muscles may dominate the perception of effort relative to heart rate.

Most physiological variables (heart rate and $\dot{V}O_2$, for example) grow linearly with work load while perceived exertion grows as a positively accelerating, power function (Borg and Noble, 1974). Blood lactate concentration is one of the few physiological variables that follows a similar function, thus supporting the blood lactate-perceived exertion relationship (Borg and Noble, 1974). As blood lactate and heart rate are often poorly correlated, there is reason to believe that differences in the physical characteristics of work will yield differences in perceived exertion relative to heart rate (Borg and Noble, 1974).

Sargeant and Davies (1973) studied ergometer work with one leg, two legs, one arm, and two arms. Regression equations were developed for the four different limb

actions using RPE (x) to predict work load, minute ventilation, cardiac frequency, and oxygen intake (y). All of the relationships were reported as significant ($p<0.05$), however, when $\dot{V}O_2$ was standardized with respect to the maximum $\dot{V}O_2$, the correlation coefficients (r) were highest (.881-.964). They concluded that "in contrast to Borg's original conception of the RPE scale, the critical variable for relating RPE in the applied situation as an indicator of exercise stress is relative workload, i.e. $\dot{V}O_2$ expressed as a percentage of $\dot{V}O_{2max}$" (Sargeant and Davies, 1973, p. 9).

Henriksson, Knuttgen, and Bonde-Petersen (1972) examined concentric and eccentric muscle contractions relative to perceived exertion using the RPE scale. At the same exercise intensities, eccentric contractions were perceived as less strenuous than concentric contractions. However, the physiological responses ($\dot{V}O_2$, heart rate, cardiac output, pulmonary ventilation, and muscle blood flow) were even lower for the eccentric work relative to RPE. Thus, eccentric contractions are perceived as less exerting than concentric ones at a constant work load, but when perceived exertion is compared relative to heart rate or $\dot{V}O_2$, eccentric contractions are perceived as more exerting. Henriksson et al. (1972) hypothesized that a forced stretch on the lengthening muscle fibers results in an increase in Golgi Tendon activity, inhibiting motor neurons, causing the subject to initiate greater numbers of motor impulses to recruit the appropriate number of motor units .

Cafarelli and Noble (1976) suggested that the interplay between local and central factors is altered depending on whether the individual is working aerobically or anaerobically. This theory had also been proposed by Gamberale (1972) for arm activity resulting in a higher local RPE due to the anaerobic nature of lifting weights. Cafarelli and Noble (1976) also hypothesized that the central factors result from work with large muscle groups, which stress pulmonary ventilation and the circulation,

adding to the local sensations of strain. Thus, central processes may result in effort signals which add to the dominant local muscular sensations.

Robertson (1982) proposed a model of perceived exertion based on sensory inputs from local factors and two dominant central factors (relative aerobic demand and ventilatory stress). Perceived exertion was believed to be driven by local muscle movement sensations and a signal proportional to $\% \dot{V}O_{2max}$ at low to moderate intensities. As exercise intensity is increased above the lactate threshold, ventilatory discomfort is increasingly added to the sense of effort. However, Pandolf, Cafarelli, Noble, and Metz (1972) found that respiratory responses reached a plateau at approximately 69% $\dot{V}O_{2max}$ while RPE accelerated most rapidly at these stages. He concluded that RPE may be partially monitoring anaerobic metabolites at high work intensities.

The findings of Demello, Cureton, Boineau, and Singh (1987) supported Robertson's (1982) theory. They examined RPE at several relative aerobic intensities and at the lactate threshold (LT) (expressed as a $\% \dot{V}O_{2max}$) for trained distance runners and untrained subjects. These groups possessed significantly different LTs measured as a percentage of $\dot{V}O_{2max}$, however, both groups consistently gave an RPE rating between 12.9 and 13.6 to the intensity corresponding with the LT. These values did not significantly differ from a 13 ("somewhat hard"). This suggested that RPE at the lactate threshold (RPE_{LT}) is a constant (roughly 13), regardless of the relative oxygen consumption at this point. The authors also noted that RPE_{LT} was not affected by state of training, the LT merely occurred at a greater percentage of $\dot{V}O_{2max}$. They concluded that the lactate threshold marks a physiological "point" where a shift occurs in the physiological processes contributing to perceived exertion.

2.6 Theories on the Integration of Effort Sensations

Pandolf (1978) proposed a model of undifferentiated perceived exertion composed of a hierarchy of subjective assessments (see Figure 2.6). This model suggests that undifferentiated ratings represent a "superordinate" level of subjective reporting. This level is an integration of numerous sensory cues from an "ordinate" level composed of inputs from signals of physical exertion, motivation, and task aversion. The subjective reporting of physical exertion is integrated using cues from a "subordinate" level of assessment consisting of signals from cardiopulmonary exertion, local muscular exertion, and a "general" exertion. The underlying physiological substrata contributing to the subordinate level include processes of heart rate, oxygen consumption, blood lactate accumulation, etc.

Gamberale (1972) analyzed RPE in three exercises: pedalling a bicycle ergometer, pushing a wheelbarrow, and lifting weights with the arms. These activities encompass different working muscle groups: lifting of weights is predominantly arm work, the ergometer pedalling is mostly leg work, and wheelbarrow pushing utilizes both arms and legs (a whole body task). In the activities involving less muscle mass (e.g., lifting of weights, pedalling the ergometer) the localized perception of exertion (local RPE) was often at a higher level than the overall RPE value. In the whole-body, wheelbarrow pushing task the overall RPE ratings were greater than either of the local ratings for the arms or legs. This raises the question of how the overall, undifferentiated rating of perceived exertion is related to the differentiated signals which are believed to contribute to this rating.

Robertson et al. (1979a) examined the hierarchical model proposed by Pandolf (1978). In bicycle ergometry at various pedalling rates and workloads, local signals from the legs dominated the perception of exertion and in some instances

were rated higher than the overall, undifferentiated exertion, similar to the results of Gamberale (1972). Robertson et al. (1979a) suggested that this was due to the relatively small muscle mass utilized per unit external work. Central signals were reported as less intense in the cycling activity, possibly as a result of attentional focus on the localized leg discomfort, as suggested by Pandolf (1975).

Robertson et al. (1979a) hypothesized that a weighted average procedure was used in the process of integrating the differentiated perceived exertion ratings. The mean of the leg rating and the chest rating (local and central ratings, respectively) was in close agreement with the overall, undifferentiated rating. The coefficient of multiple correlation between the mean of the local and central ratings with the undifferentiated rating was higher than that of either differentiated rating alone. A critical consideration related to the process of integrating differentiated signals is presented in their study. The weighted average hypothesis relies on the assumption that all contributing differentiated exertion signals are included in the model. The researchers noted that 80 to 85 percent of the variance in the overall, undifferentiated rating was accounted for by the mean of the differentiated ratings for the legs and chest. From this result, they concluded that the legs and chest signals did represent a majority of the input to the undifferentiated rating.

In a later study, Robertson, Caspersen, Allison, Skrinar, Abbott, and Metz (1982) experimentally determined differentiation threshold (DT) speeds for regional and central effort sensations in women walking with weights. The DT was the walking speed at which the local and central signals were first perceived to be different from the overall sensation of exertion, indicating a dominant differentiated effort sensation (Robertson et al., 1982). The carried loads (expressed as a percentage of subject body weight) of 0%, 7.5%, and 15% yielded DT values of 6.44, 6.44, and 4.83 $km \cdot h^{-1}$ respectively. The local leg rating was dominant above the DT for all three walking

speed conditions. Below the DT, differentiated ratings of exertion were equal to that of the undifferentiated rating of exertion.

Robertson et al. (1982) found that the DT was unrelated to the absolute metabolic cost of carrying the external loads. In fact, the 15% load DT corresponded to a lower oxygen consumption than did the 0% and 7.5% loads. However, the DT values were noted to occur at approximately the same metabolic efficiencies (10.5 $ml \cdot m^{-1}$), that is, oxygen consumption normalized by walking speed.

2.7 Symmetric Lifting

As noted previously, the symmetric, mid-sagittal lifting task was chosen for the experiment for several reasons. It is repeatable, postures can be standardized, the floor-to-overhead lift can be decomposed into component lift motions, and the techniques are learned with little difficulty. The literature related to materials handling and manual lifting is overwhelming, and will not be thoroughly reviewed here. However, this literature was valuable in the selection of suitable work loads for the lifting task.

The NIOSH (1981) Work practices guide for manual lifting was written in an attempt to establish guidelines for the general tasks of manual lifting. Interestingly, an entire chapter of the guide was devoted to a "psychophysical approach" of establishing acceptable loads. The psychophysical approaches in the lifting capacity studies have typically involved the subject selecting an appropriate load which could be lifted for some specified duration, typically several hours. Variables such as frequency of lift, height, size, distance, etc. are controlled; the subject adjusts the load to meet his/her subjective criteria. This is essentially a magnitude production method. The NIOSH Guide considered four areas in establishing the lifting standards: epidemiology,

biomechanical concepts, physiological considerations, and psychophysical lifting limits (Chaffin and Andersson, 1991).

Snook (1978) and Ayoub, Bethea, Deivanayagam, Asfour, Bakken, Liles, Mital, and Sherif (1978) compiled tables of the maximum acceptable weight of lift for quartiles of the industrial population. The NIOSH (1981) guide contains a table of the maximum acceptable weights of lift generated from both the Snook (1978) and Ayoub et al. (1978) data. The values are listed for lifting frequencies of 1, 2, 4, 6, 8, and 12 lifts$\cdot$min^{-1}, horizontal distances of 20, 38, and 46 cm, the 25 and 50 female quartiles, and the 50 and 75 male quartiles. The NIOSH guide limits, in conjunction with pilot study results, were helpful in standardizing the experimental lifting task parameters.

Selecting work loads based on a percentage of individual maximum capability was proposed as a means of "normalizing" work loads among subjects. Kroemer (1983) presented a dynamic means of assessing individual lifting capability. This isoinertial method utilizes LIFTEST, a modified "gymnasium press station" and a protocol in which the subject is unaware of the results of each lift. LIFTEST was used in this study since the carriage rails constrained the lift motion to one degree of travel freedom. This was to aid in standardizing the postures assumed by the subjects.

2.8 Summary of the Pertinent Literature

The most pertinent results from the literature review are those comparing the active muscle mass to the dominance of local effort sensations. Activities which involve multiple discrete sources of exertion, e.g., wheelbarrow pushing, have resulted in a greater undifferentiated rating of perceived exertion than either regional or central ratings (Gamberale, 1972). This was not the case for activities which utilized more

isolated body segments and less active muscle mass, e.g., lifting weights (arms) and bicycle ergometer pedalling (legs). The mode of integrating differentiated regional and central signals to form an overall, undifferentiated rating of exertion appears to be dependent upon factors such as type of activity, intensity, and number of muscle groups used (Robertson et al., 1979a, 1979b). The relative aerobic versus anaerobic stress probably affects the synthesis of the undifferentiated rating. Recent research (Demello et al., 1987; Robertson, 1982) has shown that central signals of ventilation and relative $\dot{V}O_2$ are likely to be contributors to undifferentiated perceived exertion at higher exercise intensities. The lactate threshold may also mark a point where changes in physiologic function alter the sensory cues to undifferentiated perceived exertion.

The model proposed by Pandolf (1978) identifies factors contributing to undifferentiated perceived exertion, but fails to indicate the relative importance of these factors. Physiological processes are undoubtedly the driving force to the perception of exertion, however, "non-physiological" factors such as motivation and task aversion are also likely to contribute to the undifferentiated rating.

With regard to scaling methods and rating scales, the most prevalent scale for obtaining subjective assessments of perceived exertion has been RPE. RPE scaling facilitates direct inter-individual comparisons or comparisons with heart rate, which were not the emphasis of this project. The Borg, CR-10 scale allows for comparison of both relative, intra-individual intensities and absolute, inter-individual intensities which were desired in this project. The CR-10 scale is an absolute zero, ratio scale and has been validated by Borg (1982a) with respect to the psychophysical, power function and the generally accepted exponent of 1.6. Thus , the CR-10 scale was used in this study.

3. EXPERIMENTAL OBJECTIVE

3.1 Overview

The studies by Gamberale (1972), Robertson et al. (1979a, 1979b), and Robertson et al. (1982) have kindled the author's interest in exploring the integration of sensory cues forming the perception of physical effort. The additivity hypotheses resulted as a result of the findings of Robertson et al. (1979a). The goal of the study was to apply the weighted average concept to a more comprehensive physical activity (i.e., one involving more muscle groups) by attempting to mathematically model whole-body, undifferentiated perceived exertion.

The experiment involved two paradigms to test the additivity concept in the integration of whole-body, perceived exertion ratings for a repetitive, floor-to-overhead reach lifting task. Specifically, there were two inquiries:

1. **Body-Segment Additivity Paradigm -**

   Intra-task additivity of differentiated body-segment ratings.

   A body-segment additivity hypothesis was formulated to test the additivity of differentiated ratings of perceived exertion. The perceptual weightings of regional and central effort sensations were examined for their contribution to the whole-body, psychophysical perceived exertion rating in a floor-to-overhead reach lifting activity. The regional sensations included ratings from localized muscle activity in the arms, legs, and torso. The central effort sensation was the rating of perceived exertion stemming from the chest and respiratory system.

2. **Task Additivity Paradigm -**

<u>Inter-task additivity of whole-body ratings among component subtasks</u>.

A task-additivity hypothesis was formulated to test the additivity of whole-body ratings of perceived exertion among physically additive tasks. Whole-body perceived exertion ratings of component "subtasks" were examined for their contribution to the whole-body rating of perceived exertion for a floor-to-overhead reach lifting task. The floor-to-knuckle lift and knuckle-to-overhead reach lift subtasks are *physically* additive components of the floor-to-overhead reach lifting task. This paradigm was established to determine if the tasks were *perceptually* additive.

The body-segment additivity hypothesis (1) was tested and evaluated by establishing empirical models relating psychophysical ratings of differentiated perceived exertion to the undifferentiated, whole-body ratings. The task additivity paradigm (2) was tested and evaluated by establishing models relating the whole-body perceived exertion ratings of the component subtasks to the overall task, whole-body rating. Thus, the experiment investigated the means of integrating differentiated body segment ratings *within* a whole-body lifting task, and whole-body ratings *among* subtasks which combine additively in physical work output to that of a "larger" task.

These inquiries were pursued while examining the effect of lift posture on the additivity property. Stoop posture lifting was assumed to place more emphasis on the torso musculature, squat posture lifting on the leg musculature. Separate models were developed for the two posture conditions to qualitatively examine the differences between the predictive models.

Originally, separate models were to be developed for two levels of work load. The work load conditions were based on subjects' maximum single lift capability, so that a "normalization" of work load could be achieved. Perceived exertion ratings were obtained at 40% and 75% of subject's individual maximum single lift capability. However, after the preliminary analysis it was decided to include the two work load levels in a single model. This allowed for a greater dispersion of data points facilitating a better regression fit. Two observations by each subject were included in the same model.

3.2 Symmetric, Mid-Sagittal Lifting

The (symmetric, mid-sagittal) lifting task was chosen for this experiment for several reasons. Most importantly, the lifting task is divisible into component lifting motions, that is, a floor-to-overhead reach lift can be decomposed into subtasks of floor-to-knuckle and knuckle-to-overhead reach lifts. Secondly, the floor-to-overhead lift utilizes numerous muscle groups and was thus considered a whole-body exertion. Thirdly, the lifting task was assumed to be repeatable provided that postures, loads, frequencies, and durations were standardized. Guidelines (NIOSH, 1981; Snook, 1978) have been established for selecting these parameters to minimize injury potential. Finally, the lifting task was intuitive and required minimal explanation to subjects.

Data collection was targeted toward developing regression models to predict the overall, whole-body perceived exertion rating from the independent variables (component ratings of perceived exertion). A body-segment additivity model and a task additivity model were generated for both the stoop and squat posture conditions. Thus, four regression models were constructed.

A notation system is presented to simplify descriptions of the lifting trials and rating types (see Table 3.1). SQFO*arm* represents the squat, floor-to-overhead reach lift with a local, arm rating. Conversely, STKO*wb* represents the stoop, knuckle-to-overhead reach lift, with a whole-body rating. For simplicity sake, the lifting tasks will be hereafter referred to as floor-to-knuckle, knuckle-to-overhead, and floor-to-overhead lifting.

Floor-to-overhead lifting involves a whole-body exertion. Depending upon the initial posture of the lift (squat versus stoop), different muscle groups generate the majority of the propulsive forces. The floor-to-knuckle lift, from the squat posture, emphasizes the leg muscles; from the stoop posture, the torso muscles. Knuckle-to-overhead lifting is predominantly arm work. The knuckle-to-overhead, whole-body ratings were assumed identical for both the squat and stoop postures since this task was performed from a standing posture and was independent of the squat/stoop initial postures.

3.3 Psychophysical Quantification of Perceived Exertion

Psychophysical scaling was a critical consideration in this project. An underlying assumption of the additivity concept is that humans are capable of making at least interval judgments with respect to perceived exertion. To facilitate the desired regression analysis, either an interval or ratio scaling method was prerequisite in the rating protocol. While interval scale data is legitimately analyzed by regression analysis, it has shortcomings in making relative, intra-individual comparisons.

TABLE 3.1 Lifting Trial and Rating Notation

SQ - Squat		FK - floor-to-knuckle lift	
ST - Stoop		KO - knuckle-to-overhead lift	
		FO - floor-to-overhead lift	
leg	- leg rating		
torso	- torso rating		
arm	- arm rating	*wb*	- whole-body rating
central	- central rating		

That humans can make ratio judgments of perceived exertion has been supported by the work of Borg (1962, 1982a) and Stevens and Mack (1959). The Borg CR-10 scale was developed to model the positively accelerating growth of perceived exertion as a power function of work load which has been consistently reported in studies of perceived exertion. The ratio scale properties of the CR-10 scale would allow differentiated, regional ratings of perceived exertion to be made on a relative basis.

3.4 Body-Segment Additivity Paradigm

The body-segment additivity hypothesis assumes that a whole-body, undifferentiated perceived exertion rating can be mathematically modelled by the addition of weighted, differentiated ratings of the body regions which are stressed in the activity. This perceptual weighting strategy is hypothesized to be dependent upon the task parameter of lifting posture.

To test the body-segment additivity hypothesis, the floor-to-overhead lift was performed to obtain differentiated perceived exertion ratings for the arms, legs, torso, and central effort sensation. A whole-body rating was obtained in a separate trial. This paradigm would test for a consistent weighting of the differentiated signals in synthesizing the whole-body rating of perceived exertion. The null hypothesis is expressed as:

$$H_0: \quad SQFO_{wb} = a_1\, SQFO_{arm} + b_1\, SQFO_{leg} + c_1\, SQFO_{torso} + d_1\, SQFO_{central} + e_1$$

$$STFO_{wb} = a_2\, STFO_{arm} + b_2\, STFO_{leg} + c_2\, STFO_{torso} + d_2\, STFO_{central} + e_2$$

$$H_a: \quad SQFO_{wb} \neq a_1\, SQFO_{arm} + b_1\, SQFO_{leg} + c_1\, SQFO_{torso} + d_1\, SQFO_{central} + e_1$$

$$STFO_{wb} \neq a_2\, STFO_{arm} + b_2\, STFO_{leg} + c_2\, STFO_{torso} + d_2\, STFO_{central} + e_2$$

The a, b, c and d are coefficients which would be determined by regression modelling in the data analysis. They represent the perceptual weightings of the differentiated signals by which the undifferentiated, whole-body rating is assimilated.

3.5 Task Additivity Paradigm

The floor-to-knuckle and the knuckle-to-overhead lifts are additive in vertical travel distance and external work, equivalent to the floor-to-overhead lift. The floor-to-knuckle lift, performed from either a squat or stoop posture, is the first component lifting task; the knuckle-to-overhead lift, from a standing posture, is the second. The floor-to-overhead travel distance is equal to the sum of these component lift travel distances. The total external work of the component lifts is also equivalent to that of the floor-to-overhead lift, assuming that the lifting accelerations are constant. Since the floor-to-knuckle and knuckle-to-overhead lifts are *physically* additive it was hypothesized that they might also be *perceptually* additive.

This paradigm would test for an additive relation between the subtask, whole-body ratings of perceived exertion and the floor-to-overhead lifting task, whole-body rating. The null hypothesis, for both stoop and squat initial postures, is expressed as:

$$H_o: \quad SQFO_{wb} = f_1\, SQFK_{wb} + g_1\, SQKO_{wb} + h_1$$

$$STFO_{wb} = f_2\, STFK_{wb} + g_2\, STKO_{wb} + h_2$$

$$H_a: \quad SQFO_{wb} \neq f_1\, SQFK_{wb} + g_1\, SQKO_{wb} + h_1$$

$$STFO_{wb} \neq f_2\, STFK_{wb} + g_2\, STKO_{wb} + h_2$$

The f and g are regression coefficients which represent the perceptual weightings of each component lifting task.

3.6 Heart Rate Observations

Heart rate was recorded during all trials as an objective, physiological measure of exertion. Correlation coefficients of heart rate with both the central effort rating and the whole-body rating were expected to reveal that the central effort rating was more indicative of circulatory strain than was the undifferentiated rating of exertion. Heart rate was also expected to be more related to the central, differentiated rating than any of the local ratings. In addition, heart rate is a conveniently measured physiological process to provide a physical measure of task strain (Kroemer, Kroemer, and Kroemer-Elbert, 1990). Every subject worked at the same relative work load (i.e., percentage of individual maximum single lift capability), thus, heart rates could be examined across subjects and compared with the perceived exertion ratings.

4. METHOD

This chapter describes the procedures and methods of data collection. The experimental sessions were conducted in the Industrial Ergonomics Laboratory at Virginia Tech, March 13 - 30, 1993.

4.1 Experimental Apparatus

The experimental apparatus consisted of LIFTEST, an IBM PC/2 for timing trial length and signalling the frequency of lift, and a Polar CIC Heart Watch™ transmitting heart rate monitor. The heart rate monitor consisted of a chest strap sensor with built-in electrodes, an attachable transmitting device, and a wrist watch display. The watch display was clipped on the belt behind the subject's body, to be out of his view. The experimenter could easily monitor the heart rate by standing behind the subject.

LIFTEST is a modified gymnasium "press station" which had been utilized by Kroemer (1983) in assessing individual lifting capability (see Figure 4.1). The machine consists of a carriage which runs along vertical guide rails. The experimenter could add (or subtract) weight to the carriage in 2.3 kg increments. The weight stack was concealed by a sight shield so that subjects had no visual cues of the carriage weight they were to lift. To perform a single lift, subjects grasped the handles of the carriage and lifted the unit between the designated origin and endpoint, dependent upon the particular trial. The handles were lowered in a similar, controlled manner to complete the repetition. The handles have a wide grasping area, so that subjects of all statures had no difficulty in maintaining a comfortable grip.

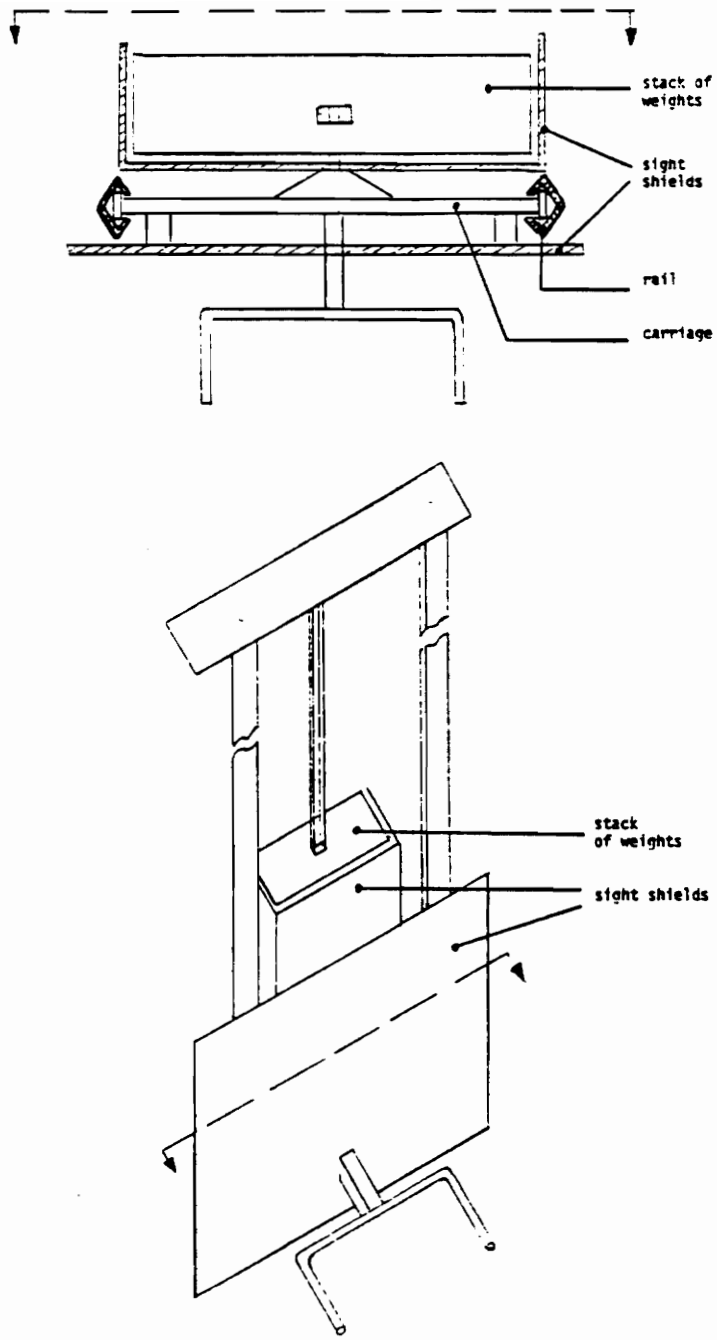


Figure 4.1 LIFTEST Schematic Diagram.

Graphic media were used to aid subjects in the rating protocol. An anatomical chart ("body diagram") with delineated regions of arm, leg, torso, and chest/respiratory system assisted the subjects in conceptualizing the anatomical framework and boundaries of the body-segments for which ratings were required (see Figure 4.2). A Borg CR-10 rating scale was posted on the wall of the testing area for easy reference.

4.2 Subjects

The experimental design utilized 16 male subjects between the ages of 18 and 29 years with the following characteristics (mean ± s.d.): age (21.93 ± 2.43 years), height (179.0 ± 7.67 cm), and weight (77.31 ± 9.94 kg). The nature of fitting the heart monitor chest strap sensor limited the subject pool to males. Subjects were recruited from the university population without regard to physical fitness level or anthropometry. A necessary requirement for all subjects was a history of good physical health. All subjects were screened in the informed consent phase for any known heart conditions, back problems, or other musculoskeletal dysfunctions (see Appendix A). Subjects were paid the standard rate of $5.00 per hour. Subjects were requested to refrain from vigorous physical activity on the days of the experimental sessions. Approval from the Institutional Review Board of Virginia Tech was obtained for all experimental procedures.

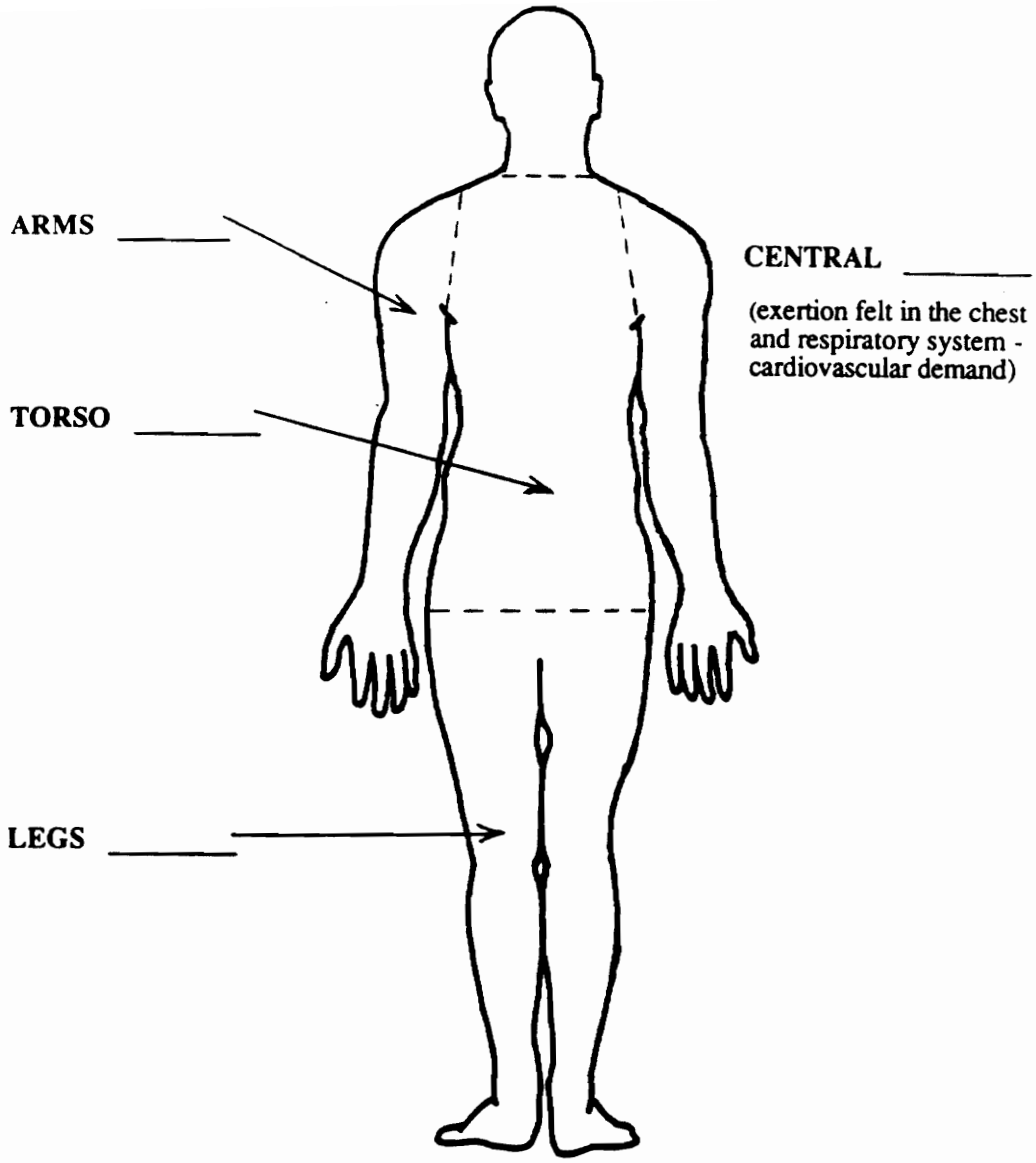


Figure 4.2 Body-Segment Diagram.

4.3 Experimental Design

4.3.1 Experimental Tasks

Eight, repetitive, symmetric, mid-sagittal lifting tasks were performed by each subject in the experiment. The perceived exertion rating data collected in these tasks were used to construct the task additivity and body-segment additivity models. The tasks (listed in Table 4.1) are classified by the required ratings, either whole-body or differentiated (i.e., arm, leg, torso, central). Only the floor-to-overhead lifting task involved differentiated ratings.

The knuckle-to-overhead lift is independent of the squat and stoop initial posture, thus the same rating was used in both models. (The notation SQKO or STKO is used in the model for consistency sake, even though the SQ and ST initial postures are meaningless for this task.)

4.3.2 Experimental Variables

For experimental design purposes the following variables were considered:

<u>Lifting Task</u> (floor-to-overhead*wb*, floor-to-overhead*diff*, knuckle-to-overhead, floor-to-knuckle height)

<u>Initial Posture</u> (squat, stoop)

<u>Work Load</u> (40% of maximum single lift, 75 % of maximum single lift).

TABLE 4.1 Experimental Tasks, Nomenclature

Squat Initial Posture

SQFK *wb* - Squat, Floor-to-Knuckle height (whole-body)
SQFO *a,l,t,c* - Squat, Floor-to-Overhead (arm,leg,torso,central)
SQFO *wb* - Squat, Floor-to-Overhead (whole-body)

Stoop Initial Posture

STFK *wb* - Stoop, Floor-to-Knuckle height (whole-body)
STFO *a,l,t,c* - Stoop, Floor-to-Overhead (arm,leg,torso,central)
STFO *wb* - Stoop, Floor-to-Overhead (whole-body)

Standing Initial Posture

SQKO *wb* - Knuckle height-to-Overhead (whole-body)
STKO *wb* - Knuckle height-to-Overhead (whole-body)

The experiment was a mixed-factor design. Initial posture was considered a between-subjects variable, work load a within-subjects variable.

Heart rate was recorded in all trials to provide a physiological measure of exertion. Heart rate is an easily monitored physiological process which served as an objective measure of physical stress. The high correlation between heart rate and undifferentiated RPE has been well established in the literature, however, the correlation between differentiated perceived exertion ratings (CR-10 scale) and heart rate has not been reported.

4.3.2.1 Lifting Task

The lifting task condition had four categories: floor-to-overhead (whole-body rating), floor-to-overhead (differentiated ratings), floor-to-knuckle, and knuckle-to-overhead. The floor-to-knuckle and knuckle-to-overhead lifts are physically additive components of the floor-to-overhead lift. Each subject performed two sets of these four lifts, at loads of 40% and 75% of their individual maximum single lift capability. The floor-to-overhead lift was performed twice at each work load to obtain a whole-body perceived exertion rating and differentiated ratings.

4.3.2.2 Initial Posture

The initial posture variable was divided equally among subjects; half performed the lifting tasks from a squat posture, half from a stoop posture. The motivation for examining lifts originating from both the squat and stoop postures was to compare the

effect of initial lifting posture on the perceptual weightings of the perceived exertion ratings between activities emphasizing different muscle groups. It was believed that confusion would be spared by instructing subjects in using only one of the two initial postures. Stoop lifts were assumed to place more strain on the torso, specifically the low back musculature. Squat lifts were assumed to emphasize the leg extensors, namely vastus lateralis, vastus medialis, and gluteus maximus. The differentiated ratings were expected to reflect the differences in muscular activity between the two postures.

Subjects were given a demonstration and description of the lifting postures. The experimental instructions (see Appendix C) included a verbal description of the posture. The explanation of the stoop posture emphasized that the knees be kept straight and that the bending be from the hip. The squat posture explanation emphasized that the back be kept straight and that the body be lowered by bending the knees. The experimenter physically demonstrated the postures in the first session before the first trial.

4.3.2.3 Work Load

Each lifting task was examined at two work load conditions, 40% and 75% of the subject's maximum single lift capability. These conditions were originally chosen to examine the effect of work load on the perceptual contribution of the differentiated ratings to the undifferentiated, whole-body rating and the effect of work load on the weightings of the component lifting tasks to the floor-to-overhead lifting task. Two work load levels were selected to simplify the data collection. All subjects performed the four lifting tasks at both work load levels. Subjects' perceived exertion ratings were expected to be similar at a given work load as these loads were expressed relative to

each subject's individually-tested maximum single lift capability. The procedure for obtaining subjects' maximum single lift capability is described in section 4.4.1. Having performed the initial data analysis, the work load levels were combined in a single model for each posture condition to obtain a greater dispersion of the data points.

The frequency of lifting and task duration were held constant in all trials. The frequency of lifting was 6 min^{-1}, as established in the pilot study phase. The task duration was held constant at six minutes for all trials. The *absolute* work loads were thus determined by the subjects' maximum single lift capabilities. However, *relative* workloads were identical among subjects, assuming that the maximum loads accurately reflected true maximum capabilities.

4.3.3 Perceived Exertion Ratings

The floor-to-overhead lifting task was performed four times by each subject so that whole-body, undifferentiated ratings, and differentiated ratings were obtained at both work load levels. The differentiated ratings for the arms, legs, torso, and central effort sensations were obtained in a separate trial from the whole-body rating. Subjects were explicitly instructed on the procedure for assessing and reporting the differentiated ratings stemming from these sensations.

Robertson has developed a protocol for obtaining a central effort sensation rating in differentiated perceived exertion studies (personal communication, November, 1992). Robertson reported that subjects have given repeatable and reliable ratings for the central effort sensation when the instructions emphasized "respiratory feelings from the chest". He said that his subjects had no difficulty interpreting the meaning of this explanation. Robertson et al. (1982) discussed the advantage of regionalizing the

central effort sensation to the chest, so that subjects are provided with an anatomical framework to evaluate this signal. In this study, however, the central effort sensation was described as "respiratory feelings form the chest *apart from any sense of strain in the working muscles* ". The accuracy of this description in terms of the physiological processes was less important than clarity and simplicity of the semantic description to the subjects. Subjects reported no difficulties in conceptualizing and rating the central effort sensation.

4.3.4 Presentation Order

Sixteen subjects were randomly assigned to the two initial posture conditions to achieve balanced Latin Squares for the treatment order within each posture condition. "Treatments" are the eight experimental trials which were performed by each subject. The Latin Square is shown only once (see Table 4.2), however, it is identical for both the squat and stoop postures. This design is advantageous because the treatment conditions are ordered systematically across subjects, that is, each task is performed first once, second once, third once, and so on. Any systematic effect associated with the presentation order can be evaluated. Randomizing the treatment presentation orders would not allow for this evaluation.

TABLE 4.2 Latin Square Presentation Order (Squat and Stoop Postures)

Treatment	Subject 1	2	3	4	5	6	7	8
1	1	2	3	4	5	6	7	8
2	2	3	4	5	6	7	8	1
3	8	1	2	3	4	5	6	7
4	3	4	5	6	7	8	1	2
5	7	8	1	2	3	4	5	6
6	4	5	6	7	8	1	2	3
7	6	7	8	1	2	3	4	5
8	5	6	7	8	1	2	3	4

Key

1 - FO wb, 40%
2 - KO wb, 40%
3 - FO diff, 40%
4 - FK wb, 75%
5 - FO wb, 75%
6 - KO wb, 75%
7 - FO diff, 75%
8 - FK wb, 40%

4.4 Experimental Procedure

4.4.1 Maximum Single Lift Capability Determination

A preliminary lifting test was administered to determine the maximum single lift capability of each subject. This test procedure, described by Kroemer (1983), was given in the first session, after subjects had given their informed consent:

> "The subject grasps both handles, located about 5 cm from the floor, and lifts them to overhead reach height then guides the handles down. Each subject starts with an initial weight of 11.4 kg to become familiar with the test equipment and procedure. The next test is with 22.7 kg. If this weight is lifted, 34 kg is attempted. If successful, another 11.4 kg increment of weight is added until the cut-off limit is achieved. If an attempt fails, the weight is reduced by 6.8 kg. If this test weight is lifted, 4.5 kg is added; if not, 2.3 kg is subtracted. This scheme of adding 11.4 kg, subtracting 6.8 kg, and adding 4.5 or subtracting 2.3 kg results in a quick determination of the weight that a subject can lift" (p. 499).

A cut-off load of 45.5 kg was proposed by Kroemer (1983), based on recommendations by Chaffin (1981), McDaniel (1981), and Snook (1978). To avoid overexertion risks, this limit was established as an upper bound for the 100% maximal single lift capability for subjects who were capable of exceeding the 45.5 kg floor-to-overhead load. However, no subject achieved a maximum single lift exceeding 43.15 kg.

The instructions for the maximum single lift determination procedure were recorded on audio tape so that subjects received identical voice inflections and verbal

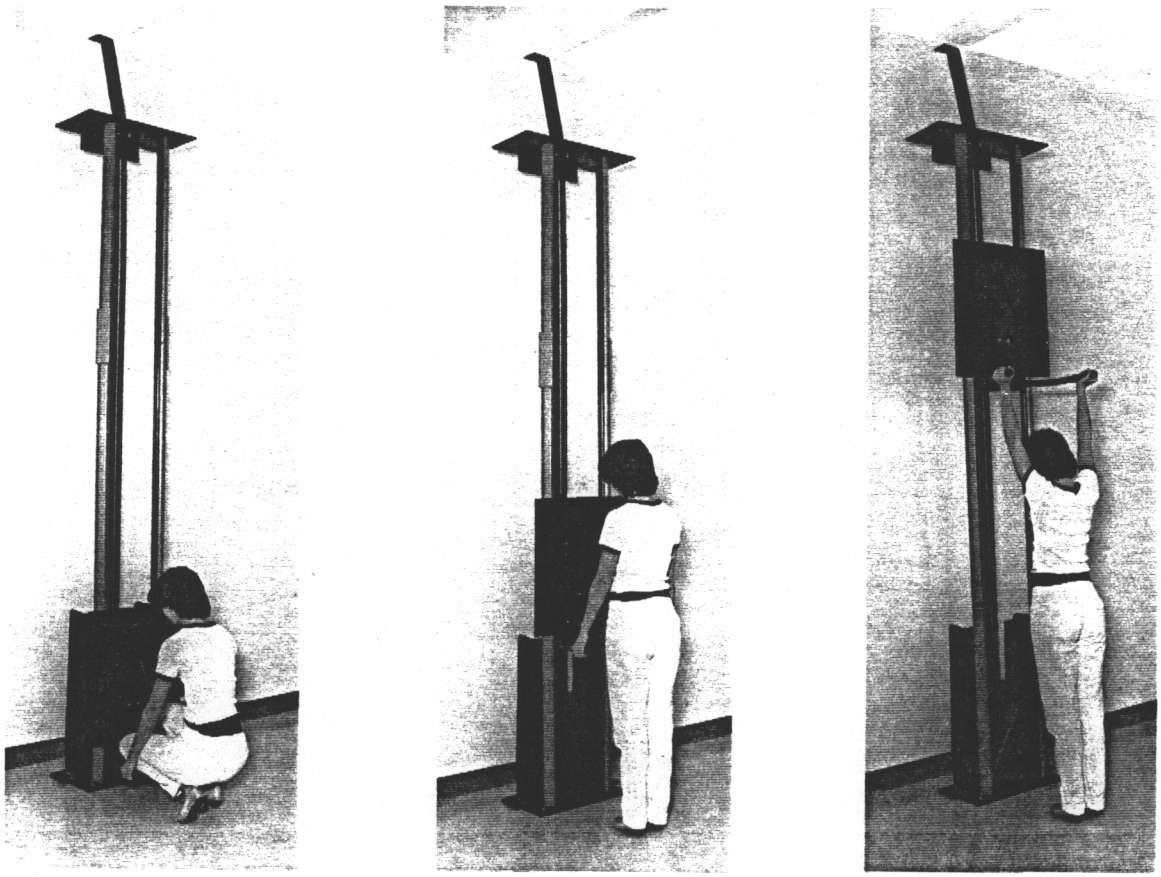
cues. The instructions (see Appendix E) emphasized that all lifts be performed in a continuous motion and with a safe effort.

4.4.2 Whole-Body Rating Trials

Each trial was performed for six (6) minutes duration. An IBM PS/2 was programmed to emit a 4000 Hz tone every ten seconds to signal the lifting cadence. Thus, 36 lift repetitions were performed in each trial. Subjects were instructed to perform a lift at each signal by raising the handles from the lift origin to the endpoint, and lowering the handles to the origin. Figure 4.3 illustrates the three lift endpoints, i.e., floor, knuckle height, and overhead reach. The floor-to-knuckle lift occurs between photos a and b, the knuckle-to-overhead lift occurs between photos b and c, and the floor-to-overhead lift occurs between a and c. LIFTEST was adjusted so that the handles rested at floor level (approximately 8 cm from the floor), or at the subject's standing knuckle height (Figure 4.3, photos a and b, respectively).

The muscular activity in lowering the load is variable, depending upon how each subject resists the inertia of the descending load. For this reason subjects were instructed to lower the load in a "controlled manner", similar to the controlled motion of the lift. Variability in the lowering muscular activity was assumed to be reduced if subjects were providing a similar resistance to the descending load.

The instructions accompanying the CR-10 rating scale are critical to obtaining the ratio results which the scale has been claimed to exhibit. Instructions for the CR-10 scale, obtained from Dr. Gunnar Borg, were appropriately modified for this experiment (see Appendix B). The instructions emphasized several important points: the word descriptions should be examined first, followed by the numeric values, fractional



a b c

Figure 4.3 Lifting Procedure Illustrated.

ratings were acceptable, there was no upper bound to the scale, and that there were no "right" or "wrong" answers. Subjects read the rating scale instructions at the beginning of each experimental session.

Instructions for performing the whole-body lifting task trial were read aloud by the experimenter before the trial began. At the conclusion of the six-minute trial the subject was reminded of the rating technique, "look at the word descriptors first, then choose a suitable number", and referred to the CR-10 rating scale posted on the wall. The subject then provided a rating of whole-body perceived exertion. This rating was recorded with the heart rate datum which was noted at the cessation of the trial.

4.4.3 Differentiated Rating Trials

The differentiated rating trial instructions are documented in Appendix D. These trials were the floor-to-overhead reach tasks at the 40% and 75% load conditions. The differentiated rating trials were conducted similarly to the whole-body rating trials; only the rating procedure differed. Since four ratings were required, written responses were believed to be more appropriate. Subjects typically pondered for several seconds before deciding on appropriate ratings. Short term memory constraints were avoided by having subjects write the ratings on the same "body diagram" used to orient them to the anatomical regions. This diagram delineated the body regions of arms, legs, and torso, and described the central effort sensation which also contained space for a written response (see Figure 4.1). Subjects were instructed to give a CR-10 scale rating for each of these differentiated sensations.

4.5 Experimental Protocol

Each experimental session followed the format depicted in the timeline of Figure 4.4. Two subjects, denoted by A and B in the figure, alternated in performing two trials (trials 1 and 2). Sessions in which only one subject could be scheduled incorporated a timed break between trials by the lone subject. The sessions began with a time period labeled "Introduction" which was allocated for the pre-data collection activities. Subjects' informed consent and maximum single lift capabilities were obtained in this period of the first session; instructions were read during this period in all sessions. After the introductory time period, data collection proceeded with "subject A" performing trial one.

The format of Figure 4.4 was determined to be the most efficient means of utilizing subject time in data collection. This schedule minimized "idle time" by requiring only one rest interval per subject in each session. Four experimental sessions were required by each subject to complete the eight experimental trials. The first sessions were approximately 60 minutes in duration; the second, third, and fourth were approximately 45 minutes.

The first experimental session began with subjects receiving a description of the experiment and screening for any possible health problems. Subjects were then asked to read and sign the informed consent form (see Appendix A). After informed consent was obtained, subjects were given detailed instructions on performing the experimental tasks, the Borg CR-10 rating scale, and written instructions for using the scale in the tasks (see Appendix B).

Upon completion of this introductory phase, one of the two subjects left the testing area and the maximum single lift capability test was conducted, as described in section 4.4.1, for the remaining subject. Both subjects were tested in this manner, with

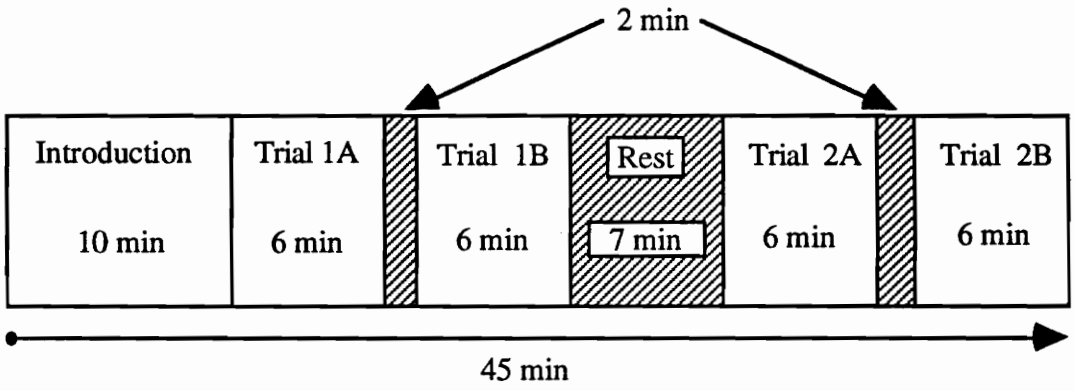


Figure 4.4 Experimental Session Timeline.

only the subject and experimenter present in the testing area. The experimental trials began after the maximum single lift capability tests were completed.

Sessions two, three, and four were conducted similarly to the first session. The introductory phase of these sessions included a brief review of the experimental and rating scale instructions. The two subjects performed two trials in alternating fashion, as shown in Figure 4.4. Both subjects departed the testing room while the LIFTEST machine was adjusted for "subject A". This subject was called into the room and rebriefed on the experimental instructions. The heart rate monitor was applied to the subject at this point, after which the subject performed the trial as described in sections 4.4.2 and 4.4.3.

After completing the trial the subject was read the post-task portion of the instructions and asked for the appropriate rating(s). The subject provided a single, verbal response for the whole-body rating trials. Differentiated rating trials required written ratings on the body diagram delineating the regions of arms, legs, torso, and chest/central effort sensation. After providing the required rating(s) the heart rate monitor was removed and subject A was excused from the testing room while the experimenter recorded the trial data and adjusted the LIFTEST machine for "subject B".

Once the machine had been adjusted the experimenter called subject B into the testing room and the procedure was repeated. This cycle was repeated for the four trials within each session. After completing a trial, each subject had approximately 15-minutes rest, which was believed to be sufficient to allow adequate recovery from the prior task. The rest period was equal to the six-minute trial of the other subject, plus the inter-trial break (approximately two minutes), plus approximately seven-minutes rest for both subjects (see Figure 4.4). The sessions in which only one subject was scheduled required the experimenter to time the rest period so that it was equivalent to those of the sessions with two subjects.

4.6 Motivation Control

Several controls were adopted in an attempt to minimize motivation differences between subjects. The informed consent form emphasized that subjects work at a maximum safe effort. Subjects were encouraged to lift with the assigned load as long as the six-minute trial was demanding, but not to the point of exhaustion or musculoskeletal pain. Subjects were reminded that they were in control of this maximum safe effort at all times and should notify the experimenter if the task became exceedingly demanding.

The results of the maximum single lift capability test were not made available to subjects during the experiment. In addition, subjects were not informed of any load they were lifting or its percentage value of the maximum single lift. Subjects were informed that all loads were based on a percentage of their maximum single lift capability and within safe limits based on manual materials handling and lifting standards. This information was revealed after all data collection for the project had been completed.

The experimenter emphasized that subjects should consciously monitor the sensations in each of the body regions of interest during the particular trial. Differentiated rating trials emphasized monitoring sensations stemming from the arms, legs, torso, and chest/respiratory system. Whole-body rating trials emphasized monitoring the sensation of overall effort. This may have given subjects something to focus their attention on, perhaps reducing the monotony of the task.

The experimenter refrained from verbally "urging on" the subject unless he was unable to maintain the required frequency of lift. In three cases, all knuckle-to-overhead, 75% work load trials, subjects were unable to complete the six minute trial. As the muscular performance visually deteriorated the experimenter intervened by

requesting that the subject complete as many repetitions as possible. Complete muscle fatigue was evident in these cases. The perceived exertion rating and heart rate datum were recorded at the time of complete muscular exhaustion and trial termination .

The difficulty of obtaining a true maximum lift capability can result from differences in subject motivation during the test. The instructions for the maximum single lift capability determination procedure were recorded so that subjects heard identical voice inflections and other verbal cues (see Appendix E). The instructions emphasized that the lift motion be continuous and within a safe effort, as determined by the subject. By eliminating the opportunity for subjects to pause during the lift, time for motivation increases during the lift were reduced. It was assumed that highly motivated subjects would have less time to "psyche themselves up" using this protocol.

Despite these attempts to control motivation, subjects may not have given identical maximum, safe efforts relative to their true capabilities. Therefore, the relative work loads based on these results may not have been equivalent among subjects.

5. RESULTS

This chapter presents the experimental results and regression models which were constructed for the task additivity and body-segment additivity paradigms. The task additivity models express the floor-to-overhead lifting task, whole-body rating as a function of the floor-to-knuckle and knuckle-to-overhead lifting task, whole-body ratings. The body-segment additivity models express the floor-to-overhead, whole-body rating as a function of the differentiated ratings from the arms, legs, torso, and central effort. Models were constructed for the stoop and squat posture conditions in both the task additivity and body-segment additivity paradigms.

The regression modelling and statistical analyses were generated using SUPERANOVA™ and MINITAB™ statistical software packages licensed to the Industrial Ergonomics laboratory at Virginia Tech. The regression models examined only main effects. Tables 5.1 through 5.4 document the results of statistical analyses on the regression models. The equation numbers appearing by the models in the text correspond to the table number containing the statistical results for that model. A p-value of 0.05 is the criterion for statistical significance. Figures 5.1 through 5.4 show the floor-to-overhead lifting task, whole-body ratings plotted versus the values predicted by the models (fitted values). The raw experimental data is included in Appendix F. Appendix G contains plots of all independent variables versus the floor-to-overhead whole-body ratings (dependent variables). Tables G.1 through G.6 correspond to the stoop posture condition ratings, Tables G.7 through G.12 correspond to the squat posture condition ratings.

5.1 Task Additivity Paradigm

5.1.1 Stoop Posture

The task additivity, stoop posture regression model is:

$$STFO\mathit{wb} = 1.723 + 0.436KO\mathit{wb} \qquad (5.1)$$

$r^2 = 0.562.$

Inclusion of the floor-to-knuckle (FK*wb*) rating in the model resulted in a small improvement in r^2 (increase to 0.580). The FK*wb* rating was thus removed from the model. The correlation between the FK*wb* and floor-to-overhead (FO*wb*) ratings was r^2=0.113, between the knuckle-to-overhead (KO*wb*) and FO*wb* rating was r^2=0.562. This indicates that the KO component accounts for the majority of the variance in the FO lifting whole-body perceived exertion rating. Table 5.1 shows the results of the statistical tests on this model. Figure 5.1 shows a plot of the FO*wb* ratings versus the values predicted by the model (fitted values).

5.1.2 Squat Posture

The task additivity, squat posture model is:

$$SQFO\mathit{wb} = 0.118 + 0.615FK\mathit{wb} + 0.389KO\mathit{wb} \qquad (5.2)$$

$r^2 = 0.693.$

The correlations of the FK and KO whole-body ratings (independent variables) with the FO rating (dependent variable) were similar ($r^2_{FO \cdot FK}$=0.403, $r^2_{FO \cdot KO}$=0.465) indicating that both of the component lifting motions contribute to the FO whole-body rating variance. Table 5.2 shows the results of the statistical tests on this model. Figure 5.2 shows a plot of the FOwb ratings versus the values predicted by the model (fitted values).

5.1.3 Analysis of the Task Additivity Regression Models

Tables 5.1 and 5.2 summarize the results of the F-tests for regression relation and t-tests on the regression coefficients for the task additivity models. The F-test for regression relation tests the relation between the floor-to-overhead, whole-body rating and the independent variables (floor-to-knuckle rating, knuckle-to-overhead rating). The null hypothesis is:

$$H_o: \beta_1 = \beta_2 = \beta_3 = \ldots = \beta_k = 0$$

$$H_a: \text{not all } \beta_k \ (k = 1,2,\ldots,k) = 0.$$

The t-test on the regression coefficients tests whether the individual coefficients are significantly different from zero. A non-zero coefficient indicates that the regressor variable has a predictable effect on the floor-to-overhead rating.

The statistical summary tables (Tables 5.1 and 5.2) reveal that both the stoop and squat posture models resulted in a significant regression relation at the 0.05 level of significance. That is, all of the models exhibited a regression relation (not all

TABLE 5.1 Statistical Summary of Task Additivity Model - Stoop Posture

STFOwb = 1.723 + 0.436KOwb

Model Summary

Count	16
R	.749
R-Squared	.562
Adj. R-Squared	.530

	df	Sum of Squares	Mean Square	F-Value	P-Value
Model	1	22.579	22.579	17.933	.0008
Error	14	17.628	1.259		
Total	15	40.207			

Model Coefficient Table

	Beta	Std. Error	t-Test	P-Value
Intercept	1.723	.618	2.790	.0145
KOwb	.436	.103	4.235	.0008

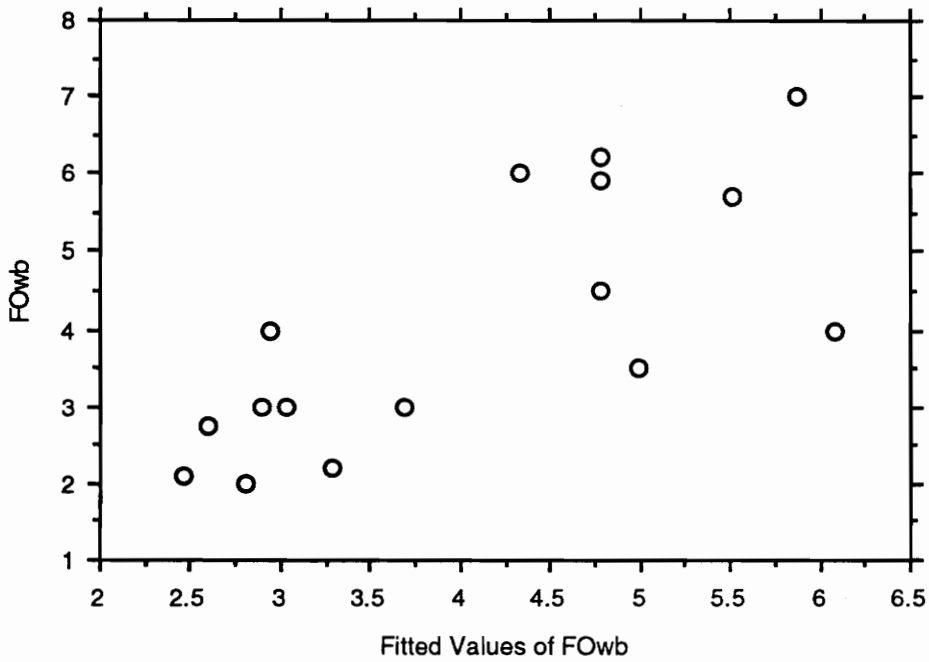


Figure 5.1 Plot of FO*wb* Ratings Versus Fitted Values - Task Additivity Model, Stoop Posture.

TABLE 5.2 Statistical Summary of Task Additivity Model - Squat Posture

SQFOwb = 0.118 + 0.615FKwb + 0.389KOwb

Model Summary

Count	16
R	.832
R-Squared	.693
Adj. R-Squared	.646

	df	Sum of Squares	Mean Square	F-Value	P-Value
Model	2	46.194	23.097	14.671	.0005
Error	13	20.466	1.574		
Total	15	66.660			

Model Coefficient Table

	Beta	Std. Error	t-Test	P-Value
Intercept	.118	.891	.133	.8966
FKwb	.615	.198	3.106	.0083
KOwb	.389	.111	3.506	.0039

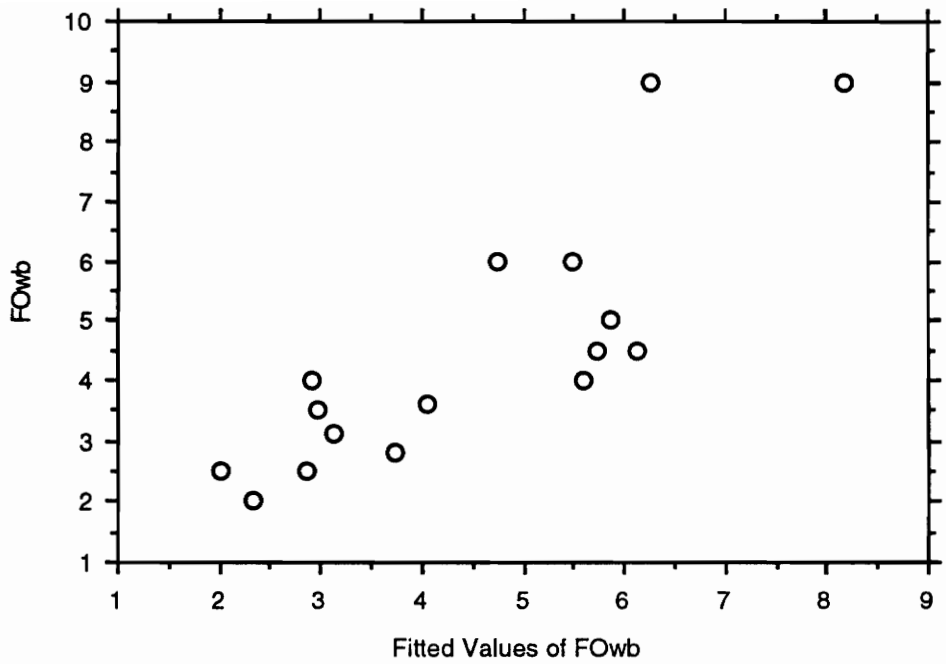


Figure 5.2 Plot of FO*wb* Ratings Versus Fitted Values - Task Additivity Model, Squat Posture.

coefficients equal zero). The t-test on the individual coefficients indicated that all of the non-intercept coefficients were significantly different from zero at $p<0.05$.

Table 5.5 shows the coefficients of simple determination ($r^2_{y \cdot x}$) between all independent variables and the floor-to-overhead, whole-body rating. The coefficients of determination ($r^2_{x \cdot x}$) are the correlations associated with all pairwise comparisons of the independent variables. The r^2 statistics measure the proportion of variation in one variable which is "explained" by the other (Neter, Wasserman, and Kutner, 1989). However, this relationship is not necessarily a causal one.

The stoop posture model exhibits a higher correlation between the knuckle-to-overhead and the floor-to-overhead ratings ($r^2_{FO \cdot KO} = 0.562$) than between the floor-to-knuckle and floor-to-overhead ratings ($r^2_{FO \cdot FK} = 0.113$). The squat posture model shows similar correlations between both of the independent variables and the FO*wb* rating ($r^2_{FO \cdot FK} = 0.403$, $r^2_{FO \cdot KO} = 0.465$).

5.2 Body-Segment Additivity Paradigm

5.2.1 Stoop Posture

The body-segment additivity, stoop posture regression model is:

$$\text{STFO}wb = 1.545 + 0.680arm - 0.673torso + 0.338central \qquad (5.3)$$

$$r^2 = 0.810.$$

Inclusion of the leg rating variable improved r^2 to 0.831, viewed as a minor improvement. The leg rating variable was thus removed from the model. Removal of

the torso variable reduced r^2 to 0.738, which was viewed as an unacceptable decrease. Similarly, removal of the central rating variable reduced r^2 to 0.737, which was also unacceptable. Therefore, the central and torso ratings were retained in the final model. Table 5.3 shows the results of the statistical tests on this model. Figure 5.3 shows the plot of FO*wb* ratings versus the fitted values.

5.2.2 Squat Posture

The body-segment additivity model of the squat posture condition is:

$$SQFOwb = 1.653 + 0.726leg \qquad (5.4)$$

$$r^2 = 0.621.$$

The squat posture model resulted in an r^2 of 0.679 when all four differentiated rating variables were included. Removal of the torso rating variable reduced r^2 to 0.642, which was viewed as an acceptable decrease. Removal of the central variable reduced r^2 to 0.622, which was again acceptable. Removal of the arm rating reduced r^2 from 0.622 to 0.621, which was negligible. Thus, the whole-body rating was predicted nearly as well with only the leg rating as with all four of the differentiated ratings. Table 5.4 shows the results of the statistical tests on this model. Figure 5.4 shows the plot of FO*wb* ratings versus the fitted values.

TABLE 5.3 Statistical Summary of Body-Segment Additivity Model - Stoop Posture

STFOwb = 1.545 + 0.680arm - 0.673torso + 0.338central

Model Summary

Count	16
R	.900
R-Squared	.810
Adj. R-Squared	.762

	df	Sum of Squares	Mean Square	F-Value	P-Value
Model	3	32.563	10.854	17.039	.0001
Error	12	7.644	.637		
Total	15	40.207			

Model Coefficient Table

	Beta	Std. Error	t-Test	P-Value
Intercept	**1.545**	.569	2.714	.0188
arm	**.680**	.173	3.917	.0020
torso	**-.673**	.316	-2.125	.0550
central	**.338**	.158	2.138	.0537

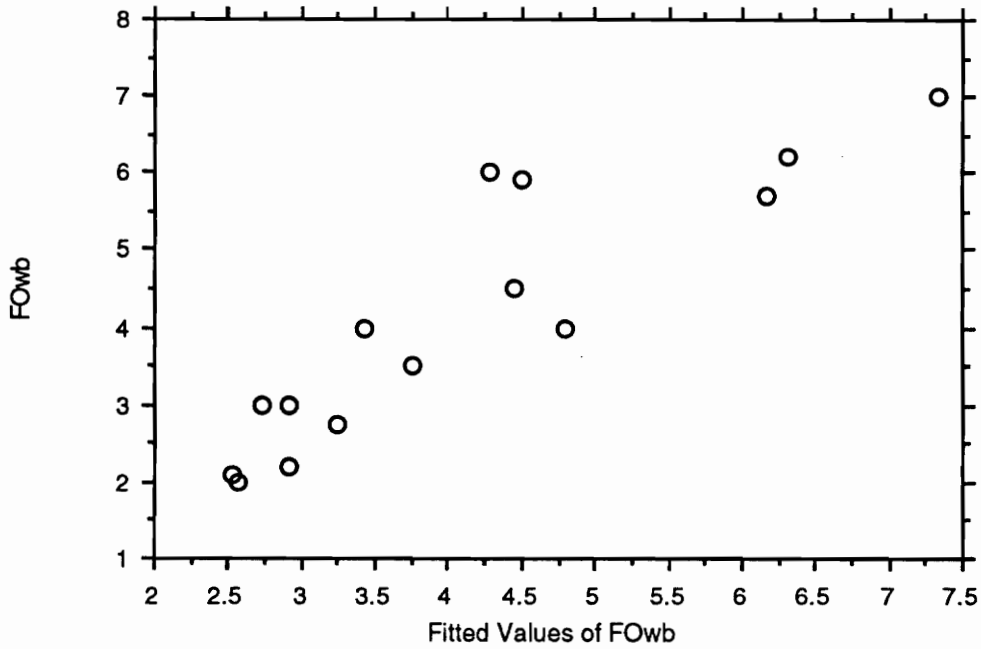


Figure 5.3 Plot of FO*wb* Ratings Versus Fitted Values - Body-Segment Additivity Model, Stoop Posture.

TABLE 5.4 Statistical Summary of Body-Segment Additivity Model - Squat Posture

SQFOwb = 1.653 + 0.726leg

Model Summary

Count	16
R	.788
R-Squared	.621
Adj. R-Squared	.594

	df	Sum of Squares	Mean Square	F-Value	P-Value
Model	1	41.411	41.411	22.962	.0003
Error	14	25.249	1.803		
Total	15	66.660			

Model Coefficient Table

	Beta	Std. Error	t-Test	P-Value
Intercept	1.653	.682	2.423	.0295
leg	.726	.152	4.792	.0003

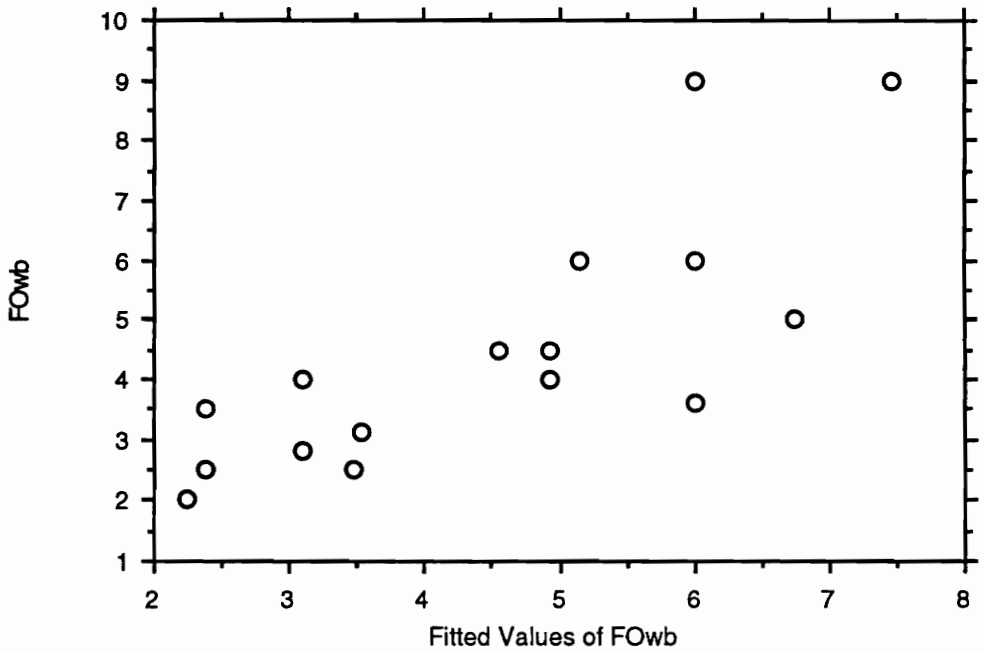


Figure 5.4 Plot of FO*wb* Ratings Versus Fitted Values - Body-Segment Additivity Model, Squat Posture.

5.2.3 Analysis of the Body-Segment Additivity Regression Models

Tables 5.3 and 5.4 summarize the results of the F-tests for regression relation and t-tests on the regression coefficients for the body-segment additivity models. Both body-segment additivity models resulted in a significant regression relation ($p<0.05$). The t-test results indicated that the squat posture coefficients were significantly different from zero at the $p<0.05$ criterion. However, the stoop posture model resulted in p-values for the torso and central rating coefficients which slightly exceeded the traditional 0.05 criterion ($p=0.055$, $p=0.054$, respectively). The arm rating and intercept coefficients were significant at $p<0.05$.

Table 5.6 contains the coefficients of simple determination ($r^2_{y \cdot x}$) and coefficients of determination ($r^2_{x \cdot x}$) for all pairwise comparisons of variables in both posture conditions. In the stoop posture condition the correlation between the leg rating and the whole-body rating was $r^2_{wb \cdot leg}=0.010$. The squat posture condition resulted in a correlation of $r^2_{wb \cdot torso}=0.156$ between the torso rating and the whole-body rating. The correlation between the leg and whole-body rating in the squat posture was $r^2_{wb \cdot leg}=0.621$. In the stoop condition the correlations between the whole-body and arm rating and the whole-body and central rating were higher ($r^2_{wb \cdot arm}=0.654$, $r^2_{wb \cdot central}=0.551$) than the whole-body·torso correlation ($r^2_{wb \cdot torso}=0.214$).

5.3 Heart Rate Analysis

Table 5.7 shows the coefficients of determination between heart rate and the differentiated and whole-body perceived exertion ratings. The heart rates between the whole-body and differentiated rating trials were expected to be equivalent for each

TABLE 5.5 Coefficients of Determination - Task Additivity Models

STOOP POSTURE

$r^2_{y \cdot x}$

	FOwb
FKwb	0.113
KOwb	0.562

$r^2_{x \cdot x}$

	FKwb	KOwb
FKwb	1	0.354
KOwb	0.354	1

SQUAT POSTURE

$r^2_{y \cdot x}$

	FOwb
FKwb	0.403
KOwb	0.465

$r^2_{x \cdot x}$

	FKwb	KOwb
FKwb	1	0.253
KOwb	0.253	1

TABLE 5.6 Coefficients of Determination - Body-Segment Additivity Models

STOOP POSTURE

$r^2_{y \cdot x}$

	FOwb
arm	0.654
leg	0.010
torso	0.214
central	0.551

$r^2_{x \cdot x}$

	arm	leg	torso	central
arm	1			
leg	0.004	1		
torso	0.626	0.067	1	
central	0.412	0.108	0.223	1

SQUAT POSTURE

$r^2_{y \cdot x}$

	FOwb
arm	0.341
leg	0.621
torso	0.156
central	0.538

$r^2_{x \cdot x}$

	arm	leg	torso	central
arm	1			
leg	0.517	1		
torso	0.323	0.471	1	
central	0.581	0.692	0.308	1

TABLE 5.7 Coefficients of Determination (r^2) of Heart Rate with Differentiated and Whole-Body Ratings

Stoop Posture

	heart rate 40% load	heart rate 75% load
arm	0.023	0.078
leg	0.027	0.059
torso	0.059	0.270
central	0.223	0.005
whole-body	0.034	0.004

Squat Posture

	heart rate 40% load	heart rate 75% load
arm	0.067	0.030
leg	0.074	0.000
torso	0.003	0.009
central	0.013	0.011
whole-body	0.315	0.254

subject because the trials were physically identical. The repeatability of heart rate was r^2=0.824.

In the squat posture condition heart rate showed a higher correlation with the whole-body ratings ($r^2_{HR \cdot wb}$=0.315 at the 40% work load, $r^2_{HR \cdot wb}$=0.254 at the 75% work load) than any of the differentiated ratings. . There was no evident trend for the stoop posture condition. The 40% work load trials showed a greater heart rate correlation with the central rating ($r^2_{HR \cdot central}$=0.223), the 75% work load trials with the torso rating ($r^2_{HR \cdot torso}$=0.270).

5.4 Summary of Results

Table 5.8 summarizes the four models presented in sections 5.1 and 5.2. The r^2 coefficients of determination range from 0.810 to 0.562, indicating that in all cases at least one-half of the variance in the whole-body rating can be explained by the independent variables.

TABLE 5.8 Summary of the Experimental Models

TASK ADDITIVITY MODELS

Stoop Posture

$$FO_{wb} = 1.723 + 0.436KO_{wb} \qquad r^2 = 0.562$$

Squat Posture

$$FO_{wb} = 0.118 + 0.615FK_{wb} + 0.389KO_{wb} \qquad r^2 = 0.693$$

BODY-SEGMENT ADDITIVITY MODELS

Stoop Posture

$$FO_{wb} = 1.545 + 0.680arm - 0.673torso + 0.338central \qquad r^2 = 0.810$$

Squat Posture

$$FO_{wb} = 1.653 + 0.726leg \qquad r^2 = 0.621$$

6. DISCUSSION

6.1 General Interpretation of the Models

The model-building process used to generate the regression equations presented in sections 5.1 and 5.2 was based on maximizing the r^2 coefficients of determination. There was no consideration given to including variables which were *expected* to be included in the best-fit models. This criterion resulted in regression models which explain between 56% and 81% of the variance in the whole-body perceived exertion ratings. All of the models resulted in a significant regression relation ($p<0.05$). Most of the model coefficients were significantly different from zero at $p<0.05$. Two coefficients slightly exceeded ($p=0.055$, $p=0.054$) this traditional criterion in the body-segment additivity, stoop posture model.

The original experimental objective was to build separate regression models for the two work load conditions (40% and 75% of the subject's maximum single lift). This was to be a "between-subjects" analysis as the models contained only one datum from each subject. Further reflection on this analysis revealed that the F-tests for regression relation were not significant because the data points were dispersed over a small range of perceptual intensities. This dilemma was overcome by including both work load levels in a single model for each posture condition. The data points were then dispersed over a range of perceptual intensities resulting in statistically significant regression relations. This is a "within-subjects" analysis as two data points from each subject were included in the models.

An interpretation problem arises when considering the meaning of negative regression coefficients in these models. A negative coefficient occurred in the stoop

posture, body-segment additivity model for the torso rating variable. It is difficult to conceptualize a *reduction* in whole-body perceived exertion in proportion to a differentiated perceived exertion signal. The models of whole-body, perceived exertion were constructed under the assumption that regional exertion cues contributed *additively* to the whole-body perceived exertion rating. One possible explanation for this phenomenon is that if a differentiated signal is overpowered by another regional signal it might contribute negatively to the whole-body perceived exertion relative to the more dominant signal.

A second explanation is that while the regression modelling may result in a significant prediction of whole-body perceived exertion, the models do not actually represent the perceptual integration process of the differentiated signals. Internal psychological processes may dominate in the synthesis of undifferentiated perceived exertion, which cannot be captured by psychophysical responses. Other physiological inputs, which are not reflected in the models, may contribute to the overall perception of effort. The simplified anatomical framework which was used to identify muscular effort sensations may not have isolated effort signals which contributed to the undifferentiated rating.

A third explanation is that the integration of the whole-body rating of perceived physical exertion may not be an additive process as was initially hypothesized. Undifferentiated perceived exertion may be formed by an additive process within each individual's perceptual framework. However, the variability in the experimental data suggest that individual differences in the perception of effort and the translation of this percept into a response metric may be too great to demonstrate a "global", additive perceptual integration process.

6.1.1 Task Additivity Models

The results obtained in this experiment indicate that the perception of whole-body exertion is different between the stoop and squat postures. The stoop posture, floor-to-overhead (FO), whole-body perceived exertion rating was predicted by the rating of whole-body exertion in the knuckle-to-overhead (KO) component lifting task. The squat posture, FO, whole-body rating was best predicted by the whole-body ratings for both the KO *and* the floor-to-knuckle (FK) component lifting tasks.

The correlation analyses also indicate differences in the whole-body rating integration between the stoop and squat postures. In the stoop posture condition, the correlation between the FO*wb* rating and the KO*wb* rating ($r^2_{FO \cdot KO}$) was greater than the correlation between FO*wb* and FK*wb*. The FK*wb* rating accounted for little of the variance in the FO lifting whole-body rating. In the squat posture condition, the correlations between the component tasks and the FO task were nearly identical. The FK*wb* and KO*wb* ratings each accounted for approximately 40% of the variance in the FO*wb* rating.

Individual variation in lifting strategy may have influenced the perceived exertion ratings, particularly in the FK tasks. Subjects were instructed to maintain the assigned posture (squat or stoop) and to keep the lifting and lowering velocities under control. Two strategies for lifting and lowering were observed for both posture conditions. Most subjects chose to stand between lift repetitions, however, some subjects lowered the carriage handles to the floor and remained in the stoop or squat position between lifts. These subjects were permitted to remain "stooped" or "squatted" if this was more natural for them. In this manner subjects were not "forced" to use a particular lift strategy, which might have affected their attitude toward the task. Making subjects conform to a particular strategy might have negatively influenced their

motivation and biased their perception of the task difficulty. Unfortunately, this introduced variability in the muscular activity involved between the two techniques. The protocol might have been improved by demonstrating the exact lifting strategy to the subjects before they had the opportunity to select a different method. This would have eliminated the dilemma of forcing subjects to conform to the standard lifting strategy versus allowing them to perform the lifting using a different technique. The knuckle-to-overhead lifting tasks appeared to be consistent among subjects in the strategies adopted for lifting and lowering. There was no noticeable variation in lifting/lowering strategy in these trials.

Individual differences in strength capabilities may have influenced this paradigm. Perusal of the raw data indicates that some subjects rated the FK lifting as more exerting than the KO lifting at equivalent work loads, but some subjects indicated the contrary. This may be attributed to the physiological makeup of the subjects in terms of regional strength abilities and/or anthropometry. A subject with longer arms (relative to stature) must raise the carriage more in the KO phase than in the FK phase relative to a subject with shorter arms (relative to stature). Regional strength variations and anthropometric differences may have been influential in the lack of consistency between the subtask ratings. Thus, subjects may form the floor-to-overhead lift, whole-body rating by a perceptual addition of perceived exertion from the FK and KO lifts, but the relative perceptual contributions from these sub-tasks vary among individuals.

6.1.2 Body Segment Additivity Models

The body-segment additivity models also indicate differences in the perceptual integration of whole-body perceived exertion between the squat and stoop postures.

The squat posture, whole-body rating of perceived exertion in floor-to-overhead lifting was predicted nearly as well by only the leg rating as by all four of the differentiated ratings. Thus, perceived exertion from the legs appeared to drive the perception of whole-body effort in floor-to-overhead, squat lifting. In the stoop posture condition the floor-to-overhead, whole-body rating was predicted by the differentiated perceived exertion from the arms, torso and central ratings. It appeared that perceived exertion from the arms accounted for the largest portion of the variance in whole-body, stoop lifting exertion, with the torso and central exertion being influential as well.

The correlation analyses are somewhat misleading in the body-segment additivity paradigm. In the squat posture condition, the central rating of exertion exhibited an r^2 of 0.538 with the whole-body rating, yet did not appreciably improve the multiple r^2 when included in the final model. The arm and torso ratings, which were not included in the squat posture model, resulted in lower correlations with the whole-body ratings ($r^2_{wb \cdot arm}$=0.341, $r^2_{wb \cdot torso}$=0.156, respectively).

In the stoop posture model, the leg variable explained virtually none of the variance in the whole-body rating ($r^2_{wb \cdot leg}$=0.010) which supported its removal from the model. This result was expected since stoop lifting involves the erector spinae, obliques, and other trunk muscles and places less stress on the leg extensors. The pairwise correlations between the arm, torso, and central rating variables and the whole-body rating were $r^2_{wb \cdot arm}$=0.654, $r^2_{wb \cdot torso}$=0.214, and $r^2_{wb \cdot central}$=0.551, respectively. Inclusion of these variables resulted in an improvement in the multiple r^2, thus, they were retained in the final model. The correlation between the torso rating and the whole-body rating was expected to be higher than 0.214 in the stoop posture. This correlation was much lower than the 0.621 leg·whole-body correlation observed in the squat posture condition.

The stoop posture, body-segment additivity model exhibited the highest r^2 (0.810) of the four models. However, the negative coefficient for the torso rating variable in this model must be carefully interpreted. Had the model contained only *positive* regression coefficients, the coefficients could be interpreted as the perceptual weightings of the regional signals which combined additively to form the undifferentiated, whole-body rating. The occurrence of this single negative coefficient casts doubt on the validity of this model in representing the perceptual integration of the regional effort signals.

There were trends evident with regard to the differentiated rating components included in the body-segment additivity models which support the validity of the models. As mentioned previously, the stoop posture model excluded the leg rating since it contributed negligibly to the variance in the whole-body rating. This result was expected since stoop lifting is more stressful on the torso musculature than on the legs. Similarly, the squat posture model excluded the torso rating as it was not effective in increasing the multiple r^2. The torso rating variable was not expected to be included in the squat posture model since squat lifting emphasizes the leg extensors.

However, other trends are evidence against the validity of the body-segment additivity models. The model of the squat posture, whole-body rating includes only the leg rating. Intuitively, one would believe that the arms should contribute *something* to the whole-body perceived exertion. The central effort sensation was also expected to contribute to squat lifting, whole-body perceived exertion, particularly at higher work intensities. Yet these regional signals were not included in the squat posture model of whole-body exertion. This casts doubt on this model's validity in representing the underlying perceptual integration process of whole-body exertion.

6.2 Comparison to the Results of Robertson et al. (1979a)

The weighted average procedure proposed by Robertson et al. (1979a) was supported by the results of this study. The Robertson et al. (1979a) study examined differentiated ratings from only two sources: legs and central sensations (chest), during bicycle ergometer pedalling. Their results showed that the rating from the chest was consistently lower than the overall rating and the leg rating was consistently greater. Furthermore, the correlation between the mean rating for the legs plus chest (mlc) with the overall rating ($r_{overall \cdot mlc}$) was greater than either the $r_{overall \cdot leg}$ or $r_{overall \cdot .chest}$ correlations. They interpreted this result as evidence supporting the weighted average hypothesis and the model of Pandolf (1978).

The present study applied the weighted average hypothesis in a more "whole-body" activity. The goal of the body segment additivity paradigm was to establish empirical relationships, subject to statistical testing, which would confirm the weighted average (additivity) hypothesis. The multiple r^2 value for the stoop posture, body-segment additivity model (r^2=0.81) was comparable to the r^2 values reported by Robertson et al. (1979a). However, the negative coefficient indicates that the model does not support a truly additive property of the differentiated ratings.

The Robertson et al. (1979a) study used a nine-point scale for subjects to rate perceived exertion. The nine-point scale contained only two semantic anchors at the "2" and "8" scale values, corresponding to *not at all stressful* and *very, very, stressful*, respectively. The scaling instructions presented to the subjects prior to each session included a standard reference for both a high and low rating. The low standard was anchored by the "feelings of exertion associated with pedalling a cycle ergometer very slowly against no resistance". The high standard was anchored by "sensations encountered during maximally exhaustive exercise." It is unclear whether the semantic

anchor for the low level was reinforced with an actual reference stimulus (i.e., allowing the subject to pedal against no resistance). The properties of the nine-point rating scale were not discussed in the study; it appears that it was assumed to be an interval scale.

The results of the Robertson et al. (1979a) study may have been somewhat coincidental, as there was no original hypothesis that the mean of the legs + chest (mlc) rating would be related to overall perceived. The authors interpreted the correlation between mlc and overall perceived exertion as evidence that a weighted averaging described the integration process at the superordinate level of sensory processing (Robertson et al., 1979a). A similar statement could be made for the models from the present investigation. However, the models with relatively high r^2 values, only indicate that a strong relation is evident and that the models are good predictors of the *output* of the perceptual processing. The models generated in this experiment may not *model* anything, rather, they may only *predict* the resultant whole-body rating from the differentiated perceived exertion ratings.

6.3 Problems with the Borg CR-10 Scale

The CR-10 scale is a relatively recent contribution to the study of perceived exertion. The scale has been demonstrated to possess ratio scale properties when applied to bicycle ergometer pedalling (Borg, 1982a). To the author's knowledge, there have been no studies validating the CR-10 ratio scale properties for other types of activities. The RPE scale, predecessor to the CR-10, has been tested in conjunction with a variety of physical activities, and its limitations have been fairly well established. In this experiment, the inter-subject reliability of the CR-10 rating scale may not have been adequate in measuring true perceptual intensities. For example, two subjects

working at the same relative intensity (at the same percentage of their maximum capability) should give identical ratings to the effort which they perceive from the exercise bout. This is the basis of the categorical properties which facilitate inter-individual comparisons. The large variability seen in the data at identical relative work loads indicate that either external sources or internal scaling problems affected the categorical properties of the CR-10 scale.

The difficulty of accurately assessing subjects' true maximum single lift capabilities have been discussed previously. The assumption that subjects were working at the same relative work loads may not be completely valid. In addition, the maximum single capability lift tests may not have accurately reflected subjects' work capacity for 35 repetitions, over a six-minute time period. The repetitive lifting tasks involved a metabolic exertion which was not tested in the "one repetition" maximum single lift determination. Thus, the comparisons between subjects' ratings at a given relative work load may have been confounded by these problems. However, "within-subject" comparisons were not affected by these factors.

6.3.1 Rating Scale Instructions

The claimed ratio properties of the CR-10 scale are based upon the placement of the semantic anchors along the numeric scale. Their placement was designed to match the power function of perceived exertion based on the perceived growth in semantic intensity of the anchors. If the ratio properties are to be effective, the semantic descriptors must be effectively used to anchor the numeric rating. The RPE scale anchors are spaced in equal intervals to match the linear association of heart rate with work load. Therefore, it appears more critical that the verbal anchors be effective with

the CR-10 scale than with RPE. In this study, subjects may not have made optimum use of the verbal anchors. The written instructions read by the subjects before each trial emphasized that the verbal descriptions should be examined first, to appropriately anchor the numeric rating. However, subjects may have made their assessment based solely on the numeric scale.

6.3.2 Interpretation and Preciseness of the Anchors

The semantic intensities of the scale anchors may have been interpreted differently by subjects. For example, the intensity difference between *extremely weak*, *very weak*, and *weak* may depend on both differences between individuals and differences within an individual from trial to trial. Borg (1962) defined the semantic concepts of "interpretation" and "preciseness". Interpretation refers to the "subjective intensity behind an expression", preciseness is the "relative dispersion showing how much different people agree on the intensity level of the expression" (p. 30).

The variability in this experimental data suggest that both the interpretation and preciseness of the CR-10 scale anchors may have been inadequate. Two subjects, both in the squat posture, 40% work load trial, gave a rating of "0" to the torso region. These were the only cases in which a "0" rating was given, suggesting that these subjects' interpretation of *nothing at all* was different from those who gave non-zero ratings to the torso effort in this posture and workload condition. This indicates that the interpretation of the semantic anchor "*nothing at all* " may be variable among subjects. A second explanation is that ambiguity may have existed in the anatomical framework within which subjects were required to regionalize the effort sensations. These two subjects may have interpreted the anatomical diagram differently when considering the

location of the muscular effort they perceived. It is more likely, however, that these subjects' interpretations of the zero scale rating (*nothing at all*) was different than were their interpretations of the effort localization.

More convincing evidence of variability in the interpretation of the scale anchors was seen in the cases of complete fatigue. Three subjects were unable to complete the knuckle-to-overhead lifting task at the 75% work load condition. In all of these cases the subject reached complete muscular exhaustion before six minutes had elapsed. However, only one of these subjects rated the whole-body exertion as a "10" (*extremely strong / almost max*); the other ratings were "8.7" and "6". The fact that these ratings were given for whole-body exertion while only the arms were exhausted may explain these occurrences. The physiological exertion in these cases can be operationally assumed "standardized" by the fact that the subjects were incapable of performing another lift. However, the perceptual intensities of this exertion were variable as seen in the range of ratings (6 to 10). This suggests that the CR-10 scale anchors may be incapable of overcoming the strength of individual differences in anchoring absolute, categorical levels.

6.3.3 Ceiling Effect

Anecdotal evidence indicated that the CR-10 scale may possess a ceiling effect to some degree, despite Borg's attempts to eliminate it. One subject gave the response "10; no, wait, make it a 9.5." This may be interpreted as reluctance by the subject to give a rating of "10" which is the uppermost numeric value written on the scale. The effectiveness of the bold dot outside of the scale to denote a maximum exertion was not apparent in this case. Subjects may still have interpreted the scale value "10" as the

maximum rating since it is the highest number written on the scale. No ratings exceeded "10", even in the cases in which subjects were incapable of completing the trial due to complete local muscle exhaustion.

6.3.4 Validity and Repeatability of the CR-10 Scale

In several instances, a higher rating was given to a regional signal at the 40% work load than at the 75% work load. This occurred once for the stoop posture leg rating and twice for the stoop posture torso rating. Equivalent ratings were given at the 40% and 75% work loads; this occurred for the leg rating three times (two in the stoop posture, once in the squat posture), once for the squat posture torso rating, and once for the arm rating. On one occasion, the whole-body rating for the floor-to-knuckle height was assigned a value of "4" at both the 40% and 75% work loads.

Another "reversal" in floor-to-knuckle, whole-body ratings occurred when a subject gave a rating of "2.7" at the 40% work load and a "2.5" at the 75% work load. Interestingly, the heart rates recorded in these trials matched the "reversed" direction of the ratings; the observed heart rate was 128 beats$\cdot$min^{-1} for the 40% work load and 115 beats$\cdot$min^{-1} for the 75% work load. This indicates that external factors may have been responsible for the apparent reversal of the ratings. The subject's perception of exertion followed the physiological stress indicator, as opposed to the work load level.

Assuming that subjects were motivated, given adequate instruction, and were not fatigued these occurrences indicate that the CR-10 scale has limitations in facilitating the ability to repeatably translate a perceptual intensity to a rating scale response. There is no physiological explanation for a lower perception of exertion from a higher work intensity, unless other confounding factors influenced the subject's

physiological state between the trials. This may have been the case for the trial in which the heart rates matched the apparently reversed direction of the ratings, based on work load. Psychological differences may explain the occurrences of "reversed" ratings which showed a normal heart rate-work load relation. These occurrences may also indicate that the sensitivity of the CR-10 scale does not facilitate discrimination among similar perceptual intensities.

The discrepancies between scale ratings and physical work intensity between trials suggest that the repeatability and validity of the CR-10 scale may have confounded the results of the experiment. The higher ratings given at lower work loads are interpreted as a lack of ability by the subject to discriminate between the two "confused" ratings. That is, the difference between "2.5" and "2.7" may not have been distinguishable and may have corresponded to identical perceptual intensities by the subject. Alternatively, a subject's interpretation of the semantic intensities may vary from day to day depending upon motivation or other psychological factors.

The psychophysical power function, expressing perceived exertion as a function of work load, is relatively flat at lower work loads. The slope of the function at these lower work loads indicates that large increases in work load correspond to relatively small perceptual increases. Therefore, inconsistencies between differentiated ratings with respect to work load (i.e., higher rating of exertion at a lower work load) were expected to occur at lower perceived intensities from the less active muscle groups. There was a slight trend to this effect. The majority of the "reversed" ratings in the stoop posture condition were from the differentiated, leg rating. Most of the squat posture "reversals" were from the torso rating. Additionally, there were no cases in which the whole-body rating was higher at the 40% work load than the 75% work load. The central effort sensation was also consistently perceived as greater in the 75%

condition. Perhaps the CR-10 scale is more valid in assessing whole-body than differentiated perceived exertion.

6.4 Heart Rate Observations

The poor correlations found in this study between heart rate and perceived exertion indicate that heart rate may not be a good indicator of perceived exertion. The CR-10 scale, based on the power function associated with perceived exertion as a function of work load, is not suitable for comparison with linearly increasing physiological processes such as heart rate. Thus, a linear relation between perceived exertion (CR-10 rating) and heart rate would not be expected along the work load continuum.

The standard deviation for maximal heart rate is ±10 beats·min^{-1} (Åstrand and Rodahl, 1970). Thus, the heart rate variability among subjects was expected to be high at any constant relative work load. The observed heart rates among subjects working at identical percentages of maximum work capacity reflected this variability. The repeatability of heart rate was r^2=0.824 (correlation between the whole-body and differentiated trials).

It was assumed that even if a high correlation did not exist between heart rate and perceived exertion, it would be higher between heart rate and the central rating than between heart rate and any of the other regional effort ratings. This was not the case, as no trend existed in the magnitude of the (r^2) coefficients of determination between heart rate and any differentiated ratings of perceived exertion at the 40% or 75% work load levels (see Table 5.9). These coefficients of determination express the correlation of heart rate among subjects at equivalent relative work loads. In the squat posture

condition heart rate was more highly correlated with the whole-body rating ($r^2_{HR \cdot wb}$=0.315, $r^2_{HR \cdot wb}$=0.254, for the 40% and 75% work load conditions, respectively) than any of the differentiated ratings. Combining the work load conditions did not result in improved heart rate·perceived exertion correlations. In the stoop posture condition heart rate exhibited the highest correlation with the central rating ($r^2_{HR \cdot central}$=0.234). In the squat posture heart rate exhibited the highest correlation with the arm rating ($r^2_{HR \cdot arm}$=0.339). In general, heart rate was poorly correlated with all of the subjective ratings.

6.5 Arguments for the Additivity Property

The results of this study lend statistical support to the additivity hypotheses proposed in chapter 2. The original modelling was performed with respect to work load (i.e., separate models at each level of work load). These models resulted in statistically non-significant models of whole-body perceived exertion. Including both of the work load conditions in the same model gave two observations from each subject to facilitate a "within-subjects" analysis. Assuming that the perceptual weighting of the perceived exertion variables is independent of work load, the within-subjects modelling is advantageous. In hindsight, the between-subjects approach at a single relative work load was an ineffective way to obtain a significant regression relation. Including multiple subjects' ratings at multiple relative intensities would yield the greatest dispersion of data points through which to fit the regression. To maintain the economy of data collection it would have been beneficial to use two levels of *absolute* work load to obtain a dispersion of data points along the perceived exertion continuum.

The stoop posture, body-segment additivity model can be interpreted as violating the original additivity hypothesis because of the negative coefficient in the predictive equation. However, an argument can be made in support of the additivity hypothesis regardless of the sign of the regression coefficients. That is, the negative sign associated with the torso rating variable may indicate that the torso exertion acts to reduce whole-body perceived exertion as the intensity from this region is increased. The perceived exertion from the arms exhibited the highest correlation with whole-body exertion in stoop lifting. The torso exertion may have been overpowered by the arm effort so that it acted as a "buffer" to the whole-body perceived exertion. Thus, whole-body perceived exertion may be most affected by the *relative difference* between the dominant and less-dominant exertion signals. That is, as the torso exertion is reduced relative to the arm exertion, whole-body perceived exertion may increase. Conversely, as the torso exertion increases relative to the dominant arm signal the whole-body perceived exertion may decrease as the effort is perceived as being more distributed over the entire body.

This theory is not supported by the results of Gamberale (1972) with regard to tasks which emphasize small, localized muscle groups. Gamberale found that in lifting weights overhead the local perceived exertion rating from the arms was consistently higher than the whole-body rating. Likewise, in ergometer pedalling with the legs, the local leg rating was consistently higher than the whole-body rating. However, in wheelbarrow pushing the whole-body rating was always greater than either of the local ratings. In Gamberale's study, whole-body exertion appeared to have *decreased* as the exertion became more localized, and *increased* as the exertion was more evenly distributed about the body.

The results of Gamberale (1972) combined with the results of this stoop posture, body-segment additivity model further complicate the understanding of whole-body

perceived exertion. The results of both studies indicate that the perceptual synthesis of a whole-body exertion rating may depend upon how the effort is distributed about the body. That is, in activities stressing localized regions, such as lifting weights with the arms and ergometer pedalling with the legs, the whole-body exertion may be perceived differently than in activities stressing a wide range of muscle groups such as wheelbarrow pushing or repetitive, floor-to-overhead lifting.

Anecdotal evidence indicated that when isolated muscle groups are stressed it may be easier to rate differentiated perceived exertion than undifferentiated, whole-body exertion. When asked to give a whole-body rating following a knuckle height-to-overhead lifting trial, one subject made the comment, "My *arms* are tired, but my *whole-body* really isn't." This subject was obviously unsure of how to evaluate whole-body perceived exertion when only a single region (arms) had perceived a high degree of exertion.

The regression modelling procedures resulted in models which account for the majority of the variance in the floor-to-overhead, whole-body rating. However, these models may not represent the actual psychophysical processing by which humans report their perception of exertion. It is very likely that the models only predict the *output* of this psychophysical processing.

The hierarchical model proposed by Pandolf (1978) (see Figure 3.6) illustrates that numerous percepts contribute to undifferentiated perceived exertion. It is possible that other psychological or physiological cues may also drive the perception of undifferentiated exertion. Psychological terminology makes a distinction between the terms sensation and perception. Perhaps, differentiated perceived exertion is dominated by kinesthetic sensations of muscle tension, respiratory stress, and chemoreceptor activity at a cellular level which are actually "sensed" by sensory receptors. Undifferentiated perceived exertion may be that which is "perceived" based on the

differentiated sensations and external psychological percepts such as motivation, task aversion, and general fatigue, as proposed by Pandolf (1978).

7. CONCLUSION

This experiment tested two hypotheses relating to the method of sensory integration of undifferentiated, whole-body perceived exertion. Two paradigms were established to statistically test the additivity of psychophysical perceived exertion ratings in floor-to-overhead, repetitive lifting.

The task additivity hypothesis asserts that a floor-to overhead lifting task rating of whole-body exertion is additively related to the whole-body ratings given to the component subtasks (floor-to-knuckle lifting task and knuckle-to-overhead lifting task ratings). Regression modelling resulted in statistically significant ($p<0.05$) regression relations with r^2 values of 0.562 (stoop posture) and 0.693 (squat posture). The stoop posture, floor-to-overhead lifting task rating was modelled by only the knuckle-to-overhead lifting task rating. The squat posture rating was best modelled by both the floor-to-knuckle and knuckle-to-overhead lift ratings. The observed variability of the ratings among subjects working at the same relative work load suggests that individual differences in lifting strategy, anthropometry, and regional strength capability influenced the differences in perceived exertion among the tasks.

The body-segment additivity paradigm examined the additive relationship between the floor-to-overhead lifting task, whole-body rating and differentiated perceived exertion ratings from the arms, legs, torso, and central effort sensations. The squat posture, whole-body rating was predicted by only the rating of leg exertion. The stoop posture, whole-body rating was predicted by the arm, torso, and central ratings. Both models resulted in a significant regression relation ($p<0.05$) with r^2 values of 0.810 (stoop) and 0.621 (squat).

Some trends in the experimental results followed what was expected. The torso rating variable could be removed from the squat posture, body-segment additivity model with little sacrifice in r^2. Squat lifting requires more force production from the leg muscles, thus, the torso rating was not expected to be influential on the whole-body exertion. Similarly, the stoop posture model did not include the leg rating variable as it resulted in minimal improvement in r^2 for the model. Stoop lifting emphasizes the torso and low back muscles, thus, the leg rating was expected to be unimportant.

Despite the relatively high r^2 coefficients of multiple determination for the body-segment additivity models, other evidence suggested that these models did not represent the actual psychophysical integration of undifferentiated perceived exertion ratings. Some of the predictor variables which were retained in the final models contradicted what was expected. The central rating variable improved the r^2 for the stoop posture model but not for the squat posture model. Since squat lifting is generally less metabolically efficient than stoop lifting, the squat posture model was expected to include the central rating variable. However, the central rating was not retained in the final squat posture model. The squat posture body-segment additivity model also excluded the arm rating variable. In the stoop posture condition the arm rating was the most highly correlated variable with the whole-body rating. The arm rating was expected to contribute to the variance in both posture conditions.

The negative coefficient which appeared in the stoop posture, body-segment additivity model casts doubt on this model's representation of the actual psychophysical processes. It seems unlikely that the perceptual processing of a whole-body rating of exertion would include the *subtraction* of a regional effort signal. Yet, two interpretations of this phenomenon can be offered. The negative coefficient may indicate that these models reasonably predict the whole-body, perceived exertion rating,

but do not model the mode of sensory integration of undifferentiated perceived exertion, as was reported by Robertson et al. (1979a).

A second interpretation is that negative coefficients represent a reduction in whole-body exertion as a result of increased effort in a less dominant local region. As the relative difference between regional sources of perceived exertion decreases, whole-body perceived exertion may decrease as a result of the effort being "more spread out". For example, the perceived exertion from the arms accounted for most of the variance in the stoop lifting whole-body rating. The torso rating accounted for a much smaller portion of this variance. The negative torso coefficient in this model may indicate that as the torso exertion increases, whole-body exertion decreases as the arm exertion is reduced (relative to the torso). This hypothesis contradicts the findings of Gamberale (1972) who found that whole-body perceived exertion was decreased in activities stressing localized muscle mass (lifting weights and ergometer pedalling) and increased in activities involving multiple limbs and muscle groups (wheelbarrow pushing). Both hypotheses suggest that the perception of whole-body exertion is affected by the degree of localization versus "globalization" of the effort.

The results of this study point to future perceived exertion research, namely in conjunction with psychophysical scaling methods. The validity of the Borg, CR-10 scale was taken on assumption in this experiment. It is possible that these results were limited by the validity and reliability of the CR-10 rating scale. Anecdotal evidence was observed which caused one to question the reliability of the CR-10 scale, which may not be as strong as has been reported in the literature. A rigorous examination of the CR-10 scale is recommended, especially for its reliability in a wide range of physical activities. The ratio properties are certainly disputable, even the categorical properties have been challenged by the cases of higher ratings observed at lower work intensities.

Perceived exertion studies have been reported mostly in the exercise physiology/sport science literature. Exercise prescriptions have been made based on self-regulated intensities monitored through perceived exertion ratings. The convenience of such a method over laboratory physiological instrumentation is obvious. The results of this study indicate that the effectiveness of such a method is questionable.

Perceived exertion should by no means be the sole criterion for establishing *safe* levels of performance or work intensity. However, it may be appropriate to incorporate perceived exertion into criteria for establishing performance standards. This has occurred to some degree in human factors/ergonomics studies, unfortunately, without a thorough understanding of the perceptual processes which occur when perceived exertion is assessed.

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APPENDIX A

PARTICIPANT'S INFORMED CONSENT FORM

APPENDIX A

PARTICIPANT'S INFORMED CONSENT FORM

This form constitutes informed consent by you to participate in this study. Please read the form in its entirety and sign on the next sheet.

Thank you for participating in this research. The experiment is being conducted in the Industrial Ergonomics Laboratory of the Human Factors Engineering Center at Virginia Polytechnic Institute and State University as part of a thesis project. The tasks which you will perform involve a simple, repetitive lifting procedure which is intended to elicit a feeling of physical strain. You will be giving subjective ratings of the exertion which you feel during the activity.

You will be asked to participate in four experimental sessions which will be held approximately twice per week. In each session you will perform two, six-minute tasks. The tasks will involve repetitively lifting and lowering the handles of a lifting machine between the following designated endpoints: floor-to-standing knuckle height, knuckle height-to-overhead reach, and floor-to-overhead reach. Two sources of data will be collected in each task. You will be asked to give a rating for the exertion felt in the task and your heart rate will be measured throughout the task.

There is a remote possibility of physical injury through participation in this experiment. The activities will involve whole-body, dynamic efforts of about six minutes duration. It is for this reason that you should consider your state of physical condition and musculoskeletal health before participating in the experiment. The paragraph below contains a checklist of medical screening questions for you to answer. Signing this informed consent form acknowledge that you believe yourself to be in acceptable condition to perform the activity described. If you answer yes to any of these questions, it is advised that you do not participate.

Medical Screening Questions

Please answer the following questions with complete honesty. The questions are intended to insure your protection and safety to the highest possible degree. Please circle yes (Y) or no (N).

Y N I have a history of low back or other musculoskeletal problems.

Y N I have asthma.

Y N I have a history of heart problems or high blood pressure.

Y N I am currently under the care of a physician or taking a prescription drug.

Y N I believe that I may have a physical condition which would prevent me from safely performing vigorous physical activity for six minutes duration.

It is critical for you to perform all activities within what you feel to be a safe effort, that is the maximum effort you can exert without risking injury. Only you can be the judge of what your maximum safe effort is, and you should not exceed this level. No one associated with this experiment will request that you exceed this maximum safe effort.

As a participant in this study you are entitled to certain rights:

1) You may withdraw from the experiment at any time for any reason without forfeiting pay for time spent prior to the point of withdrawal.

2) You have the right to see *your* data and withdraw them from the study if you so desire. This must be done during the experimental session as all data will be handled anonymously and will not be traceable after analysis.

3) The research team members will answer any questions you may have regarding the experiment. You should not sign this consent form until you understand fully all of the terms involved. The members of the research team are:

Brian D. Lowe, Graduate Student (phone 552-4247)
Dr. Karl H.E. Kroemer, Professor, Department of Industrial and Systems Engineering (phone 231-5677)

Additional questions regarding your rights as a subject should be addressed to Dr. R.J. Beaton, I.S.E. Representative of the Institutional Review Board, 549 Whittemore Hall (phone 231-5936).

Your signature below indicates that you have read this description of the experiment, understand your rights as a participant, understand the physical risks involved, and consent to participate in the study.

Signature: _____ Date: _____

Printed name: _____

Address: _____

_____

APPENDIX B

RATING SCALE INSTRUCTIONS

APPENDIX B

RATING SCALE INSTRUCTIONS

You will be performing lifting tasks, each for a duration of six minutes. At each tone signalled by the pc timer you are to raise the handles from (starting point) to (endpoint) and then lower the handles to the lift origin. It is important that you pay close attention to the signal device and be sure to perform a lift at each signal. Make each lift a controlled and steady motion to the best of your ability. Be sure to lower the handles in a controlled motion at a velocity similar to that of the lift. The tasks should be stressful, however, if you feel as though you are overexerting (i.e. above your maximum safe effort) inform the experimenter immediately.

At the conclusion of the task, you will be asked for a rating. You will use the rating scale which is posted on the wall to tell how strong your perception of exertion is. As you can see the scale stretches from "Nothing at all" to "Maximal". "Nothing at all" is 0 and means that you do not perceive any exertion whatsoever. "Extremely strong" is 10 and is "almost maximum". For most people this corresponds to the heaviest exertion they have ever experienced - i.e. your own perceived maximum from earlier experience. You might, however, think of an exertion that is even a little stronger than what you yourself have experienced as strongest, therefore the absolute maximum of the scale is marked with a " • " (bold dot) and placed a little further down the scale. If you would perceive something that is above your own maximal exertion from your earlier experience, you may thus use numbers on the scale above 10, e.g. 11, 13, or even higher. "Extremely weak", corresponding to 0.5 on the scale, is something just noticeable, on the edge of what is possible to perceive.

You will use the scale in the following manner: Always start by looking at the descriptive words to the right of the numbers. Then choose a suitable number. If your perception of exertion corresponds to "Very weak" you should say 1. If it is "Moderate" you should say 3, and so on. You may use whatever numbers you want, also half values, e.g. 1.5, or decimals such as 0.8, 1.7, or 2.3. It is very important that you answer what you perceive, and not what you believe you should answer. Be as honest as possible and try neither to overestimate nor underestimate the intensities.

Remember to start by looking at the descriptive words before every rating, then give a number. Two points need to be emphasized. You may use any decimal number between scale values - do not feel confined to the integer values. Most importantly, there are no right or wrong answers, only your perception of the exertion.

APPENDIX C

WHOLE-BODY RATING TRIAL INSTRUCTIONS

APPENDIX C

WHOLE-BODY RATING TRIAL INSTRUCTIONS

You will now perform a (type of lift) lifting task for six minutes. It is important that you maintain a consistent posture for each lift.

You will be lifting from what will be referred to as a squat posture. A squat lift is performed by bending the knees to lower and lift the handles. Your back should remain as straight as possible. Locate your feet so that they are somewhere between the handles, making it easy to raise and lower the handles by bending only at the knees. Your feet should not be moved during the trial.

You will be lifting from what will be referred to as a stoop posture. A stoop lift is performed by bending from the hips to lift the handles. Your legs should remain straight and your knees should not bend. Locate your feet so that they are somewhere between the handles, making it easy to raise and lower the handles by bending from the hip. Your feet should not be moved during the trial.

You will be performing this lift from a standing position, lifting from your standing, knuckle height to overhead reach. The handles should be resting at your knuckle height. You should not have to bend down at the bottom of the lift. Your feet should be positioned so that they do not move during the trial.

At each signal tone you will lift the handles from (*the floor* or *knuckle height*) to (*knuckle height* or *overhead*). When the handles have reached (the lift endpoint) lower them in a similar, controlled manner. It is important that you pay close attention to the signal tone and be sure to perform a lift at each tone. Make each lift a controlled and steady motion to the best of your ability.

At the conclusion of this six-minute trial, you will be asked to give a rating for the overall effort you feel in your whole body. As you perform the task, begin to monitor your overall feeling of exertion. The rating you give at the end of the task should be for the effort sensation you perceive upon completion of the task.

(Subject performs six-minute trial)

Using the rating scale posted on the wall, how would you rate the overall perceived exertion of your whole body. This rating should include all feelings of discomfort and physical strain. Remember to look at the word descriptions first, then choose a suitable number.

APPENDIX D

DIFFERENTIATED RATING TRIAL INSTRUCTIONS

APPENDIX D

DIFFERENTIATED RATING TRIAL INSTRUCTIONS

You will now perform a (type of lift) lifting task for six minutes. It is important that you maintain a consistent posture for each lift.

You will be lifting from what will be referred to as a squat posture. A squat lift is performed by bending the knees to lower and lift the handles. Your back should remain as straight as possible. Locate your feet so that they are somewhere between the handles, making it easy to raise and lower the handles by bending only at the knees. Your feet should not be moved during the trial.

You will be lifting from what will be referred to as a stoop posture. A stoop lift is performed by bending from the hips to lift the handles. Your legs should remain straight and your knees should not bend. Locate your feet so that they are somewhere between the handles, making it easy to raise and lower the handles by bending from the hip. Your feet should not be moved during the trial.

At each signal you will lift the handles from the floor to overhead reach. When the handles have reached your overhead reach, lower them in a similar, controlled manner. It is important that you pay close attention to the signal tone and be sure to perform a lift at each signal. Make each lift a controlled and steady motion to the best of your ability.

At the conclusion of this six-minute trial, you will be asked to give a rating for different sensations of effort perceived throughout your body. Specifically, you will be asked to rate the exertion perceived in your arms, legs, torso, and through your chest and respiratory system, what will be called a central rating of exertion. The regions of arms, legs, and torso are shown in the diagram and are relatively self explanatory. The central rating is more difficult to illustrate. Think of this rating as your feeling of respiratory effort from the chest,, apart from any sense of strain in the working muscles.

The different body segment ratings are not necessarily dependent upon one another, that is, you may feel a high degree of exertion from your legs, while your chest and respiratory system may not feel a great deal. Conversely, you may feel a high level of exertion from your chest and respiratory system while relatively little exertion in your legs. As you perform the task think about these three sensations (arms, legs, torso, central) and begin to discriminate the degrees of exertion perceived through each of them. The ratings which you give at the end of the task should be for the effort sensations which you perceive upon completion of the task.

(Subject performs six-minute trial.)

Using the rating scale posted on the wall, and remembering to first look at the word descriptions and then choose a suitable number, how would you rate the exertion in:

your arms ?
your legs ?
your torso ?

How would you rate your central effort sensation as perceived in your chest and respiratory system ?

APPENDIX E

MAXIMUM SINGLE LIFT CAPABILITY TEST INSTRUCTIONS

APPENDIX E

MAXIMUM SINGLE LIFT CAPABILITY TEST INSTRUCTIONS

(played to subjects on audio tape)

You will now be performing a series of single lifts to determine the maximum weight you can lift safely. We will start with a light load for you to get a feel for the lift motion. Lifting from a (stoop/squat) posture you should raise the handles from the floor level to overhead reach in a continuous motion. If you are unable to lift the handles in a continuous motion with what you feel to be a safe effort, tell me. The test weight will then be lowered.

With each successful lift the test weight will be increased. If a weight is too heavy, the test weight will be lowered. There is no advantage to finalizing a weight which is too heavy for you to lift in a continuous motion with a safe effort. Likewise, there is no reward for underestimating your physical lifting capability by not attempting a weight which you can lift safely, in a continuous motion. The final test weight which is successfully lifted should be the maximum weight you can lift in a continuous motion with what you believe to be a safe effort.

APPENDIX F

EXPERIMENTAL DATA

APPENDIX F

EXPERIMENTAL DATA - STOOP POSTURE

subj.	FOwb40	FKwb40	KOwb40	arm40	leg40	torso40	central40
1	3.00	4.00	4.50	2.50	2.00	2.00	3.00
2	3.00	2.30	3.00	1.00	0.50	0.50	2.50
3	2.75	2.25	2.00	2.50	1.00	1.50	3.00
4	3.00	2.70	2.70	2.75	0.50	2.00	2.50
5	2.10	3.10	1.70	2.00	0.80	1.50	1.90
6	4.00	2.90	2.80	3.00	2.00	1.00	1.50
7	2.20	2.00	3.60	3.00	5.00	2.50	3.00
8	2.00	1.70	2.50	1.50	1.00	1.50	3.00

	FOwb75	FKwb75	KOwb75	arm75	leg75	torso75	central75
1	4.00	6.00	10.00	7.00	2.00	4.00	3.50
2	5.70	3.80	8.70	5.70	2.70	2.80	7.80
3	4.50	3.00	7.00	5.50	3.50	4.00	5.50
4	7.00	2.50	9.50	8.75	0.50	3.00	5.50
5	5.90	3.90	7.00	4.30	0.50	2.50	5.10
6	6.00	4.00	6.00	5.00	0.50	3.00	4.00
7	6.20	3.00	7.00	6.00	6.00	2.00	6.00
8	3.50	3.00	7.50	1.50	1.00	0.50	4.50

Heart Rate Data

	FOwb40	KOwb40	FKwb75	KOwb75	FKwb40	FOdiff75	FOwb75	FOdiff40
1	109	112	114	163	96	135	138	115
2	122	108	120	130	103	143	150	113
3	136	121	124	161	115	154	174	152
4	123	98	115	170	128	166	175	131
5	112	95	110	125	99	134	140	109
6	134	127	130	160	117	152	162	130
7	134	121	145	173	109	145	155	140
8	154	133	147	190	153	176	178	159

APPENDIX F

EXPERIMENTAL DATA - SQUAT POSTURE

subj.	FOwb40	FKwb40	KOwb40	arm40	leg40	torso40	central40
1	4.00	2.00	4.00	3.00	2.00	1.00	3.00
2	3.10	3.00	3.00	2.10	2.60	0.20	2.30
3	2.00	2.00	2.50	3.00	0.80	0.50	3.30
4	3.50	4.00	1.00	1.00	1.00	0.00	4.00
5	2.50	3.50	1.50	0.75	2.50	1.00	3.50
6	2.50	1.50	2.50	0.30	1.00	0.00	0.80
7	3.60	4.50	3.00	2.50	6.00	3.00	4.00
8	2.80	4.00	3.00	0.75	2.00	0.50	3.00

	FOwb75	FKwb75	KOwb75	arm75	leg75	torso75	central75
1	5.00	3.00	10.00	6.00	7.00	4.00	9.00
2	6.00	4.00	7.50	3.50	4.80	0.20	5.30
3	4.50	3.10	9.50	5.00	4.50	2.00	5.00
4	9.00	4.00	9.50	4.00	6.00	3.00	7.00
5	4.00	4.50	7.00	3.00	4.50	2.00	7.00
6	9.00	8.50	7.30	4.00	8.00	1.00	8.50
7	6.00	5.00	4.00	3.50	6.00	4.50	5.00
8	4.50	6.00	6.00	2.00	4.00	3.00	5.00

Heart Rate Data

	FOwb40	KOwb40	FKwb75	KOwb75	FKwb40	FOdiff75	FOwb75	FOdiff40
1	139	124	123	160	111	160	164	138
2	117	102	111	162	104	147	151	122
3	158	128	133	167	144	184	183	175
4	133	103	153	173	143	164	190	139
5	139	111	136	148	134	169	166	143
6	158	105	140	144	138	174	182	147
7	137	104	135	136	118	155	159	144
8	140	140	143	140	140	166	168	138

APPENDIX G

FLOOR-TO-OVERHEAD, WHOLE-BODY RATINGS PLOTTED AGAINST THE INDEPENDENT VARIABLES

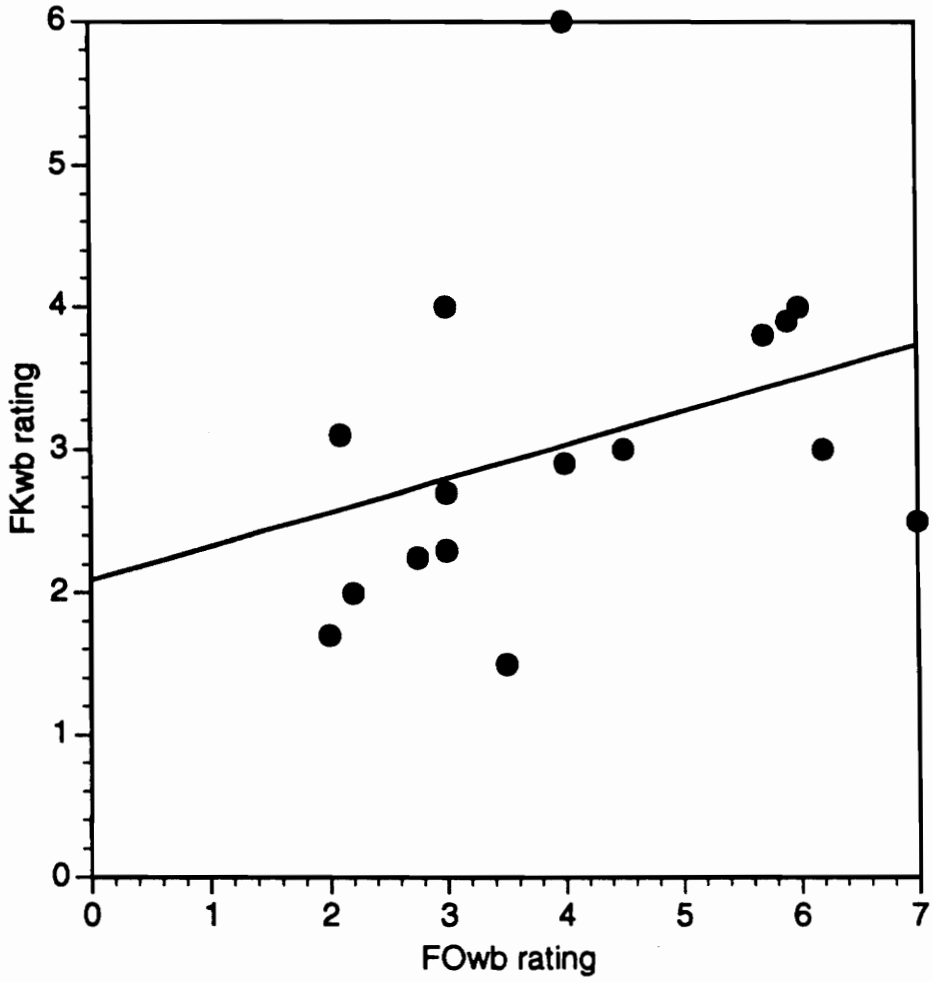

Figure G.1 FK*wb* Ratings Versus FO*wb* Ratings - Stoop Posture.

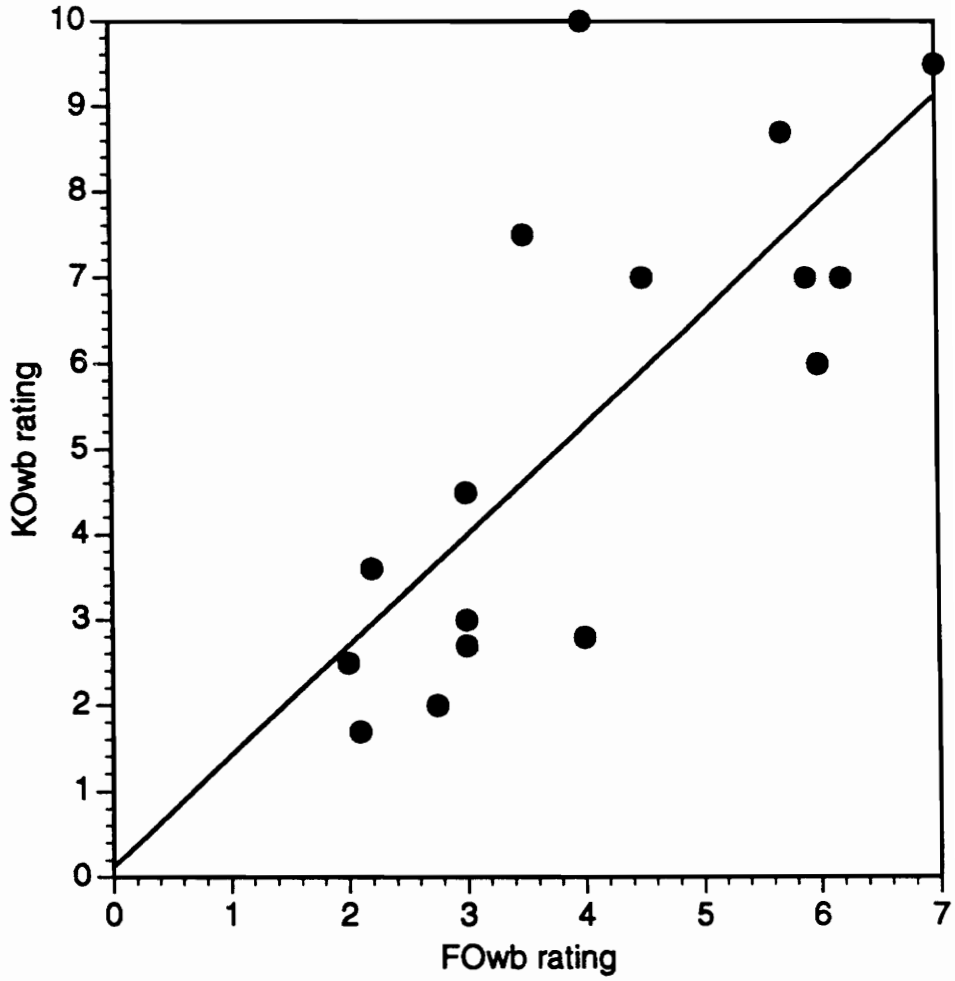

Figure G.2 KO*wb* Ratings Versus FO*wb* Ratings - Stoop Posture.

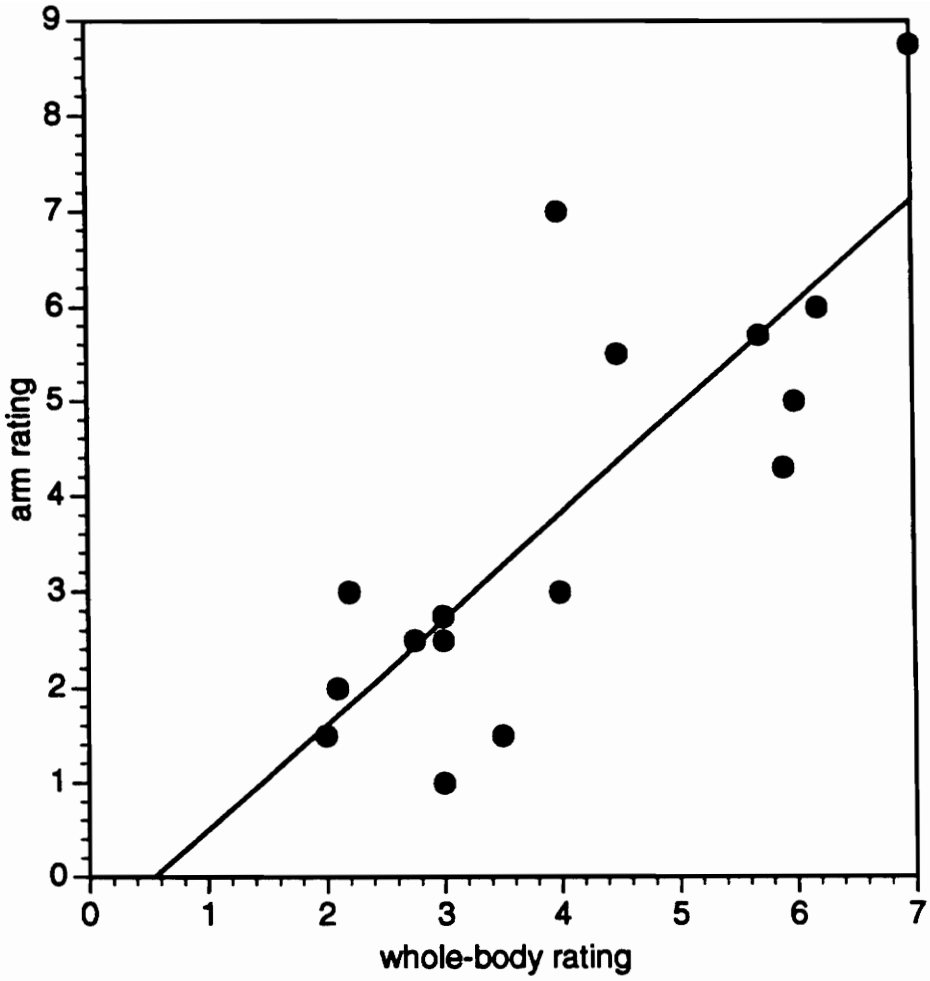

Figure G.3 Arm Ratings Versus Whole-Body Ratings - Stoop Posture.

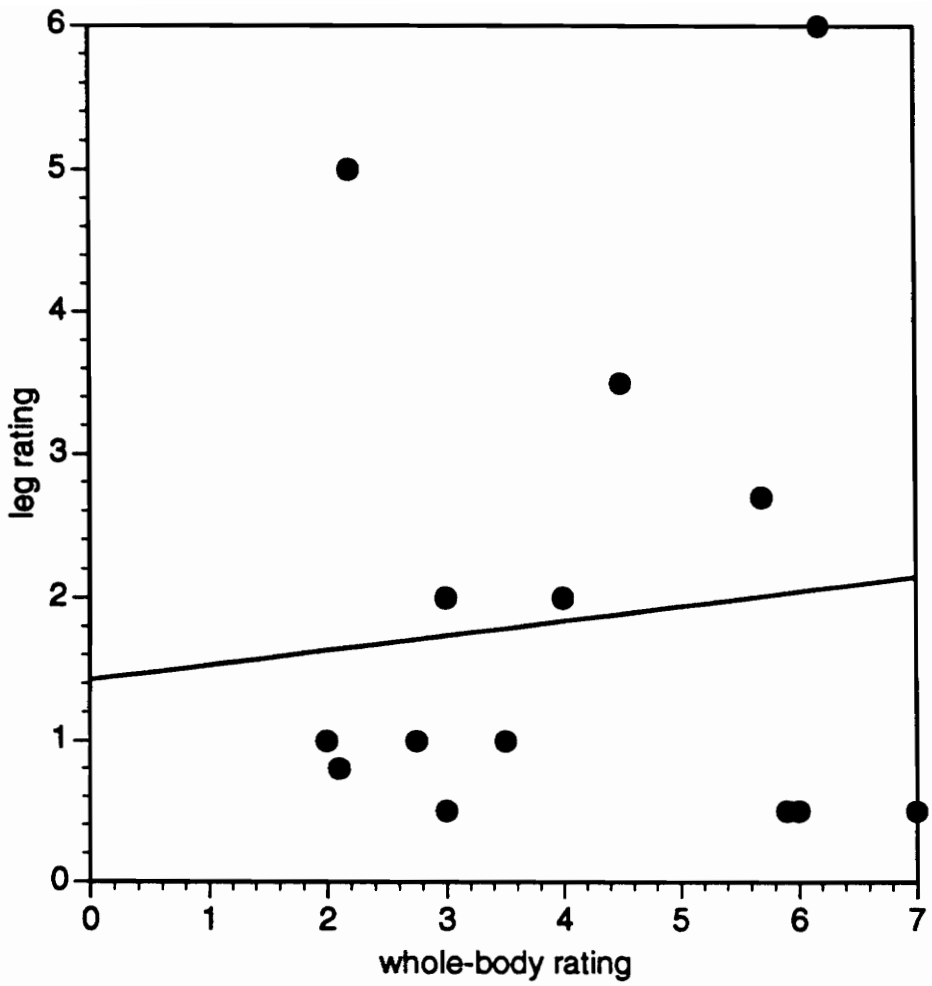

Figure G.4 Leg Ratings Versus Whole-Body Ratings - Stoop Posture.

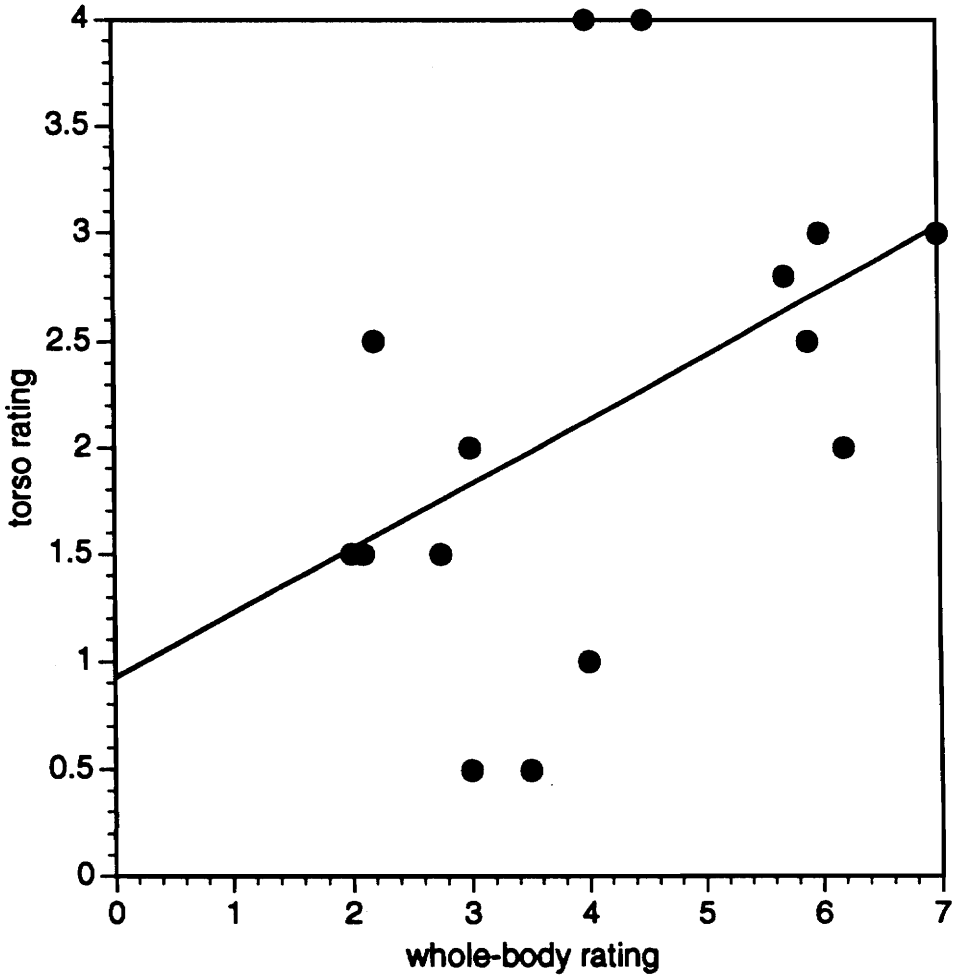

Figure G.5 Torso Ratings Versus Whole-Body Ratings - Stoop Posture.

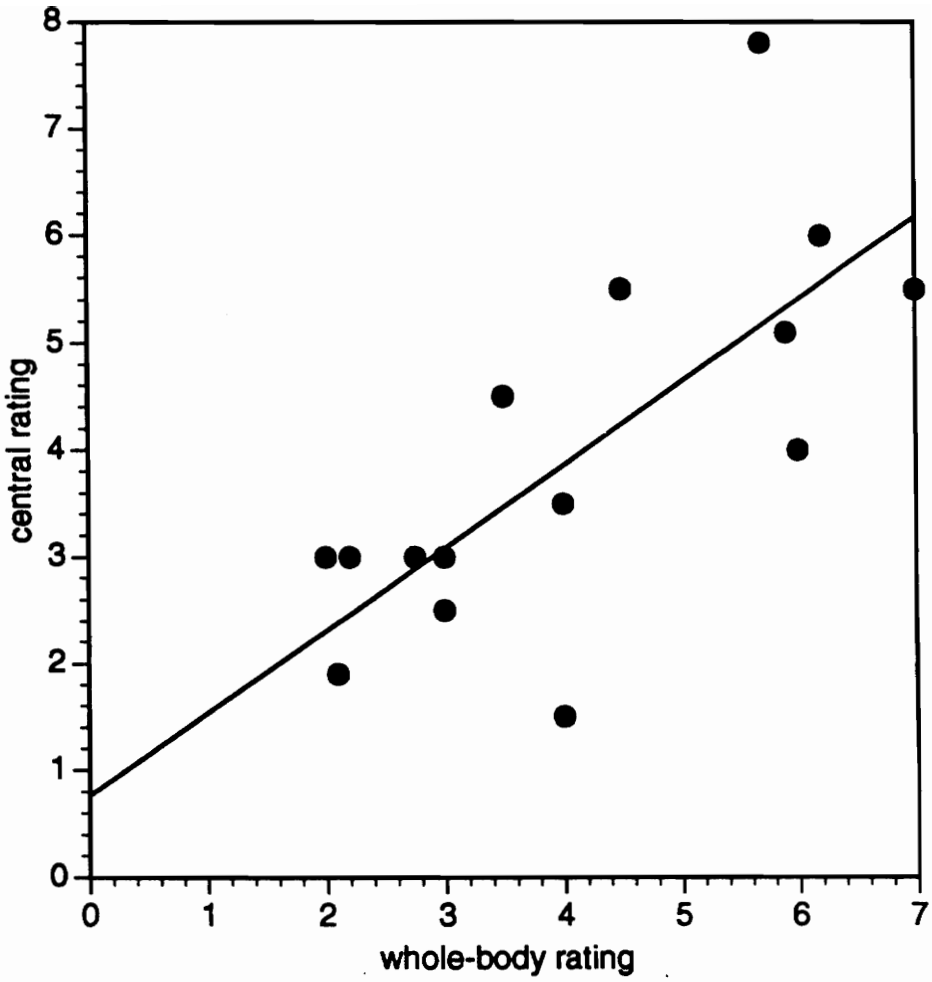

Figure G.6 Central Ratings Versus Whole-Body Ratings - Stoop Posture.

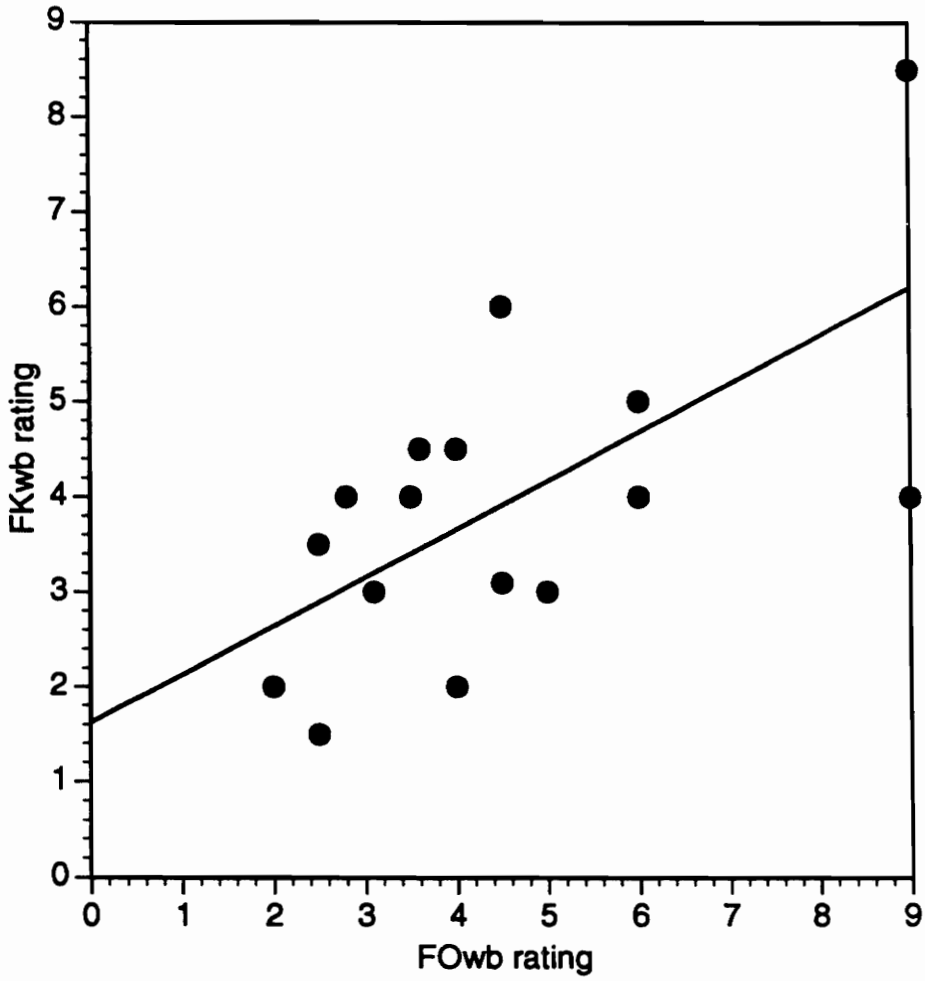

Figure G.7 FK*wb* Ratings Versus FO*wb* Ratings - Squat Posture.

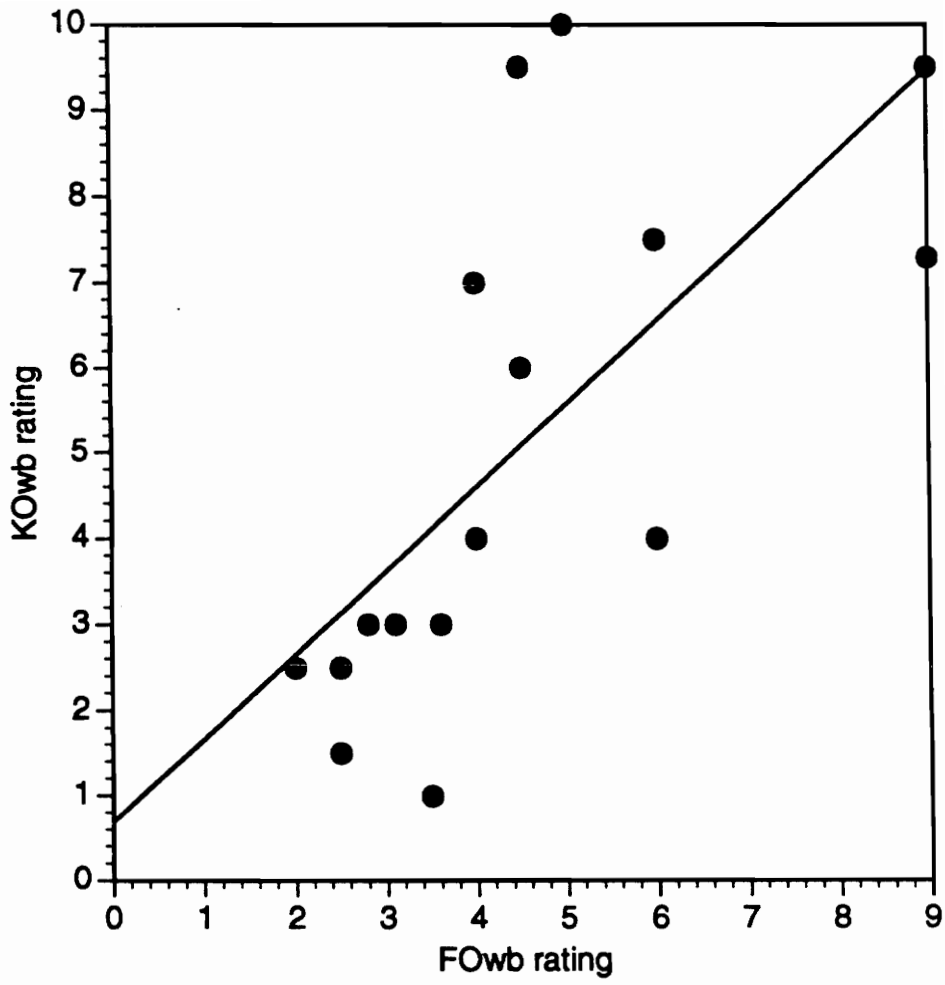

Figure G.8 KO*wb* Ratings Versus FO*wb* Ratings - Squat Posture.

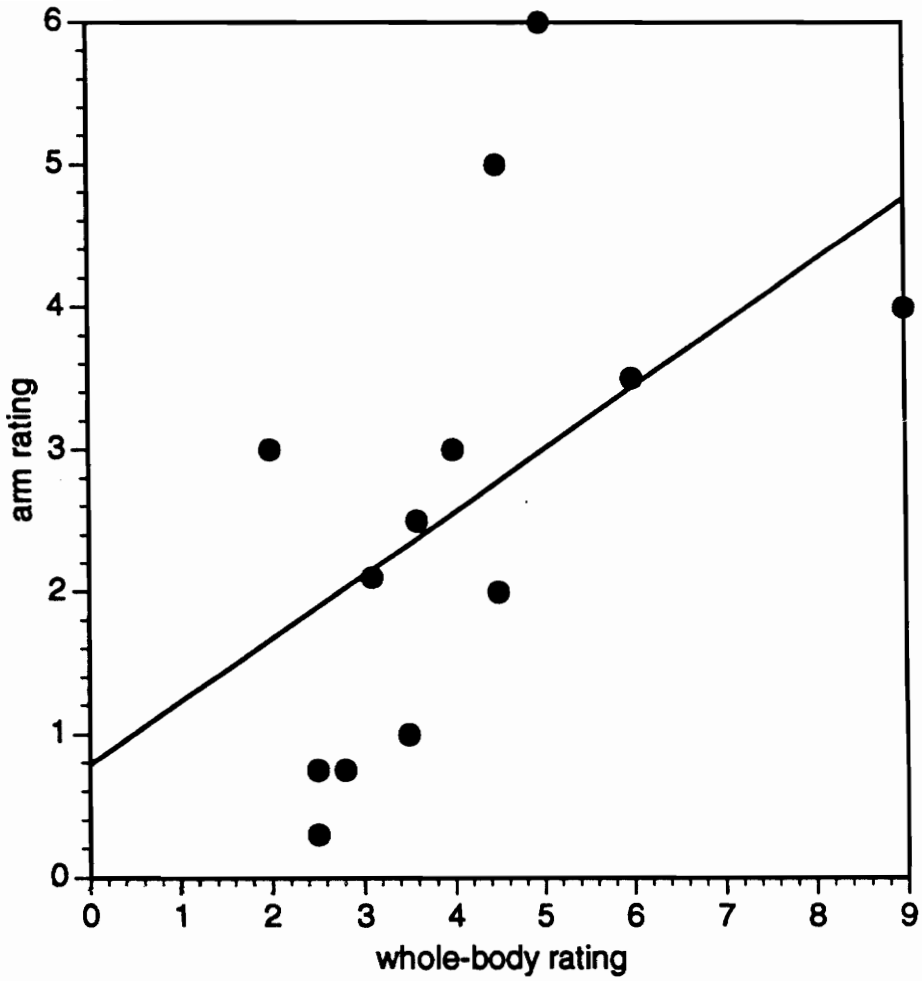

Figure G.9 Arm Ratings Versus Whole-Body Ratings - Squat Posture.

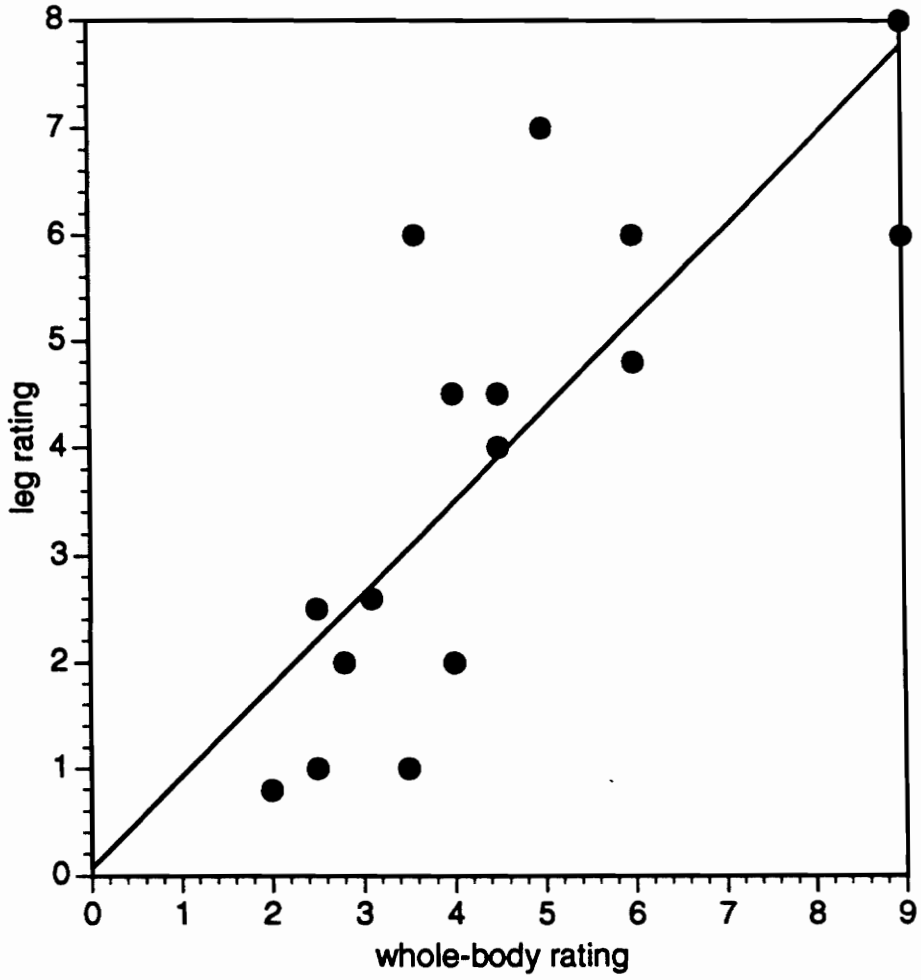

Figure G.10 Leg Ratings Versus Whole-Body Ratings - Squat Posture.

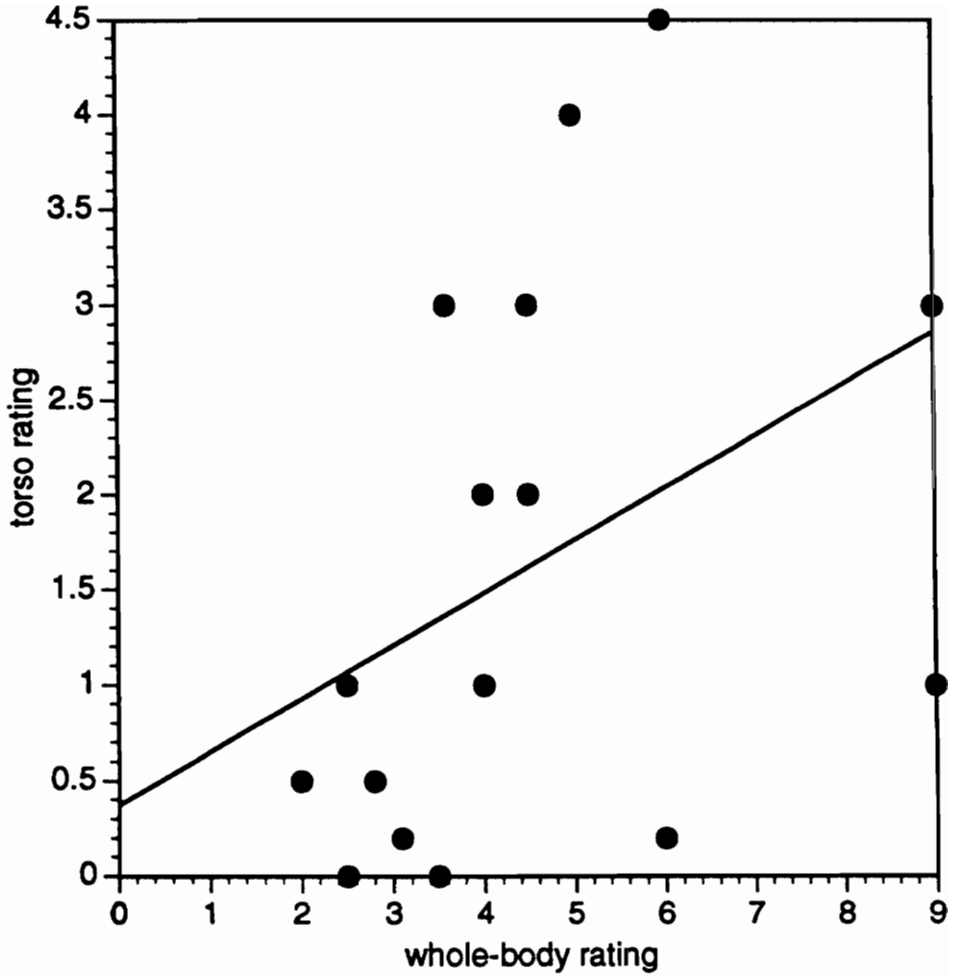

Figure G.11 **Torso Ratings** Versus Whole-Body Ratings - Squat Posture.

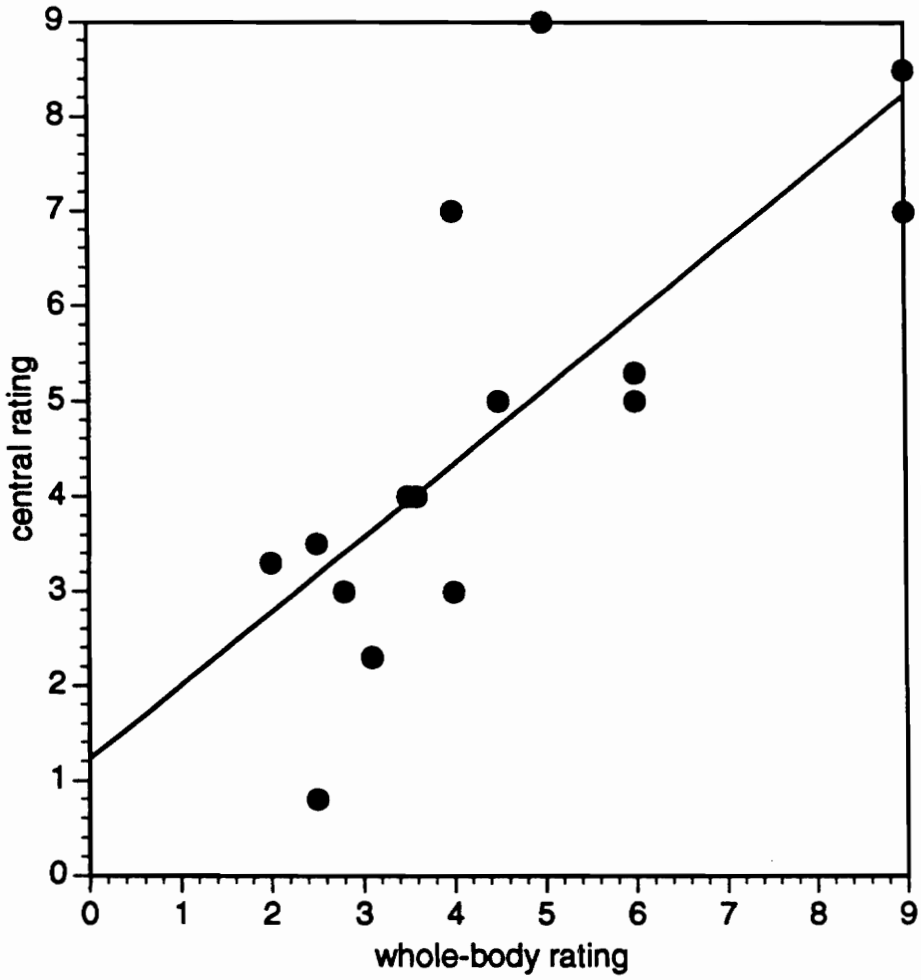

Figure G.12 Central Ratings Versus Whole-Body Ratings - Squat Posture.

VITA

Brian D. Lowe was born on February 21, 1969 in Bryn Mawr, Pennsylvania. He received a Bachelor of Science degree in Industrial Engineering from the Pennsylvania State University in May, 1991. Prior to his graduate studies he assisted several experimental psychologists in performing driver performance research for the Ketron division of the Bionetics Corporation in Great Valley, Pennsylvania. He followed his interests in industrial ergonomics and human factors engineering in the fall of 1991 at Virginia Polytechnic Institute and State University. He is a member of Tau Beta Pi, Alpha Pi Mu, and the Human Factors and Ergonomics Society.

Brian D. Lowe