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Psychophysical Methodology and the Evaluation of Manual Materials Handling and Upper Extremity Intensive Work

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I. INTRODUCTION: WHY PSYCHOPHYSICS?

Psychophysical methods are a consistent, reproducible, quick, inexpensive, and convenient way to assess the degree of physical strain on the human body. Psychophysical criteria have also been correlated with physiological criteria and some injury indices. Psychophysical methods utilize the results of the central nervous system integration of various information, including the many signals elicited from the peripheral working muscles and joints, and from the central cardiovascular and respiratory functions. All of these signals, perceptions, and experiences are combined and utilized by means of psychophysical methods.

Various physical stressors found in manual work, such as excessive forces, high rates of repetition, and awkward or sustained postures have been associated with musculoskeletal injuries. There is an absence of quantitative dose-response data that examine the relationship between work parameters and morbidity patterns. Epidemiological studies that examine the relationship between work and morbidity patterns require a lot of time and resources for data collection [1]. Biomechanical methodologies cannot address issues of repetitive work and fatigue [2,3]. Separate physiological criteria are needed for whole body or lower body tasks and upper body work [4-12]. More information is needed about the relationship between risk factors, work parameters, and the development of musculoskeletal injuries so that work can be designed to reduce the risk of the development of musculoskeletal injuries.

Another approach is a psychophysical methodology, in which subjects or workers determine the relationship between work factors and the perception of physical stress, exertion, fatigue, and discomfort on the body. Since localized muscle fatigue may be an early symptom of some use-related musculoskeletal injuries [13-15], psychophysical methodologies may serve as a more sensitive indicator for the risk of the development of musculoskeletal injuries [16].

The psychophysical methodology is an approach that allows for the simultaneous evaluation of the combined effects of different physical stressors. Specifically, the effects of different work task parameters, as well as the combined effects, can be evaluated using psychophysical methods. Psychophysical methods have been used extensively to evaluate manual materials-handling tasks, upper extremity-intensive tasks, and other manual work. A major advantage of psychophysical studies is that the results can be readily applied as guidelines in the workplace. Psychophysical data can provide guidance in the analysis and design of repeti-
tive manual work that is commonly found in manufacturing and production assembly facilities, warehouses, retail trades such as grocery and discount stores, and other workplaces.

II. BACKGROUND

Psychophysics is an old branch of psychology that studies the relationship between sensation and physical stimulus intensity. Weber’s law, from the early 1800’s, states that

\[
\frac{\Delta I}{I} = k
\]

where \(I\) = intensity of a physical stimulus, \(\Delta I\) = increment of \(I\) producing a just noticeable difference (jnd), \(k\) = constant. In essence, this means that the percentage error stays constant. The constant \(k\) is a function of the particular parameter being measured. For instance, the constant \(k\) is 3% for brightness, 7% for length, and about 2.5% (or 1/40) for weight. In practice, one cannot tell the difference between a 40-g weight and a 40.5-g weight. For one to be able to just notice the difference the second weight would have to weigh 41 g.

Fechner’s law, which is based on Weber’s law, states that sensation increases as the logarithm of physical stimulus intensity:

\[
S = k \log I
\]

where \(S\) = strength of sensation, \(k\) = constant, and \(I\) = intensity of a physical stimulus. For instance, in the judgment of loudness of sound, the sound energy increases logarithmically with respect to linear judgments, and that is why the decibel (dB) scale is used.

Over the years, it became clear that the logarithmic-linear relationship between physical stimulus intensity and sensation was an accurate description over only a limited range of physical stimulus intensity. In 1960, Stevens showed that a wider range of physical stimulus intensity could be accurately described if sensation were expressed as a power function of physical stimulus intensity [17].

III. RELEVANT CONCEPTS AND TERMINOLOGY

A. Psychophysical Methodology and Physiological Criteria

1. Psychophysical Power Law

The general form of Stevens’ power law is:

\[
\psi = k(\phi - \phi_0)^n
\]

where \(\psi\) = psychological magnitude, \(k\) = constant, \(\phi\) = physical magnitude, and \(\phi_0\) is a constant value corresponding to the threshold of detection [17]. The value of \(\phi_0\) is usually negligible, but its importance assumes larger proportions when subjective scales are extended downward to very low values [17]. For ranges of stimuli well above the minimum detectable level, the value of \(\phi_0\) is usually negligible [17].

Thus, neglecting \(\phi_0\), the psychophysical power law proposed by Stevens states that the psychological magnitude \(\psi\) is related to the physical magnitude \(\phi\) by:

\[
\psi = k\phi^n
\]

or, as stated in the terms used previously:

\[
S = k^n
\]
where $S =$ strength of sensation, $k =$ constant, and $I =$ intensity of a physical stimulus. The constant $k$ is a function of the particular unit of measurement. The exponent $n$ depends mainly on the modality tested. For perception of muscular force $n$ is about 1.6 [18], and for force of hand grip it is 1.7 [17]. The value of $n$ ranges from 0.33 for brightness to 3.5 for electric shock and is determined by magnitude estimation [17]. Using this method, the observer estimates the apparent strength or intensity of his or her subjective impressions relative to a standard. Magnitude estimation is the most useful of four principal methods to construct these ratio scales of apparent magnitude.

The power function is plotted as a straight line in log-log coordinates, with the slope of the line equal to the value of the exponent $n$. Accordingly, modern psychophysical theory [17] provides that the strength of a sensation is related by a power function to the intensity of its physical stimulus [16–26]. Most psychophysical relations may be described by this power function [17].

2. Borg Scales

The above ratio scaling methods are very good methods to describe how the subjective intensity varies with physical stimulus intensity. One major drawback of the above ratio scaling methods is that they do not provide absolute levels for interindividual comparisons. Although general functions for a group of subjects can be determined, it is difficult to compare subjects with each other because subjects are asked only to make relative comparisons. To overcome the difficulties associated with the ratio scaling methods, a category scale was developed by Borg [18]. Borg’s [18] first subjective rating scale had 21 grades. All of the odd scale values from 3 to 19 were anchored with verbal expressions, chosen so that the scale should receive a good interindividual reliability. The scale was presented to the subjects with equal distances between the figures and in the following terms: 3. Extremely light; 5. Very light; 7. Light; 9. Rather light; 11. Neither light nor laborious; 13. Rather laborious; 15. Laborious; 17. Very laborious; and 19. Extremely laborious. Very high correlations have been obtained between heart rate and these ratings during work tests [18]. This indicates the differential value of the scale but not the general validity of the growth function [27]. Since perceived exertion determined by ratio scaling methods increased with an exponent of about 1.6, Borg [18] concluded that an integration of central factors (such as heart rates) and peripheral factors (such as blood lactates, with an exponent of about 2) would explain the psychophysical variation better than any single physiological variable [27].

Another category scale for ratings of perceived exertion (RPE), shown in Table 1, was constructed by Borg [28] to increase linearly with the exercise intensity for work on a cycle ergometer. Since oxygen consumption and heart rate increase linearly with work load, this would be a convenient means of constructing a scale, even if it did violate the true growth of the perceived intensities [27]. The values of the RPE scale, shown in Table 1, grow fairly linearly with work load. The correlation between the ratings and heart rate is also very high [28]. For middle-aged persons at work loads of medium intensity, heart rate should be fairly close to 10 times the RPE value.

The Borg RPE scale has been widely used to study the perception of exertion in laboratory, clinical, and occupational settings. One of the most common uses of the RPE scale is in the clinical diagnosis of patients with coronary and respiratory disturbances. The normal growth pattern and the level of exertion change dramatically in different clinical populations. The RPE scale is also used in rehabilitation, and for the prescription and regulation of exercise intensities, or as a means to evaluate certain training situations [16]. A similar use, of interest to ergonomists, is in the evaluation of different work tasks. Perceived exertion has been used in ergonomic evaluations of heavy aerobic work tasks. However, the value of subjective estimations may be especially evident in job situations where the work tasks con-
Table 1  The Borg Scale for Ratings of Perceived Exertion (RPE)

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<tr>
<td>6</td>
<td>Very, very light</td>
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<td>7</td>
<td>Very light</td>
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<tr>
<td>8</td>
<td>Very light</td>
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<td>9</td>
<td>Fairly light</td>
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<td>10</td>
<td>Somewhat hard</td>
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<td>11</td>
<td>Hard</td>
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<td>12</td>
<td>Very hard</td>
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<tr>
<td>13</td>
<td>Very, very hard</td>
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Sist of short-term static work, intermittent or varied work, or upper extremity intensive work for which valid physiological measurements are difficult to obtain. Borg [27] suggests that the RPE scale is the best one for most applied studies of perceived exertion. The RPE scale is one of the most frequently used indices of physical stress [16-20, 22-25, 27-30].

To meet the twofold demands of ratio scaling and level estimations, Borg [27] developed the category ratio (CR) scale, shown in Table 2, so that perceptual ratings would increase as a positively accelerating function. This scale contains some of the category properties of the RPE scale, and also contains ratio properties. The verbal expressions are set so that perceptual intensity increases according to a power function. The number "10" is defined as the strongest effort and exertion a person has ever experienced [16]. Since a person may imagine an intensity that is even stronger, the "absolute" maximum is somewhat higher. By

Table 2  The Borg Category Ratio (CR) Scale of Perceived Exertion, Which Was Constructed as a Category Scale with Ratio Properties

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<tbody>
<tr>
<td>0</td>
<td>Nothing at all</td>
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<tr>
<td>0.5</td>
<td>Very, very weak (just noticeable)</td>
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<tr>
<td>1</td>
<td>Very weak</td>
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<tr>
<td>2</td>
<td>Weak</td>
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<tr>
<td>3</td>
<td>Moderate</td>
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<tr>
<td>4</td>
<td>Somewhat strong</td>
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<tr>
<td>5</td>
<td>Strong (heavy)</td>
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<tr>
<td>6</td>
<td>Very strong</td>
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<td>7</td>
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<tr>
<td>10</td>
<td>Very, very strong (almost max)</td>
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<td>*</td>
<td>Maximal</td>
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anchoring the highest number at a well-defined perception, with some degree of “sameness” for different individuals, a good point of reference is obtained [16]. Thus, two individuals working at their respective maximal working capacities will be experiencing the same degree of perceived exertion, even though their physical outputs may be different. Similarly, two individuals working at 50% of their respective working capacities will experience the same amount of perceived exertion, even though their physical outputs may be different [31]. This scale gives psychophysical functions comparable to those obtained with magnitude estimation. Exponents of about 1.6 have been obtained for perceived exertion in cycle ergometer exercise. In addition, close correlation between scale ratings and both blood lactate and muscle lactate levels have been obtained [32]. Borg [27] suggests that this scale may be best suited for subjective symptoms, such as aches and pain.

3. Visual Analog Scales

The visual analog scales (VAS) [19, 26, 30–31, 33–39] is another frequently used measurement of physical stress. One of the most common visual analog scales consists of a horizontal 10-cm line with verbal anchors or descriptions at the endpoints. The subject is instructed to indicate the degree of perceived sensory intensity by placing a vertical line at the appropriate position along the horizontal continuum. The distance from the left end of the VAS to the subject's vertical line is measured in centimeters to obtain a value between 0 and 10. A visual analog scale that has been used for the evaluation of upper extremity intensive work [30, 35–38] is shown in Figure 1.

Ulin et al. [30] used this scale and another VAS with the verbal anchors “very uncomfortable work” and “very comfortable work” on the left and right ends, respectively, and Borg’s CR scale for university students in the assessment of screw-driving tasks at different heights. She found that the scales compared in sensitivity and that any one could be used with reliable results. She suggests that the VAS may be preferred by subject populations that are not as verbally oriented as university students, or in production situations where workers do not have the time to read and consider all of the verbal anchor points of the Borg scale.

In an automobile assembly plant, Armstrong et al. [39] utilized 10-cm visual analog scales for worker assessments of hand tool mass, tool handle circumference, horizontal work location, vertical work location, and overall ratings. For tool mass, the verbal anchors used were “too heavy,” “just right,” and “too light” at 0, 5, and 10 cm, respectively, and “very uncomfortable,” “somewhat uncomfortable,” and “very comfortable” at 0, 5, and 10 cm, respectively. For tool handle circumference, the verbal anchors were “too large,” “just right,” and “too small” at 0, 5, and 10 cm, respectively. For the horizontal and vertical work locations, the verbal anchors were “very uncomfortable,” “somewhat uncomfortable,” and “very comfortable” at 0, 5, and 10 cm, respectively. The overall ratings had the verbal anchors

For a normal 8-hour workday:

![Figure 1](image-url) A 10-cm visual analog scale (VAS) with the verbal anchors “easiest imaginable work” and “hardest imaginable work” at the left and right endpoints, respectively, that has been used for the evaluation of manual work.
“very good,” “fair,” and “very poor” at 0, 5, and 10 cm, respectively. Males and females did not differ significantly in their assessments. The workers’ subjective assessments using the 10-cm visual analog scales showed strong correlations with the tool characteristics and the work tasks.

Borg [19] compared different rating methods, among them a 11-cm VAS with the verbal anchors “no exertion at all” and “maximal exertion” on the left and right endpoints of the scale, respectively. For short-time work on a bicycle ergometer, good correlations between heart rate and perceived exertion ratings were obtained independently of which scale was used. In addition, the correlation coefficients between heart rate and perceived exertion ratings were very similar for the different methods of the physical work tests. Similarly, Harms-Ringdahl et al. [33] found that there was no significant difference between the ratings made on a 10-cm VAS and Borg’s category scale for ratings of perceived pain (BRPP), which is similar to the CR scale, for the assessment of pain in response to loading of soft tissue structures at the radial side of the elbow joint.

Neely et al. [31] compared a 10-cm VAS with the verbal anchors “MIN” and “MAX” on the left and right endpoints, respectively, with Borg’s CR scale, heart rate, and blood lactate levels for leg exertion during an exercise test using a bicycle ergometer. As is usual in these kinds of tests, heart rate correlated well with power. The physiological measures of heart rate and blood lactate levels (an indicator of peripheral strain) were correlated with both the CR and VAS ratings of leg exertion.

Seymour et al. [34] evaluated VASs of different lengths (5, 10, 15, and 20 cm) with the verbal anchors “no pain” and “worst pain imaginable” on the left and right endpoints, respectively. Also evaluated were 10-cm VASs with different verbal anchors on the right endpoints (“troublesome,” “miserable,” “intense,” “unbearable,” and “worst pain imaginable”). For dental pain among males and females, high correlations were found between the scores on all of the scales. Scales of length 10 or 15 cm had the smallest measurement error. Considering the different verbal anchors, the scale with the verbal anchor “worst pain imaginable” was found to be the best choice for comparing present pain or worst pain between different groups. Using this scale, no significant difference was found between males and females, or between patients with different dental conditions. Seymour et al. [34] suggest that the use of a 10-cm VAS with the verbal anchor “worst pain imaginable” was the most suitable in the measurement of dental pain. Similarly, Price et al. [26] found that a 15-cm VAS was a valid and reliable measure for both the intensity and the unpleasantness of experimentally induced pain from noxious heat stimuli delivered to the forearm, or for chronic back and/or shoulder pain.

In conclusion, it appears that visual analog scales with a length of approximately 10 cm and verbal anchors suited to the extremes of the intensity of the physical stress of concern may provide results that are well correlated with both physical measures (e.g., tool characteristics, work tasks) and physiological measures.

4. Preferred Maximums

In ergonomic assessments of physical work tasks, the various Borg scales and visual analog scales have been used to rate the physical intensity of the work tasks. The subjects are given a task to perform and then are instructed to rate the work, utilizing the scales as if they were performing the task for a normal 8-hr workday. Thus, a determination of the intensity of the work can be made to compare different work tasks and their parameters, such as weight, frequency, and so forth.

Another way that psychophysics has been applied in the study of work is in the determination of preferred maximums. The subject is given control of one of the task parameters
or variables, usually the weight of the object being handled. All of the other task parameters or variables, such as frequency, size, distance, and so on are kept constant. Subjects are instructed to work as hard as they can without straining themselves or without becoming unusually tired, weakened, overheated, or out of breath [40,41]. Individual subjects integrate all of their sensory inputs, monitor their feelings of exertion and fatigue, and adjust the weight accordingly. In this way, a preferred maximum for the particular task is obtained.

This preferred maximum methodology has been utilized extensively in studies of manual materials handling [24,40-58], to determine maximum weights or forces, frequencies, and so on for various lifting, lowering, pushing, pulling, and carrying tasks. When weight is the variable that is adjusted, the resulting preferred maximum may be referred to as the maximum acceptable weight of lift (MAL) [42]. When weight and/or frequency are the variables adjusted, the resulting preferred maximum workload may be calculated for comparison purposes as the maximum acceptable workload (MAWL), which is equal to the load in kg × frequency in actions/minute × distance lifted in meters [43].

This preferred maximum methodology has also been utilized in upper extremity intensive work. Krawczyk et al. [35,37] had subjects adjust the weight for a repetitive upper extremity transfer task. The results are shown in Figure 2. As frequency and distance increased, the preferred weight decreased. Similarly, Kim and Fernandez [59] and Marley and Fernandez [60,61] had subjects determine the maximum acceptable frequency for hand-held pneumatic drilling tasks. Likewise, Putz-Anderson and Galinsky [62] had subjects psychophysically determine maximum work durations for repetitive elevated arm movement tasks. Snook et al. [63] had subjects psychophysically determine maximum forces for wrist flexion and extension.

Researchers [42,44] have found significant differences in psychophysical studies between male industrial workers and students, and between female industrial workers and housewives, respectively. Thus, in psychophysical studies, it is especially important that the subject population be the same type as the target population in which the psychophysical results are to be

Figure 2 Mean preferred weights for each of the frequency and distance combinations for an upper extremity transfer task, over an 8-hr workday, for 20 industrial subjects. 95% confidence intervals are shown by error bars.
applied. For instance, if the target population is industrial workers, then the experimental subject population should also be industrial workers.

5. Lower Body Versus Upper Body Work

For whole body or lower body tasks, where the large muscle groups in the legs are used, perceived exertion ratings and physiological criteria, such as heart rate and oxygen consumption, are highly correlated [5, 19, 24, 28, 31, 64–66]. Some physiological measures, such as heart rate, do not respond equivalently for whole body or lower body tasks and upper body work. Physiological methodologies where heart rate, measures of oxygen consumption, and energy expenditure criteria are monitored are not as sensitive to upper extremity work [4–12]. For instance, heart rate tends to increase more for arm work than for whole body or lower body tasks. Thus, physiological fatigue criteria that have been developed from leg or whole body exertions cannot validly be applied to tasks performed by the arms. Separate physiological fatigue criteria are needed for tasks that involve mainly arm work.

Snook and Irvine [4] found that there were no significant differences in heart rate for arm work in a laboratory setting and at a shoe factory. However, there was a significant heart rate difference between arm lifts and leg lifts performed in the laboratory. They concluded that fatigue criteria that have been developed from leg tasks cannot validly be applied to tasks performed mainly by the arms; energy expenditure rate guidelines for arm tasks should be lower than those for leg tasks. Based on their results, the mean heart rate should not exceed 99 beats/minute for arm tasks and 112 beats/minute for leg tasks.

Gamberale [5] examined the relationships between perceived exertion and physiological indicators of exertion during different exercises. Borg’s RPE scale was used to determine perceived exertion at different work loads for lifting weights with the arms, working with a wheelbarrow, and also exercising on a bicycle ergometer. In addition, heart rate, oxygen uptake, and blood lactate concentration were measured. There was a linear relationship between RPE and heart rate independent of the kind of work producing the physical exertion. For all three exercises, a closer relationship to heart rate was obtained when the subjects rated their overall feeling of exertion, rather than the exertion on the arms or on the legs. However, the highest level of perceived exertion in relation to heart rate was found in the exercise of lifting weights with the arms. This exercise also yielded the highest level of blood lactate concentration in relation to oxygen uptake. The blood lactate concentrations in the exercise of lifting weights were higher than in the exercise of pushing the wheelbarrow, even though the oxygen uptake was lower. At a given level of oxygen uptake, the exercise of lifting weights was more anaerobic in character than the exercise of pushing the wheelbarrow and of working on the bicycle ergometer. These results suggest that the higher the blood lactate concentration an exercise produces as compared with oxygen uptake, the higher will be the level of the overall perception of exertion as compared with heart rate. In addition, the higher the blood lactate concentration an exercise produces as compared to oxygen uptake, the higher will be the perceived exertion on the most involved muscle groups as compared with the overall perceived exertion.

Similarly, Borg et al. [6] examined perceived exertion using the RPE and the CR scales related to heart rate and blood lactate concentration during arm and leg exercise. The arm and leg exercise was performed on bicycle ergometers, one of which was specially adapted for arm exercise. The responses obtained were at least twice as high for arm cranking as for cycling. The largest difference was found for blood lactate concentration, and the smallest for RPE and heart rate. The incremental functions were similar in both exercises, with approximately linear increases in RPE and heart rate, and positively accelerating functions for CR and blood lactate concentration.
Psychophysical Methodology and Manual Materials Handling

When perceived exertion on the CR scale was set as the dependent variable and a simple combination of heart rate and blood lactate was used as the independent variable, a linear relationship was obtained for both kinds of exercise, as had been previously found for cycling, running, and walking. Thus, for exercise of a steady-state type with increasing loads, the incremental curve for perceived exertion can be predicted from a simple combination of heart rate and blood lactate [6].

Mermier et al. [7] also compared upper and lower body activities and found significantly different results for upper body versus lower body tasks. Three tasks were used: exercising on a cycle ergometer, lifting (waist to shoulder height), and vacuuming. Their goal was to estimate ventilation by using ventilation-on-heart-rate regressions established during exercise testing to estimate ventilation in the field. For men and women, ventilation increased more steeply relative to heart rate for the exercises involving the upper body (lifting and vacuuming) compared with the lower body exercise (cycling). The regression coefficient describing the increase of ventilation with heart rate was approximately 30% greater with upper body exercise. The differences in the mean regressions for upper and lower body exercise tended to be greater in women than in men. However, these physiological criteria were consistent in that ventilation-on-heart-rate regression slopes derived from tests in which progressively increasing workloads were used were comparable to those obtained during variable and non-progressive protocols.

From these studies, it can be concluded that the psychophysical indices are correlated with the physiological indices; however, the relationships are different for arm work than for whole body or lower body work. The physiological indices are clearly more sensitive for upper body or arm work than for whole body or lower body tasks. Thus, different physiological guidelines should be used for arm work compared with whole body or lower body work.

B. Psychophysical Consistency and Reproducibility

1. Borg Scales and Visual Analog Scales

The Borg scales, VASs and variations of these scales have been shown to be consistent and reproducible for measurement and comparison of physical stimuli [4,34–38,40,45–53, 56,59,60–61,67–68] regardless of which scale was used [19,25–26,30–33]. Borg [19] compared four different rating methods: the RPE scale, graded from 6 to 20; the original Borg scale: graded from 1 to 21; a 9-point graded scale; and an 11-cm visual analog scale. Good correlations between heart rates and perceived exertion ratings were obtained independently of which scale was used. The correlations between the different ratings were also satisfactory. Similarly, Aristila et al. [25] compared three variations of the Borg scale and found good correlation of the perceived exertion ratings with heart rate and excellent reproducibility.

Krawczyk et al. [35,37] found that the VAS perceived exertion ratings for an upper extremity transfer task were consistent throughout an 8-hr workday, as shown in Figure 3. Harms-Ringdahl et al. [33] compared Borg's category scale for ratings of perceived pain (BRPP) and a 10-cm VAS and found no significant difference between the two scales. There was also no significant difference between the first and second time a scale was used by the same subject. Ulin et al. [30] found equivalent results for Borg's CR scale and two different 10-cm visual analog scales with different sets of verbal anchors in the evaluation of pneumatic screw-driving tasks. Seymour et al. [34] compared visual analog scales of different lengths (5, 10, 15, and 20 cm) and 10-cm visual analog scales with different verbal anchors on the right endpoints. High correlation was found between the scores on all of the scales. No significant difference was found between scores recorded by males and females or between those given by patients with two different dental conditions. Likewise, Price et al. [26] found that 15-cm
Figure 3. Overall mean VAS-perceived exertion ratings combined for all frequencies and distances at the end of each hour throughout an 8-hr workday, for an upper extremity transfer task, for 20 industrial subjects. 95% confidence intervals are shown by error bars.

VASs can be used as a valid and reliable measure for both the intensity and the unpleasantness of experimentally induced pain or chronic (back and/or shoulder) pain.

2. Manual Materials Handling

Psychophysical methodologies have been shown to be consistent for manual materials-handling tasks. Ciriello et al. [45] found that subjects were able to determine their maximum acceptable weights and forces for various manual materials-handling tasks during the first 40 min of testing, and that they remained consistent throughout the 4-hr duration of the test session. Ljungberg et al. [24] found that it took subjects only 5–10 min to select a weight for lifting tasks that remained consistent over one hour. Snook and Irvine [40] found that subjects were able to determine their maximum acceptable frequency of lifting in 40 min.

Psychophysical methodologies have been shown to be reproducible for manual materials handling tasks. Snook and Irvine [40] replicated an experiment three times and showed only insignificant differences among the three replications. Griffin et al. [46] found only a 7% decrease, which was not significant, between test and retest one week later for acceptable weights of lifting. Similarly, Foreman et al. [47] found a 7% decrease in the rating of acceptable dynamic lifting strength between two days, and the difference was not statistically significant. Fernandez et al. [48,49] concluded that the psychophysical approach was reproducible as subjects arrived at the same estimates of lifting capacity in repeated trials. Legg and Myles [52,53] found that maximum acceptable load for lifting determined two times a day for five days did not change significantly. When this load was used over an 8-hr workday, soldiers performed the lifting and lowering tasks without metabolic, cardiovascular, or subjective evidence of fatigue.

Conversely, Mital [54] found a larger decrease in the maximum acceptable weight of lift throughout an 8-hr workday when compared to estimates made at 25 min. Much of this decrease in the maximum acceptable weight took place by the completion of the second hour. After two hours, the slope of the decrease in acceptable weight had leveled off.
The differences in results from these manual materials-handling studies may be due to a frequency effect. Ciriello and Snook [55] reported the tendency of the psychophysical method to produce overestimates of maximum acceptable weights and forces for tasks with very high frequencies. This was verified with experiments of 4-hr duration by Karwowski and Yates [50–51] and 8-hr duration by Fernandez et al. [48,49]. These studies [48–51] found that selected lifting weights did not differ significantly with time at low frequencies, but that at high frequencies there were larger, sometimes significant decreases. Since Mital [54] combined all frequencies in his results, the decrease with time may have been due to this frequency effect.

3. Upper Extremity Intensive Work

Psychophysical methods have been shown to be consistent for upper extremity intensive work. Krawczyk et al. [35,37] found that subjects could accurately predict their perceived exertion for a normal 8-hr workday for a repetitive upper extremity transfer task after one hour. After subjects performed the same task throughout a full 8-hr workday, the difference in the perceived exertion between the first two hours and the last two hours of performing the repetitive upper extremity transfer tasks was only 8%, as shown in Figure 3. Thus, the perceived exertion rating made in the first two hours, where subjects were supposed to imagine what it would be like to perform the task “for a normal 8-hr workday,” closely agreed with what they thought eight hours later, after they had actually performed the transfer task for eight hours. Likewise, the difference in the maximum preferred weights between the first two hours and the last two hours of performing the repetitive upper extremity transfer tasks was only 5%, as shown in Figure 4.

Thus, perceived exertion and preferred weight were both consistent when determined at hourly intervals throughout an 8-hr workday. In addition, these results verified that a psychophysical determination for a “normal 8-hr workday” does not require a full 8-hr workday.

Other studies have also shown that perceived exertion is consistent over time. Krawczyk and Armstrong [35,36] found no significant differences in perceived exertion at 30, 60, 90, and 120 min for a similar repetitive upper extremity transfer task performed over a 2-hr time period. Likewise, in another study, Krawczyk et al. [35,38] found no significant differences

![Figure 4](image)

Figure 4 Overall mean preferred weights combined for all frequencies and distances at the end of each hour throughout an 8-hr workday, for an upper extremity transfer task, for 20 industrial subjects. 95% confidence intervals are shown by error bars.
in perceived exertion determined after 30 and 60 min for combinations of transferring and screw-driving tasks.

Psychophysical methods have been shown to be reproducible for upper extremity intensive work too. Ulin et al. [30] used Borg and two different VASs to rate perceived exertion for pneumatic screw-driving tasks and found equivalent results regardless of which scale was used. Kim and Fernandez [59] and Marley and Fernandez [60, 61] found no significant differences in the maximum acceptable frequency for three experimental replications of hand-held pneumatic drilling tasks.

4. Preferred Maximums: Initially Heavy Versus Initially Light

In the determination of maximum acceptable preferred weights, when subjects started with a heavy container weight, Krawczyk et al. [35, 37] found that the resultant preferred weight for an upper extremity transfer task was greater than that determined when starting with a light weight. This is shown in Figure 4, where hours 1, 3, 5, and 7 were started with a heavy container weight and hours 2, 4, 6, and 8 were started with a light weight. This difference was statistically significant. However, it is not of practical significance since this difference was only about 3%. The perceived exertions shown in Figure 3 also reflect this; hours 1, 3, 5, and 7 were slightly greater than hours 2, 4, 6, and 8. Legg and Myles [52, 53] found this same trend for manual materials-handling tasks. The difference was 15%; however, it was not statistically significant. To eliminate the effect of the initial weight, the resultant preferred weights determined from an initially heavy container weight and an initially light container weight should be averaged together.

IV. PSYCHOPHYSICAL CRITERIA FOR ERGONOMIC APPLICATION

A. Psychophysical Criteria and Injury Indices

Psychophysical measures of physical stress have been correlated with health outcomes, disability, and compensation [69, 70]. Psychophysical criteria have been used in developing recommendations for permissible workloads. After numerous studies investigating different manual materials-handling tasks, Snook [56] concluded that designing the job to fit the worker, using psychophysically determined guidelines, can reduce up to one-third of industrial back injuries. Other studies [69, 71–72] have shown that overexertion injuries would be reduced if manual materials-handling tasks were designed to match acceptable levels of perceived exertion. Snook [70] reviewed a number of studies, suggesting that the setting of maximum permissible workloads in industry would have a significant effect upon low-back disability and low-back compensation.

B. Psychophysical Studies in Manual Materials Handling and Upper Extremity Intensive Work

1. Overview

The psychophysical methodology: is an approach that allows the evaluation of the combined effects of different physical stressors to be evaluated simultaneously. Psychophysical methodologies have been used extensively in the evaluation and design of manual materials handling tasks [5, 22, 24, 40–58, 64–68, 73–78] such as lifting, lowering, pushing, pulling, carrying, and also walking tasks. The National Institute for Occupational Safety and Health (NIOSH) [79–81] equation for the design and evaluation of manual lifting tasks utilizes biomechanical, physiological, and psychophysical criteria. Researchers at the Liberty Mutual
Insurance Company [56-57] have composed extensive tables of psychophysically determined maximum acceptable weights and forces for manual materials handling tasks to serve as guidelines that are consistent with worker capabilities and limitations. The variables in these studies included task frequency, distance, height and duration, object size and handles, extended horizontal reach, and combination tasks. The guidelines are intended to assist industry in the control of low back pain through reductions in initial episodes, length of disability, and recurrences [82].

Likewise, utilizing psychophysically determined guidelines for upper extremity intensive work may reduce the risk of the development of upper extremity cumulative trauma disorders (CTDs) or repetitive stress injuries (RSIs), such as carpal tunnel syndrome (CTS). Psychophysical methodologies have been used to assess upper extremity intensive work and different hand tools, to derive guidelines for the design of upper extremity work [4,10-11,30,35-39,59-62,83-96].

At present, the psychophysical methodology may be the most appropriate way to evaluate upper extremity intensive work. Unfortunately, there are no definitive data concerning what constitutes excessive quantities of the work-related risk factors: force, repetition, awkward postures, mechanical stresses, vibration, and cold temperature [97,98]. More information is needed about the relationship between risk factors, work parameters, and the development of CTDs so that work can be designed to reduce the risk of the development of CTDs. Epidemiological studies that examine the relationship between work and morbidity patterns require a lot of time and resources to collect these types of data [1]. Biomechanical methodologies cannot address repetitive work and fatigue issues [2,3]. As discussed earlier (Section III.A.5.), physiological methodologies, where heart rate, measures of oxygen consumption, and energy expenditure criteria are monitored, are not as sensitive for upper extremity work [4-12].

In the absence of validated epidemiological, biomechanical, or physiological methods of assessing upper extremity intensive work, an alternative approach is a psychophysical methodology, in which subjects or workers determine the relationship between work factors and the perception of physical stress, exertion, fatigue, and discomfort on the body. Since localized muscle fatigue may be an early symptom of use-related CTDs [13-15], psychophysical methodologies may serve as a more sensitive indicator for the risk of the development of CTDs [16].

2. Task Variables

Weight. An increase in perceived exertion with increased weight has been found in manual materials-handling tasks (whole-body exertions) [5,22,24,52,64,74,99], as well as a decrease in working endurance time [77]. Similarly, an increase in perceived exertion with increased weight or force on the upper extremity has been found by researchers examining one-handed lifts [10,11,35-37], repetitive arm elevations [12], screw driving [93,95], drilling [59], and gripping tasks [91]. Decreased psychophysically determined work durations [62] and increased electromyographic activities [100] have also been found in the upper extremities with increased weight or force.

When the variable adjusted by the subject is weight, how does the preferred maximum weight for an 8-hr workday compare to maximum strength? Pytel and Kamon [58] found that for males and females, the maximum acceptable load selected for repetitive lifting (manual materials handling, whole-body exertions) was 22% of the experimental maximum load that an individual was able to lift once without risk of injury. In comparison, Krawczyk et al. [35,37] found that for males and females, the maximum preferred weights for a repetitive upper extremity transfer task ranged from 3.3 to 6.1 kg, as shown in Figure 2. The smallest preferred weight of 3.3 kg occurred at a repetition rate of 30 transfers/minute and a transfer
distance of 1.0 m, and the largest maximum preferred weight of 6.1 kg occurred at 10 transfers/minute and 0.5 m distance. These maximum preferred weights were 16–29% of the measured "upper extremity strength."

As frequency increases, preferred weight decreases in studies of maximum preferred weights or forces, when weight or force is the variable adjusted by the subject. This is shown in Figure 2. Numerous studies have shown a frequency and weight tradeoff: as frequency increased, psychophysically determined acceptable weight or force decreased [35,37,41,45, 48–51,55,56,66,67,74]; or, as weight or force increased, psychophysically determined acceptable frequency decreased [11,40,56,59,74,91,92].

Some upper extremity studies have shown that the effect of weight was greater than the effect of frequency [10,35,36,100]. For manual materials-handling tasks, the total psychophysically determined maximum acceptable workload (load in kg × frequency in actions/minute × distance lifted in meters) was affected more by weight than by frequency, which results in a higher workload performed at higher frequencies [24,43,56,75]. This result is in accordance with the frequency effect discussed earlier (Section III.B.2.) for manual materials-handling tasks: the tendency of the psychophysical method to produce overestimates of maximum acceptable weights and forces for tasks with high frequencies. Similarly, the results of an 8-hr study [35,37] of preferred maximum weights for the upper extremity, showed that subjects tolerated a higher perceived exertion rating with higher task frequency, as shown in Figure 5, even though they were always supposed to be working at their maximum level.

Frequency. An increase in perceived exertion with increased task frequency has been found in manual materials handling tasks [64,66,74,76], as well as a decrease in working endurance time [76,77]. Similarly, an increase in perceived exertion with increased task frequency for upper extremity tasks has been found by researchers for one-handed lifts [10,35–37], as shown in Figure 5, and for screw-driving tasks [96]. Decreased psychophysically determined work durations [62] and increased electromyographic activities [100] have also been found in the upper extremities with increased task frequency.

![Figure 5](image_url)

**Figure 5** Mean VAS perceived exertion ratings for each of the frequency and distance combinations for an upper extremity transfer task, over an 8-hr workday, for 20 industrial subjects. 95% confidence intervals are shown by error bars.
Increasing frequency obviously does not increase the static strength required for the task. However, the rate of energy expenditure will increase as transfer frequency increases, and to a lesser degree as weight increases. Increases in the rate of energy expenditure have been shown to increase perceived exertion for whole-body exertions [5, 19, 24, 64–66, 73]. However, remember (Section III.A.5.) that physiological methodologies are not as sensitive for upper extremity work [4–12].

Energy expenditure rates do not appear to be the limiting factor in upper extremity intensive work. By process of elimination, this provides more credence that inadequate recovery time for the upper extremity, and the resulting localized discomfort and fatigue, may be a limiting factor. For the upper extremity, a frequency threshold may exist [35, 36]. Below this threshold significant increases or decreases in perceived exertion do not occur, and above this threshold there is inadequate recovery time for the upper extremity, resulting in greater perceived exertion, localized discomfort and fatigue, and presumably greater risk of the development of CTDs. Indeed, morphological tissue changes (resembling peritendinitis crepitans) may occur in over exercised limbs and have been experimentally induced by over-exercising the hind limb in rabbits [101]. Thus, time and load characteristics have been correlated with a subsequent cumulative trauma injury. Likewise, an accumulation of strain was found to occur in tendinous tissues of the upper extremity during physiological loading in human cadaver hands [102].

Distance. Distance is a task variable that consists of yet another whole series of variables. The NIOSH [81] equation for the design and evaluation of manual lifting tasks has three distances: the vertical travel distance between the origin and the destination of the lift, the vertical distance of the hands from the floor, and the horizontal distance of the hands from midpoint between the ankles. The Liberty Mutual Insurance Company [56, 57] tables of psychophysically determined maximum acceptable weights and forces for manual materials-handling tasks also have many aspects of distance: the vertical distance of lifting or lowering; the distance away from the body (box width); the distances of floor level to knuckle height, knuckle height to shoulder height, and shoulder height to arm reach for lifting and lowering; the distances of close to the body and extended horizontal reach for lift; the distance of pushing, pulling, or carrying; and the vertical distance from the floor to the hands for the pushing, pulling, and carrying tasks. Usually these distances are significant and should be considered, but for some tasks they may not be significant. This will depend on the distance considered and the task involved. For instance, no significant differences in maximum acceptable weight were observed among six different box sizes in the carrying tasks [57]. Thus, one should refer to the psychophysical tables [56, 57] to determine what is appropriate for the application involved.

Similarly, there are many aspects of distance for upper extremity intensive work. For upper extremity work, the distance component may be significant in that it acutely affects posture. In a repetitive upper extremity transfer task [35, 37], as distance increased, perceived exertion increased and preferred weight decreased for distances of 50 and 100 cm, as shown in Figures 5 and 2, respectively. The distance was lateral, producing a side-to-side motion in front of the subjects. The 50-cm distance neither challenged nor exceeded the reach envelope (where one can reach) for all subjects, while the 100-cm distance challenged the reach envelope. Thus, the different distances had some effect on the trunk posture and the resultant moments produced about the shoulder, elbow, and wrist. However, in a similar repetitive upper extremity transfer task, Krawczyk and Armstrong [35, 36] found no significant distance effect on perceived exertion for distances of 25, 51, and 76 cm. Again, these transfer distances required a lateral displacement, producing a side-to-side transfer motion right
in front of the subject. However, none of these distances challenged or exceeded the reach envelope for all subjects. Thus, postural changes were not required at the different distances.

In a similar study [11] of upper extremity one-handed lifts in the horizontal plane that considered distances measured from in front of the body, subjects stood in front of a 91-cm-high work table and were required to move dumbbell distances of 38 and 63 cm towards themselves. This task required some trunk flexion, and the distances were found to be significantly different for a 2.3-kg load, while no significant difference was found between the two distances for a 4.5-kg load. In another study where the distance parameter required postural changes, Ulin et al. [94] found that ratings of perceived exertion increased with increasing horizontal distance away from the body for screw-driving tasks. In a checkstand configuration study [89], design variations (89- and 76-cm heights, and 8- and 23-cm distances), which ultimately affected the transfer distance and body posture, had significant effects on some comfort ratings. Likewise, postural discomfort has been shown to increase as a function of horizontal and vertical distance from the body for automobile assembly tasks [39]. Other upper extremity studies have found significant distance effects when the distances studied were vertical work heights [30,62].

Another factor which was shown importance is the direction of the transfer distance. Increased electromyographic activities [100] have been found in the upper extremity with different directions of movements from outward points within the reach (20–230° measured from the frontal plane of the subjects) to a fixed point near the body for a constant 38-cm transfer distance.

3. Design Applicability

Psychophysical methodologies are quick, relatively inexpensive, and convenient. Psychophysical criteria have also been shown to be consistent and reproducible, and well correlated with physiological criteria and some injury indices. In addition, a major advantage of psychophysical studies is that the results can be readily applied as guidelines in the workplace, such as in manufacturing and production assembly facilities, warehouses, and retail trades, for example, grocery and discount stores.

The results of preferred maximum studies can be directly applied, such as the Liberty Mutual Insurance Company [56,57] tables of psychophysically determined maximum acceptable weights and forces for manual materials-handling tasks, and the preferred weight results for the upper extremity transfer tasks shown in Figure 2. In this case, work tasks can be designed within these work parameters. The objective would be to modify the weight, frequency, distance, and other task parameters singularly or in combination to fit both the psychophysically determined acceptable task parameters (Liberty Mutual Insurance Company tables or Figure 2) and then given requirements for the particular work task. For instance, if for a given transfer task the frequency were fixed, say, at a particular assembly line speed, weight and/or distance could be modified appropriately. Conversely, if weight were held constant, frequency and/or distance could be modified. For example, Figure 2 shows that the average maximum preferred weight should be 6.1 kg for a one-handed upper extremity transfer task at a work pace of 10 transfers/minute and a distance of 0.5 m. Conversely, for a one-handed upper extremity transfer task of 6.1 kg at a distance of 0.5 m, the frequency should be ≤10 transfers/minute.

The NIOSH [81] equation for the design and evaluation of manual lifting tasks utilizes biomechanical, physiological, and psychophysical criteria, and thus provides another method to directly apply psychophysical criteria as workplace guidelines. For studies of perceived exertion, at least a relative rating with respect to different work tasks and sometimes an absolute measure with respect to heart rate (Borg RPE scale) can be obtained. In addition, Section
IV.C. shows how discomfort analyses may be used to determine the effects of specific task and workstation attributes.

For both manual materials handling tasks and upper extremity intensive work, weight or force has been shown to have the most significant effect [10, 35, 36, 100]. Thus, weight and force may be the most important work parameter to consider in the analysis and design of work. For example, to decrease the weight for the worker, the following questions should be considered: Does the object to be lifted need to be that heavy? Could the object be made out of a lighter material? Could the object be made less bulky, so that it could be lifted closer to the body? Could it be lifted in parts? Does the object need to be manually lifted and/or transferred? Could the workstation be modified to partially or fully support the weight of the object? Could a mechanical assist (e.g., hoist, articulating arm) be used to transfer or support the object? Weight or force guidelines are shown in the Liberty Mutual Insurance Company tables and in Figure 2.

The second most important parameter to consider may be frequency or work pace [35, 36]. As frequency increases, perceived exertion increases and preferred weight decreases, as shown in Figures 5 and 2, respectively. The Liberty Mutual Insurance Company tables and Figure 2 show some frequency guidelines. Recalling that there may be a frequency threshold for upper extremity transfer tasks [35, 36], if the task frequency were 30 or more transfers/minute, a decrease in perceived exertion would occur if the frequency were decreased to 20 transfers/minute. However, further decreases in frequency below 20 transfers/minute may not have a significant effect on perceived exertion.

Distance may also be an appropriate parameter to consider in the analysis and design of work. As distance increases, perceived exertion increases and preferred weight decreases, as shown in Figures 5 and 2, respectively. The Liberty Mutual Insurance Company tables and Figure 2 give some distance guidelines. For the upper extremity, some studies have shown the importance of different distances, especially if the different distances produce postural changes, whereas lateral, side-to-side distances within the reach envelope may have only a minimal effect on perceived exertion [35, 36]. Thus, decreases in distance within the reach envelope may not significantly decrease perceived exertion.

In conclusion, psychophysical data can provide guidance in the analysis and design of manual materials-handling tasks, upper extremity intensive tasks, and other manual work. Further studies of work-related musculoskeletal injuries and health surveillance will be required to determine the effect of decreased perceived exertion, discomfort, and fatigue, and to verify the effectiveness of psychophysically determined guidelines in reducing the risk of work-related musculoskeletal injuries. Until psychophysically determined guidelines are validated as effective in helping to reduce the risk of the development of work-related musculoskeletal injuries, they should be used in conjunction with both an active and passive surveillance program. If it is found that workers are adversely affected while using psychophysically determined guidelines, appropriate workplace and medical interventions should be implemented.

4. Work Enlargement

Psychophysical studies can be used to verify the positive effects of work enlargement. Krawczyk et al. [36, 38] used a psychophysical methodology to examine combination tasks consisting of upper extremity transferring and screw-driving components. Five combination tasks were performed with different proportions of transferring and screw driving: 100% transfer, 75% transfer and 25% screw drive, 50% transfer and 50% screw drive, 25% transfer and 75% screw drive, and 100% screw drive. The left hand always performed the transferring component and the right hand always performed the screw-driving component of the combination tasks. The positive effect of using both extremities to perform the different components of the
combination tasks was verified using VAS perceived exertion ratings and body part discomfort analyses.

Overall VAS perceived exertion decreased as the work was enlarged to utilize both upper extremities. Figure 6 shows that the lowest mean overall VAS perceived exertion rating was for the 50% transferring and 50% screw-driving task. The workload of this task was evenly distributed between the left and right upper extremities, since the transferring was done with the left hand and the screw driving was done with the right hand. By allowing different extremities to perform the task components, the frequency for each extremity was effectively decreased. Consequently, this task allowed the maximum amount of physiological recovery time that could be provided simultaneously for both the left and right upper extremities. Most subjects reported a preference for the balanced nature of this combination task.

The overall VAS perceived exertion increased as the combination task utilized more of one upper extremity than the other and involved more of either the transferring or screw driving task components, as shown in Figure 6. Thus, the left upper extremity (transferring component) or the right upper extremity (screw-driving component) would become the limiting factor of the work. Even though the less varied tasks affected only one extremity, this limiting factor affected overall VAS ratings.

The highest overall perceived exertions were for the tasks that required only transferring or only screw driving, as shown in Figure 6. These tasks allowed the least amount of physiological recovery time for the upper extremity (left or right) that was responsible for performing the task. When there is not enough recovery time, the body part experiences fatigue and discomfort. Body part discomfort surveys showed a proportional increase in frequency and severity of discomfort (using a discomfort VAS, shown in Section IV.C., Figure 8) in the respective upper extremity that was required to perform a greater proportion of the combination tasks.

In addition to the overall VAS perceived exertion, the subjects used separate visual analog scales to rate the perceived exertion of the transferring and screw-driving components. As shown in Figure 7, as the transferring proportion of the task increased, the transferring perceived exertion increased. Likewise, as the screw-driving proportion of the task increased, the screw-driving perceived exertion increased. Psychophysical methods are usually used to

![Figure 6](image_url)

Figure 6 Mean overall VAS perceived exertion ratings for an upper extremity combination task involving transferring (performed with the left hand) and screw-driving (performed with the right hand) components, for 24 industrial subjects. 95% confidence intervals shown by error bars.
combine the effects of physical stressors such as weight and frequency [5, 22, 24, 35–37, 40–58, 64–68, 73–78]. However, in these upper extremity combination tasks that required two components (transferring and screw driving), subjects were able to do the opposite: to separate the effects of physical stressors. Subjects were able to discriminate between the transferring and screw-driving parts of the tasks, and to give a psychophysical rating accordingly.

The body part discomfort surveys revealed that the less varied work, which utilized more of one upper extremity than the other and involved more of one particular task component (transferring or screw driving), produced greater body part discomfort severity concentrated in fewer body parts. Conversely, the more varied work produced decreased body part discomfort severity, and the discomfort was more evenly distributed throughout the different body parts. Similarly, Westgaard and Jansen [103] found that production workers had significantly higher symptom scores of self-reported musculoskeletal complaints for some body parts than did the group with more varied work tasks.

### C. Discomfort Analyses

Psychophysical methodologies utilize an individual's perception of physical strain on the human body. From this perception, individuals may rate how hard they feel that they are working using Borg or VASs, or they may adjust a work variable to achieve a maximum level of normal workday exertion. When carried out over a period of time, this perception will incorporate feelings of exertion and also feelings of fatigue and discomfort.

Another way to assess individual perception of exertion over time is by tracking discomfort directly. Both overall and body part discomfort can be monitored for both frequency (how often) and severity (how much) [30, 35–39, 65, 83–90, 95, 96, 99, 104–107, 109–112]. The frequency of overall and body part discomfort can be determined simply by asking individuals if they have any discomfort, either overall or in particular body parts or regions of the body. Likewise, the severity of discomfort can be quantified using various rating scales for overall discomfort or discomfort in particular body parts or regions of the body. A VAS such
as the one shown in Figure 1, with the verbal anchors “easiest imaginable work” and “hardest imaginable work” on the left and right endpoints, respectively, can be used to determine overall discomfort. As explained earlier, the results from the VAS shown in Figure 1 were comparable to the results from the VAS with “very uncomfortable work” and “very comfortable work” anchors [30]. Thus, it appears that as long as the two verbal anchors represent extremes of some work-related physical intensity, the results will be comparable. For body part discomfort, separate VASs can be used for each body part or region, with the anchors “no discomfort at all” and “worst imaginable discomfort” [35,38], as shown in Figure 8. A simple numerical scale may also be used to quantify discomfort severity. In this case, the individual picks a number to represent his or her discomfort, say, from 0 to 7 or from 0 to 9 [104], where the numbers are verbally anchored by comfort and discomfort descriptions. This can be done for overall discomfort and also separately for each body part or region. Specific types of discomfort, such as pain, soreness, stiffness, numbness, and tingling, may also be quantified [63]. The relative severity of body part discomfort may be determined by using a body part discomfort survey that shows a body part diagram and asks the individual to rate the different body parts from most discomfort to least discomfort [105,106].

Discomfort has been associated with poor work performance [84,85,105–107]. Corlett and Bishop [105,106] found that relieving the discomfort of workers increased work output and reduced production costs. Many upper extremity intensive tasks cause discomfort, fatigue, and pain [30,35–38,88–90,95,96,108]. Discomfort analyses have been shown to be beneficial in the evaluation of various work apparatus [39,65,95,109–111], tasks [35–38,83–87, 96,99,104,112], and workstations [30,39,88–90,95,96,105–107]. For instance, for automobile assembly tasks, postural discomfort has been shown to increase as a function of horizontal and vertical distance from the body [39]. Since localized muscle fatigue may be an early symptom of use-related upper extremity cumulative trauma disorders [13–15], discomfort analyses may serve as a more sensitive indicator for the risk of the development of some work-related musculoskeletal disorders.

Krawczyk et al. [35–38] used both VAS perceived exertion ratings and body part discomfort data to verify that the overall VAS perceived exertion ratings were a reflection of

![Figure 8](image)

Figure 8 A body part discomfort survey with 10-cm VASs for each body part, with the verbal anchors “no discomfort at all” and “worst imaginable discomfort” on the left and right endpoints, respectively, that has been used for the evaluation of manual work. Using this body part discomfort survey, discomfort frequency and severity can be assessed for particular body parts or regions of the body.
the discomfort in the upper extremities due to the performance of upper extremity intensive work, and that perceived exertion ratings may be an appropriate measure to use for overall assessment of the tasks. The tasks were repetitive upper extremity transfer tasks and pneumatic screw-driving tasks. Hagberg [12] found that increases in ratings or perceived exertion with work load indicated an importance of local factors, that is strain on muscles and tendons. Likewise, Wiker et al. [86,87] found that global reports of discomfort or fatigue were strongly related to the severity of symptoms experienced in specific muscle groups. Similarly, Yoshitake [104] found that general fatigue correlated well with symptoms of fatigue in some part of the body. Nevertheless, Kuorinka [83] concluded that local discomfort ratings were more sensitive to differences in work methods, and thus, more reliable than general discomfort ratings for ergonomic purposes.

Body part discomfort analyses may provide specific information about the relationship between task and workstation attributes (e.g., upper extremity intensive, height adjusted, standing) and their effects on the body. In a checkstand configuration study [89], subjects were found capable of distinguishing specific symptoms related to different checkstand designs.

Body part discomfort analyses may reveal additional aspects of a job that may be important for task analysis and redesign. For example, Krawczyk et al. [35-37] used body part discomfort analyses in two different studies of upper extremity transfer tasks and verified a positive effect of table height adjustment with respect to lower back, torso, and buttocks discomfort. In one study [37], where the height of the horizontal conveyor was adjusted so that the vertically oriented container handle was at elbow height for each subject, the reported lower back, torso, and buttocks discomfort was minimal, with an cumulative response rate of less than 14%. Whereas, in the other study [36], when the table height was fixed at 91 cm for each subject, the lower back, torso, and buttocks region was reported to be among most uncomfortable body regions. A full 75% rated this as one of the five most uncomfortable body regions (of a total of eleven). On average, the lower back, torso, and buttocks region was the fourth most uncomfortable body part—ranked just after the dominant upper extremity body parts and just ahead of the lower legs and feet. This was despite the fact that in the former study with minimal lower back, torso, and buttocks discomfort, the experimental workday was a full 8-hr duration. And, in the latter study with much more lower back, torso, and buttocks discomfort, the experimental task was carried out for only two hours each day, with lower weights and shorter distances too. These studies certainly suggest that the discomfort of the lower back can be decreased or minimized by adjusting the workstation height appropriately for each worker. These discomfort analyses show the relative importance of the effects of different workplace design attributes that may be addressed to minimize body part discomfort. Similar results have been shown in other upper extremity intensive work. Ayoub [88] found that all cashiers experienced some type of body pain. The areas that caused discomfort were the back, feet, legs, shoulders, neck, knees, hands, elbows, and wrists. Back pains occurred among 90% of the cashiers.

In Krawczyk et al.'s [35-38] studies of upper extremity intensive work, the subjects were standing while performing the work tasks. Even though the experimental tasks were mainly upper extremity intensive, the standing component taxed the lower extremities. This was evident since in addition to upper extremity discomfort, there was also a substantial number of discomfort responses in the lower legs and feet, and the number of discomfort responses for the lower legs and feet increased throughout the workday. Similarly, in a study of seven supermarkets, Ryan [90] found that the checkout department had the highest rates of discomfort or pain symptoms for almost all body areas. The lower back, lower limbs, and feet were the body areas with the highest rates of discomfort or pain symptoms. Ryan [90] found a positive and significant correlation between the proportion of time spent standing and symptoms
in the lower limb and foot, especially in the checkout department, where 90% of the time was spent standing in one place. Rys and Konz [110] also found that body comfort decreases as the duration of the standing work increases, regardless of the type of floor. They found the greatest increases in discomfort in the lower body parts. None of the upper parts of the body had comfort significantly affected by floor surface.

In conclusion, discomfort analyses may serve as a sensitive indicator for the risk of the development of work-related musculoskeletal disorders. Overall and body part discomfort analyses may provide specific information about aspects of the work apparatus, tasks, and workstations that need to be addressed. Minimizing work-related discomfort may improve worker performance, increase output, decrease production costs [84,85,105–107], and increase worker satisfaction.

V. CONCLUSION

Psychophysical methods are a consistent, reproducible, quick, inexpensive, and convenient way to assess the degree of physical strain on the human body. Psychophysical criteria have been correlated with physiological criteria and some injury indices. Psychophysical methods utilize the results of the central nervous system integration of various information, including the many signals elicited from the peripheral working muscles and joints, and from the central cardiovascular and respiratory functions. All of these signals, perceptions, and experiences are combined and utilized with psychophysical methods.

The effects of different work task parameters, as well as the combined effects, can be evaluated using psychophysical methods. A major advantage of psychophysical studies is that the results can be readily applied as guidelines in the workplace. Psychophysical data can provide guidance in the analysis and design of repetitive manual work tasks, such as those found in manufacturing and production assembly facilities, warehouses, retail trades (e.g., grocery and discount stores), and other workplaces. The objective should be to modify the weight, frequency, distance, and other task parameters singularly or in combination to fit both the psychophysically determined acceptable task parameters and the given requirements for a particular work task. In addition, body part discomfort analyses may contribute specific information about the relationship between task and workstation attributes (e.g., upper extremity intensive, height adjusted, standing) and their effects on the body.

Health surveillance is required to verify the effectiveness of psychophysically determined guidelines in reducing the risk of work-related musculoskeletal injuries. Further studies of work-related musculoskeletal injuries and health surveillance is required to determine the effect of decreased perceived exertion, discomfort, and fatigue, and to verify the effectiveness of psychophysically determined guidelines in reducing the risk of work-related musculoskeletal injuries. Until psychophysically determined guidelines are validated as effective in helping to reduce the risk of the development of work-related musculoskeletal injuries, they should be used in conjunction with both an active and passive surveillance program. If it is found that workers are adversely affected while using psychophysically determined guidelines, appropriate workplace and medical interventions should be implemented.

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