Chapter 4

Perceived Exertion as a Function of Physical Effort

Vern Putz-Anderson, PhD
Katharyn A. Grant, PhD

Introduction

To what extent can a worker's perception of exertion be used to establish what is an acceptable level of work? There is an increasing body of knowledge that suggests that safe levels of work can be established using psychophysical and psycho-scaling tools to assess the worker's perception of exertion. The purpose of this chapter is to (1) review laboratory methods used to assess the perceived exertion of workers, (2) examine the role of task variables that affect perceived exertion (ie, force, work rate, and type of work—static versus dynamic) and (3) assess the potential of psychological methods for achieving the goal of establishing safe levels of work.

Numerous studies over the last 10 years have investigated the occupational causes of upper extremity musculoskeletal disorders. Armstrong and associates[1] recently reviewed a series of epidemiologic studies that linked various job or task attributes with disorders affecting the musculoskeletal system. To date, however, relatively few studies have been conducted that provide information which defines the limits of acceptable or safe manual work for the majority of healthy workers. One reason may be the manner in which human work capacity is assessed.

To assess work capacity and the potential for musculoskeletal injury, investigators rely on one or two approaches: If the work is heavy, but intermittent, biomechanical measures of strength may serve as indicators of work capacity. If the work is light, but continuous, physiological measures of endurance may be needed. Studies of muscle endurance, for example, provide useful information on the strength of an individual muscle or even a group of muscles. However, the problem is that even simple manual work activities can require the use of numerous muscles, joints, ligaments, and tendons in varying degrees.[2] Information on the functioning of one or more muscles cannot provide much predictive insight as to the level of exertion a worker is *willing* to experience to carry out the job safely.

The findings from a number of studies of muscle fatigue suggest that few muscle groups can maintain a static exertion or contractile force for more than a few minutes without the subject experiencing significant pain.[3] The actual duration of exertion depends on the load and the individual muscle group used. To measure the maximum duration of contraction, a load is selected that is some fraction of the individual's maximum voluntary contraction (MVC). The higher the level of MVC, the more rapid is the onset of fatigue and the shorter is the voluntary contraction duration. Rohmert[4] recognized this relationship as logarithmic. There is a logarithmic relationship between the holding time of a muscle group and the maximum force it is required to maintain; ie, as force increases, holding time decreases in a geometric progression.

The results of maximum-effort studies are useful in establishing the limiting endurance levels of physiologic fatigue for various exertions. The findings provide little guidance, however, in establishing submaximal or acceptable levels of effort for work performed over the course of an 8-hour day.

Ultimately, what work a person is willing to do each day depends on the level of fatigue experienced. When the discomfort from muscle fatigue exceeds a personal threshold, the worker seeks ways in which to reduce the aversive state. Depending on the job and supervision, a worker may conceal a rest break, change a work routine, or, at the extreme, stop working. If these recourses are prohibited and the worker is compelled to continue to work with increasing fatigue or pain and with reduced capacity, the safety of work is endangered and, over time, occupational impairments are likely.

Attempts at evaluating the effects of fatigue on worker behavior have been largely impeded by the lack of adequate methods of measurement. In the past researchers have tried to identify a single test to measure industrial fatigue.[5] Today, most industrial psychologists recognize that fatigue is more than a decline in muscle contraction, a fall in critical flicker fusion, or an increase in blood lactate concentration. Work fatigue can be regarded as a perceptual issue, an "experienced self-evaluation," integrating psychological (motivational) and sensory information.[6]

Although there are no single tests for isolating the experience of fatigue, psychophysical techniques have been used to research methods for quantifying the perception of physical events.[7] Psychophysics is concerned with the quantitative relationship between physical changes in stimulation and the subject's awareness of that stimulation. Some of the earliest psychophysical studies explored the perception of weight and force.[8,9] More recently, the variables of exertion, discomfort, and effort involved in work performance have been investigated.[10]

Perceived Exertion

Psychophysical studies of perceived exertion during work, for example, on a bicycle ergometer, indicate that perceived intensity increases with the physical work load according to a positively accelerating function, which can be described by a power function with an exponent of 1.6.[11] This relationship is consistent with Stevens's power model for subjective assessments.[12]

Stevens and Cain[13] expanded the research on the perception of muscular fatigue to include the role of duration. Recognizing that work is a function of force applied over time, Stevens and Cain identified a power function that describes the growth of perceived exertion (PE) with respect to load and duration of the exertion. Using data from hand grip contraction, the exponent for force was twice that for duration, as shown below. The relationship is expressed as $PE = k * Load^{1.7} * Duration^{0.7}$. The constant, k, defines individual strength differences.

The exponent for load indicates that the perception of exertion increases at a rapid rate relative to changes in the physical load, whereas the exponent for duration indicates a more gradual change in perceived exertion as duration increases. The exponents were derived from studies of highly repetitive work, such as bicycle pedaling. For static or eccentric work, the exponent would be larger. The implication is that with an equivalent load, perceived fatigue increases at a faster rate for static work than for dynamic work.[14,15] Regardless of the size of the exponent, it is apparent from the multiplicative relationship between load and duration (holding perceived effort constant) that variations in load will produce compensatory variations in duration. This reflects the everyday experience that heavy loads cannot be supported for as long as lighter loads.

Studies also indicate that individuals are capable of reliably estimating their endurance in a physical task and that there is a strong positive correlation between the objective and subjective aspects of a fatigue state.[16–18] Caldwell and Smith[19] and Park and Rodbard[20] suggested that the sensation of local muscle/joint pain is a reliable indicator of physiologic stress associated with physical work load. Moreover, Park and Rodbard noted that the subjective feelings associated with static loads increase consistently with the level of accumulated pain-inducing metabolites.

Further evidence of the close relationship between subjective and objective aspects of work endurance is reported by Tanii and associates.[21] In computing the endurance time course for different forces that loaded the arm, they found that the median time for onset of pain sensation occurs at between 30% and 40% of the maximum endurance time. For example, if the maximum endurance was 60 seconds for a given task, the subject would begin to experience pain between 18 and 24 seconds after the task began. Hence, the sensation of pain can be used as an early warning sign for overexertion that is time-locked to the course of maximum work endurance. Corlett and associates[22,23] also recognized that "acceptable discomfort" was a valid measure for evaluating how long a person could hold a work posture.

In addition to pain, several other studies in recent years have been conducted to evaluate the importance of physiological cues in the rating of exertion. Pandolf[24] concluded that two factors determine the level of perceived exertion: a local factor (ie, sensations or feelings of strain in the working muscles and/or joints) and a central factor (ie, sensations or feelings primarily associated with the cardiorespiratory system). Central factors contribute to the sensation of exertion when large muscle groups are involved and the work exceeds intensities of 50% aerobic power. Local factors contribute to the sensation of exertion for tasks in which static postures are maintained. For static postures, sensory cues are extracted primarily from muscle spindles, Golgi tendon organs, and various mechanoreceptors. As a result, joints such as the shoulder girdle with its rich supply of muscles and tendons are capable of responding to very distinct levels of static or repetitive loading.

Rating Scales

The two Borg scales provide a practical example of the application of psychophysical methods in the field of ergonomics.[25] In 1970, Borg[26] published the first of his scales, entitled the Rating of Perceived Exertion (RPE) scale (Table 1). The RPE scale consists of 15 numbers from 6 to 20, accompanied by nine descriptive labels that ranged from "no exertion" at one end to "maximum exertion" at the bottom of the scale. For practical purposes, he chose a simple category rating scale, in contrast to the ratio scaling methods used by Stevens and Cain.[13] The RPE scale was designed to grow linearly with exercise intensity and heart rate during work on a bicycle ergometer. Borg chose the numerical values on the RPE scale to correspond to one-tenth value of the heart rate. For example, a person performing a task in which a heart rate of 90 beats

Table 1 Borg 15-point rating of perceived exertion (RPE) scale*

Rating	Scale
6	No exertion at all
7	
8	Extremely light
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

* Scale of perceived whole-body exertion

per minute occurs would likely rate that task on the RPE scale as a 9 (very light). The RPE scale has proven useful in exercise physiology for the evaluation and monitoring of exercise intensities. In 1982, Borg[27] developed the second of his scales, which has become known as the CR-10 scale because it is based on category ratios of 0 to 10 (Table 2).[27] The CR-10 scale is widely used for assessing the level of muscular exertion during manual work, such as lifting or carrying. The numbers on the CR-10 scale are assigned expressions that are simple and understandable by most people. Exertions assigned a "10" are defined as "very, very strong" or "very, very heavy," usually the heaviest physical work perceived by the subject. Exertions rated as a "0.5" are considered "very, very weak" intensity or "very, very light" work. When using the scale, people are permitted to use decimals and to use values greater than 10.[25] Anchoring the highest number in a very well-defined maximum effort or exertion provides a point of reference for individuals, which aids in defining "same-

Table 2 Borg CR-10 Discomfort Rating Scale*

Rating	Scale
0	No discomfort at all
0.5	Very, very weak
1	Very weak
2	Weak
3	Moderate
4	Somewhat strong
5	Strong
6	
7	Very strong
8	
9	
10	Very, very strong (maximal)

* Scale of perceived muscular exertion

ness" for different individuals. The concept of the level of effort required to assign a value of 10 on the Borg CR-10 scale has become a public unit for comparisons between noise, vibration, pain, and exertion.

Because the Borg CR-10 scale is conceptually very simple and easy to administer, the rating procedure can be carried out at almost any stage during a work task. Typically, a subject provides a response by verbally indicating the numerical point on the scale that best represents his or her degree of exertion. An alternate procedure is to use one or more points on the scale as a criterion or target value for adjusting work load.

Yonda[28] and Deeb and associates[29] tested the hypothesis that the values on the Borg CR-10 scale, when multiplied by 10, are roughly equal to the percentage of maximum muscle strength (% MVC) that a given effort requires. For example, if an individual exerts a force and rates it as a "6" on the CR-10 scale, then that person is using roughly 60% of his or her maximum strength. This relationship is not perfectly linear; studies have shown that subjects consistently overestimate their efforts at lower forces and underestimate their efforts at high forces, with nearly perfect estimation occurring near 55% of MVC.[29,30] Deeb and associates[29] demonstrated that the RPE for a specific level of effort tends to increase with age, which is consistent with what is understood about the effect of aging on strength. To account for this age effect, psychophysical recommendations for working limits may need to be based on workers representing the spectrum of the working population.

Hogan and Fleishman[31] conducted a series of psychoscaling studies to assess the reliability and validity of subjective methods for measuring perceived physical effort (PPE). They developed a PPE index, which was a condensed version of the Borg 15-point RPE scale (Table 1). The PPE index consisted of a 7-point scale with the same labels as the Borg RPE scale with the numerical intervals reduced by half, beginning with "1" instead of "6." They found that relatively inexperienced participants could accurately and reliably characterize the physical effort of various common tasks using the PPE index. The tasks included activities such as sawing wood, carrying trays, operating a crane, and stocking shelves. The actual task ratings provided by the inexperienced participants were highly correlated (r = .88) with actual metabolic costs and measures of biomechanical or ergonomic demands. The authors concluded that the PPE index, even in the hands of inexperienced individuals, would be very useful as a job analysis method for physically demanding work.[32]

Acceptability Scaling

Much of the original psychophysical research into manual work has focused on ratings of maximum acceptable loads (RALs), ie, the individual's assessment of the maximal work load that can be tolerated without feeling overexertion or fatigue.[33] Measures of maximum acceptable frequency for a task are labeled as MAFs and, similarly, measures of maximum acceptable torque are labeled as MATs. The rationale for "acceptability scaling" is based on the view that the worker can best determine an appropriate individual work load based on his or her own interpretation of physical sensations resulting from the task. Psychophysical test protocols are usually designed to give the subject control over one task variable, such as load or frequency of exertion. The subject, based on perceived sensations of fatigue or exertion, adjusts the variable so that the subject can perform the task without experiencing excessive strain or fatigue.

Psychophysical methods including the use of both RPEs and RALs have proved valuable in the assessment of the individual's working capacity in manual material handling tasks. Chaffin and Andersson[34] concluded that until comprehensive dynamic testing methods and biomechanical models are developed, psychophysical limits, based on simulations of specific tasks of interest, may be the most accurate means of determining a person's acceptable performance limit for a given task. Poulton[35,36] also concluded that subjective rating techniques represent a valid procedure for assessing the subject's response to physical stimuli, reasoning that subjective assessment is the individual's "own perception" of a stimulus and, as such, provides a unique and valid response measure that no "objective measure" can replace.

Applications to Upper Extremity Work Activities

Despite widespread use in manual materials handling research, the application of psychophysical methods to the study of upper extremity work activities has only recently been explored. Interest in psychophysical techniques emanates from industry demands for guidelines or limits designed to prevent cumulative trauma disorders, combined with the difficulties inherent in assessing upper extremity work using more objective approaches. These difficulties with more objective work were demonstrated by Snook and Irvine[37,38] and Garg and Saxena,[39] who showed that physiologic measures of metabolic energy expenditure or heart rate criteria have little meaning in the study of upper extremity work. Similarly, although electromyography (EMG) can be helpful for quantifying muscular activity and fatigue, it requires expensive instrumentation, careful calibration, and an experimental design that preserves characteristic relationships between EMG and muscle. An advantage of psychophysical measures is that (unlike EMG) they are applicable to highly dynamic tasks, intermittent tasks, or exertions that involve combinations of several different muscles. Furthermore, psychophysical methods are less invasive in the workplace, require no expensive instrumentation or painstaking calibration to implement, and provide data that are readily interpretable.

Recent laboratory studies using psychophysical techniques to examine the effects of different variables on perceived exertion are described below (Table 3). These studies have also served to identify appropriate tool, task, and workstation designs for various manual activities. Much of this research yields insight into the reliability and reproducibility of psychophysically derived limits and the relationship between psychophysical measures and other measures of upper extremity exertion.

Variables Affecting Psychophysically Perceived Exertion

The results of psychophysical studies of upper extremity work are generally consistent with the results of biomechanical and epidemiologic studies; ie, conditions that impose biomechanical loads on the body and are associated with increased risk of musculoskeletal injury are also perceived as more stressful and less "acceptable" to workers than conditions that do not.

Force

Several studies clearly demonstrate that force of movement has a powerful effect on perceived exertion and the acceptability of manual work activities. As manual effort increases (often because the weight of a tool or object increases), the RPE increases.[40–47] Furthermore, increased manual force requirements generally have significant deleterious effects on the length of time sub-

Table 3 Psychophysical studies of upper extremity work

Reference	Task	Independent Variable(s)	Dependent Variable(s)	Psychophysical Method(s)	Results/Recommendations
Snook and Irvine[37,38]	Lifting boxes using arms	Box weight Lift height	MAF* of lift Heart rate	MAF determined using method of adjustment over 1 hour	MAF decreased with height and weight of lift. No difference in heart rate between conditions.
Garg and Saxena[39]	One-handed lifting in the horizontal plane	Load Reach distance	MAF of lift Heart rate RPE†	MAF determined using method of adjustment over 40-minute period Borg RPE scale	Increasing the load weight and lifting distance reduced MAF. At MAF, subjects rated exertion as fairly light to somewhat hard. No heart rate variation.
Hammarskjöld et al[60]	Sawing, nailing, and screwing (carpentry work)	Task type Day Time of day	RPE EMG¶ Force exerted Motions Work time	Borg RPE scale	Screwing consistently rated as hard or very hard, sawing as somewhat hard, and nailing as fairly light.
Armstrong et al[52]	Powered hand tool use (assembly work)	Tool weight Tool handle diameter Vertical work distance Horizontal work distance Gender, stature, hand size	Rating of weight, handle size, grip force, and comfort of tools used	Attribute rated using a continuous scale (0–10), anchored at 0, 5, and 10	Weight and grip force assessments correlated with tool mass. Perceived handle size related to handle circumference. Discomfort increased with horizontal and vertical work distance.
Garg and Beller[61]	One-handed handle pulling	Speed of pull Vertical height of handle Angle of pull	RPE for elbow, shoulder, and back Comfort Pulling strength	Borg RPE scale	RPE and strength decreased, comfort increased with increased pulling speed. Pull height and angle had little effect on RPE.
Genaidy et al[40]	Holding weights and moving the	Task type (static, dynamic, and	RPE Heart rate Blood pressure	Borg RPE scale	RPE increased, endurance time decreased with weight. Static task

Table 3 Psychophysical studies of upper extremity work (cont.)

Reference	Task	Independent Variable(s)	Dependent Variable(s)	Psychophysical Method(s)	Results/Recommendations
	lower arm about the elbow.	combination) Weight Lift frequency	Time until exhaustion		associated with greatest RPE and blood pressure, shortest endurance time. Lift frequency had no effects.
Park et al[62]	Carpet trimming (3 studies)	Carpet type Type and direction of cut Knife temperature Blade angle	RPE, EMG Wrist deviation Grip force Length of cut	Borg CR-10 scale	RPE affected by carpet type and blade angle (straight blade associated with lowest RPE).
Snook et al[49,56]	Wrist motion against resistance (2 studies)	Wrist motion and grip type Repetition rate Days of exposure (2 vs 5 days/ week)	MAT[§] Isometric wrist strength Tactile sensitivity Symptoms Errors Duration of force	MAT determined using method of adjustment (averaged and recorded each minute for 7 hours) Discomfort recorded on series of graded scales (0 to 3)	MAT decreased with repetition and hour of day; greater for wrist flexion than extension. No MAT difference between days. Increase in weekly work load (from 2 to 5 days) produced 36.3% decrease in MAT.
Ulin et al[45,50,53,54]	Driving screws (4 studies)	Vertical and horizontal work location Tool type Tool mass Work rate	RPE Discomfort rating	Borg CR-10 scale Body part discomfort survey	RPE increased with tool mass, vertical and horizontal work distance, and work pace.
Marley and Fernandez[41] Kim and Fernandez[42] Dahalan and Fernandez[43]	1. Drilling holes in sheet metal 2. Wire crimping (All simulated tasks)	1. Force, wrist flexion 2. Grip force as a % of MVC,** grip duration	MAF RPE Blood pressure EMG No discomfort measure	MAF determined using method of adjustment over a 20-minute period RPE-Borg scale	MAF decreased, RPE increased with increasing force, duration, and wrist flexion. RPE and MAF (–) correlated. RPE, HR[††], EMG, and blood pressure (+) correlated.
Krawczyk[44]	3 studies: 1. Moving plastic bottles	1. Bottle weight, frequency and distance of	1. RPE, discomfort 2. PW,** RPE,	RPE—10 cm visual analog scale (anchored at ends) Discomfort of 11 body parts	RPE increased with weight and frequency but not distance of transfer. For combination task, RPE

Table 3 Psychophysical studies of upper extremity work (cont.)

Reference	Task	Independent Variable(s)	Dependent Variable(s)	Psychophysical Method(s)	Results/Recommendations
	2. Moving containers (combination task)	movement, time 2. Frequency and distance of movement, time 3. % time spent on each task	discomfort 3. RPE, discomfort	(ranked) PW determined using method of adjustment over 8-hour period	and discomfort were minimized when time was evenly split between tasks. PW decreased with increased frequency and distance of movement. RPE and PW stable during workday; discomfort increased.
Putz-Anderson and Galinsky[48]	Lifting and lowering a tool handle (4 studies)	1. Discomfort level, force as a % of MVC 2. Repetition rate, force 3. Repetition rate, tool weight 4. Repetition rate, reach height	Work duration (time until onset of a specified level of fatigue)	Borg CR-10 scale used to designate fatigue/discomfort criterion	Work duration increased with fatigue criterion; decreased with increased force, tool weight, reach, and repetition. Increases in force or repetition attenuated the other's effect. No change in average work time through workday. Limiting fatigue maintained rest effectiveness.
Harber et al[47]	Repetitive grasping motions	Wrist position Force Repetition rate Grip type	RPE Comfort (overall and wrist)	Borg CR-10 scale (RPE) Discomfort scale (1–8, anchored at 4 points)	RPE and discomfort affected by grip type, force, wrist position, and rapid repetition.
Grant et al[46]	Grasping and moving tool handles (3 studies)	Handle shape/diameter Tool weight	RPE Grip force Forearm EMG	RPE measured using Borg CR-10 scale	RPE increased with weight, not affected by handle shape or diameter. RPE correlated with grip force, EMG.

* MAF, maximum acceptable frequency
† RPE, rating of perceived exertion
‡ EMG, electromyography
§ MAT, maximum acceptable torque
** PW, preferred container weight; MVC, maximum voluntary contraction
†† HR, heart rate

jects can work without becoming excessively fatigued and the rate of work subjects find acceptable for an 8-hour period.[37,39,41–43,48]

Repetition

Likewise, researchers are in nearly universal agreement that the repetitiveness of manual work (ie, the work rate) has a direct impact on the RPE and RAL.[44,47–50] All agree that increasing the rate of task repetition increases the level of perceived stress associated with the task. Furthermore, as the rate of repetition increases, the length of time workers are able to work without fatigue decreases and the acceptable force of exertion required by the task is reduced.[44,48,49] There is also evidence that as repetition rates continue to increase, compensatory mechanisms for reducing the stress associated with manual work become less effective. For example, Putz-Anderson and Galinsky[48] found that at extremely high rates of repetition, reducing the force required to perform the task was relatively ineffective in forestalling shoulder fatigue and discomfort. Similarly, Snook and associates[49] found that even though subjects were encouraged to adjust force requirements to avoid discomfort, and subjects actually did reduce force levels as repetition rates increased, subjects reported more discomfort throughout the workday when repetition rates were high. Although these findings do not invalidate studies that suggest that tradeoffs are possible to achieve acceptable work loads, they do challenge the assumptions and recommendations of many ergonomists—namely, that high rates of repetition are permissible if awkward postures or manual forces associated with manual work can be reduced.

Posture

Awkward working postures frequently result from the faulty layout and design of workstations and tools.[51] It has been suggested that psychophysical measures represent a direct method for evaluating the interface between tools, tasks, and workers for the purpose of establishing design criteria for tools and workstations.

To evaluate this hypothesis, Armstrong and associates[52] asked workers in an automotive assembly plant to rate the handle size, grip comfort, and posture comfort of tools used during their work activities. Objective measures of handle circumference and the horizontal and vertical location of the tool relative to the body were collected, along with data on worker gender, stature, hand breadth, and hand length. The results indicated that workers' subjective assessments strongly correlated with tool, task, and worker attributes (Table 3). While acknowledging a need for further studies, Armstrong and associates argued that psychophysical ratings could be used to target and prioritize areas for ergonomic interventions.

In an extension of this work, Ulin and associates[45,50,53,54] conducted a series of laboratory studies to examine the effect of work location/orientation on the RPE in manual assembly operations. Subjects rated the exertion associated with driving screws into perforated sheet metal at different horizontal and vertical work locations with different pneumatic screwdrivers using the Borg CR-10 scale. The results agreed favorably with predictions based on anthropometric and biomechanics data, indicating that exertion is minimized when tools and workstations allow workers to maintain neutral wrist and shoulder postures during their work activities. As a result, specific design guidelines for minimizing perceived exertion were offered.

Other studies tend to confirm that worker tolerance for various work conditions is increased when extreme joint deviations are avoided. Garg and Saxena[39] and Krawczyk[44] found that doubling the reach distance in a manual transfer task reduced the maximum acceptable frequency of transfer by about 18% and the preferred weight of transfer by 37%. Marley and Fernandez[41] and Kim and Fernandez[42] found that the MAF of work in a drilling task was optimized when workers were allowed to perform the task with a neutral wrist posture. As angle of wrist flexion increased, the MAF decreased and RPE increased.

Job Content

Rotating workers between dissimilar jobs or giving workers responsibility for a larger number of work tasks is frequently proposed as an administrative means of controlling musculoskeletal stress. The goal of these strategies is to reduce the load on any one muscle group by breaking up long periods of static muscle contraction and by spreading the work load over additional body parts.

Recognizing that the mechanisms of injury associated with static and dynamic exertions are different, and that many jobs have both static and dynamic activities, Genaidy and associates[40] undertook a study to examine the effects of static and dynamic arm tasks on RPEs, endurance time, blood pressure, and the heart rate. Subjects performed three tasks: (1) a static task in which subjects held equal loads in both hands with the upper arms freely hanging at the sides and the elbows flexed at 90°; (2) a dynamic task in which subjects lifted loads in both hands by repetitively flexing and extending the elbow; and (3) a combination task in which the subject held a load in the left hand as described in (1) and lifted an equal load in the right hand as described in (2). The RPE and blood pressure measures indicated that the static arm task was the most stressful, followed by the combination task and the dynamic task. This agrees with findings by Stevens and Krimsley[14] and deVries[15] that perceived fatigue increases at a faster rate for static work than for dynamic work, if load is held constant. Genaidy and associates[40] also noted that static effort induces the blood vessels in the working muscle to compress; therefore, the muscle does not receive sufficient nutrients from the blood and waste products rapidly accumulate. Although energy expenditure and heart rate measurements are usually insensitive to disturbances in small muscle groups, Genaidy and associates demonstrated that psychophysical measures provide a valid indicator of these effects during manual work tasks.

The effect of varying job content on psychophysical stress was also examined by Krawczyk.[44] Workers either transferred objects along a conveyor with the left hand or drove screws with a pneumatic screwdriver using the right hand. Various amounts of time were recorded for each task. The results indicated that perceived exertion and body part discomfort were minimized when the workers' time was evenly divided between the two tasks. Krawczyk noted that not only did the evidence indicate the positive effects of work enlargement but also that this evidence would have been more difficult to obtain using more objective means.

Potential of Psychophysical Methods for Establishing Safe Levels of Work

Reliability Reliability refers to the consistency or stability of measures of a variable over time or across representative samples.[55] Researchers have repeatedly examined the reliability of psychophysically derived limits for upper extremity work by replicating trials under similar task conditions. Garg and Saxena[39] reported no significant differences in RPEs or in the maximum frequency of lift selected by subjects in two replications of a one-handed lifting task conducted using six weight-distance combinations. In two studies to identify MATs for various patterns and frequencies of wrist motion, Snook and associates[49,56] reported no significant differences in MATs from day to day during either experiment. Similarly, Putz-Anderson and Galinsky[48] compared work trial durations resulting from three replications of various repetitive arm tasks. In each trial, subjects were instructed to initiate a rest pause each time sensations in the shoulder exceeded a prespecified threshold of discomfort. The researchers reported no significant differences in average work trial duration between replications of the same task. This finding was interpreted as demonstrating that subjects were able to reliably monitor their own feelings of discomfort, and that providing appropriate rest breaks was an effective method of preventing overaccumulation of fatigue. Finally, Marley and Fernandez[41] and Kim and Fernandez[42] both reported that subjects were consistent in their selection of acceptable work rates for three experimental replications of a hand-held pneumatic drilling task.

Validity Measurement techniques are considered valid if they measure what they purport to measure. As previously discussed, evidence for the validity of RPEs and RALs is provided by several studies that demonstrate strong correlations with objective measures of muscular exertion. More recent studies of upper extremity work tasks tend to corroborate the reports of earlier researchers. In experiments in which subjects were required to repeatedly grasp and move various tool handles, Grant and associates[46] found that the RPE was significantly correlated with both the grip force exerted during the task (measured using a strain gauge embedded in the handle) and with the amplitude of EMG signals measured in the forearm. Marley and Fernandez,[41] Kim and Fernandez,[42] and Dahalan and Fernandez[43] also found that the RPE was strongly correlated with the pulse rate, systolic blood pressure, and forearm EMG amplitudes during drilling and gripping tasks.

With reference to laboratory experiments, results are also considered valid to the extent to which the findings can be generalized to nonlaboratory situations.[57] The validity of applying limits derived from laboratory studies to industrial settings has only recently been addressed. One issue relates to the selection of subjects for psychophysical studies of manual work. There is evidence from manual material handling research to indicate that subjects who are inexperienced or are not sufficiently trained (usually college students) tend to overestimate their capacity to work for an 8-hour period. This source of bias is easily avoided by limiting study participation to experienced industrial workers and by providing training at the beginning of the experiment.

There is also a concern that certain psychosocial processes, such as high arousal, that can occur at a specific workplace may not be present in a laboratory setting where psychophysical data usually are collected. High arousal can temporarily lower or elevate the threshold for experiencing a sensation of discomfort from the locomotor system. This effect could reduce the generalizability of laboratory-based psychophysical data for use at the work site.[58] For example, an individual experiencing extremely high levels of arousal, such as from fast-paced, high-demand work conditions, could fail to notice the onset of local muscle discomfort until many minutes after the incident occurred.

Another concern relates to the validity of generalizing from laboratory data that are collected on subjects during psychophysical tests which are considerably shorter in duration than the 8-hour typical work duration experienced by most workers. Are workers able to accurately judge from a 20-minute or even a 2-hour test what their capacity for work is over an 8-hour day? Because increasing trial duration can considerably increase the cost of experimentation, some researchers have attempted to examine and characterize the bias introduced by limited trial durations. Krawczyk[44] compared preferred weights and RPEs gathered at intermediate points during a manual transfer experiment (ie, after 1 or 2 hours) with results gathered at the end of an 8-hour work period. The difference between weights and RPEs selected in the first 2 hours and the last 2 hours of work averaged only 5% and 8%, respectively.

Slightly different findings were reported in two experiments by Snook and associates.[49,56] In two experiments, Snook and associates found that although MAT tended to decrease during the course of an 8-hour workday, the difference between forces selected after the first hour of work and the fifth hour of work was generally less than 10%, and forces did not decline significantly after the fifth hour. However, Snook also found that the duration of the workweek had a significant effect on the acceptability of manual forces. Comparing results from study I (in which subjects worked 2 days per week for 10 weeks) with results gathered in study II (in which subjects worked 5 days per week for 4 weeks—a work schedule more typical of industrial operations), the average force that workers found acceptable was 36.3% lower in study II, if all other task-related factors are held constant. Because the difference in work schedule was the only explanation that was provided for the dramatic difference in the results of these two experiments, a need for additional research on this topic is suggested.

Perhaps the ultimate test of the validity of psychophysical measures is their ability to separate safe work conditions from those that cause injury. Some of the most compelling evidence for the validity of psychophysical methods in establishing safe levels of manual lifting, pushing, and pulling has been reported by Snook and associates, noted above. In a report in which they compared three approaches to the prevention of low back injuries, they concluded that designing jobs with maximum weight limits that are acceptable to 75% of the population will reduce back injuries by 33%.[59] To date, however, there are limited work site data to demonstrate that designing tasks in accordance with psychophysically derived limits will reduce the morbidity associated with forceful and repetitive manual tasks. One main explanation is that psychophysical methods have been used only recently to derive recommendations for preventing upper extremity disorders. Field studies are needed to relate the incidence and severity of upper extremity injuries to the extent to which manual demands are judged acceptable by experienced workers.

Summary

There is growing evidence that, when carefully applied, psychophysical methods provide a practical means for achieving the goal of establishing safe levels of work. To date, laboratory results indicate that psychophysically derived limits are consistent and reproducible. Psychophysical measures of effort also appear to correlate with other physiologic measures of effort, as well as predictions based on anthropometric and biomechanical analyses. Additional evidence is needed to demonstrate that designing work in accordance with psychophysically derived limits will eliminate or reduce the rate of musculoskeletal injury associated with manual work.

References

1. Armstrong TJ, Buckle P, Fine LJ, et al: A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scand J Work Environ Health* 1993; 19:73–84.
2. Engin, AE. On the biomechanics of the shoulder complex. *J Biomech* 1980;13:570–590.
3. Chaffin DB: Localized muscle fatigue: Definition and measurement. *J Occup Med* 1973;15:346–354.
4. Rohmert W: Problems in determining rest allowances: Part 1. Use of modern methods to evaluate stress and strain in static muscular work. *Appl Ergonomics* 1973;4:91–95.
5. Broadbent DE: Is a fatigue test now possible? *Ergonomics* 1979;22:1277–1290.
6. Bartley SH: *Fatigue: Mechanism and Management.* Springfield, IL, Charles C Thomas, 1965.
7. Stevens SS, Galanter EH: Ratio scales and category scales for a dozen perceptual continua. *J Exp Psychol* 1957;54:377–411.
8. Stevens JC, Mack JD: Scales of apparent force. *J Exp Psychol* 1959;58:405–413.
9. Eisler H: Subjective scale of force for a large muscle group. *J Exp Psychol* 1962;64: 253–257.
10. Jones LA: Perception of force and weight: Theory and research. *Psychol Bull* 1986; 100:29–42.
11. Borg G: Simple rating methods for estimation of perceived exertion, in Borg G (ed): *Physical Work and Effort.* Oxford, UK, Pergamon Press, 1977, pp 39–47.
12. Stevens SS: On the psychophysical law. *Psychol Rev* 1957;64:153–181.
13. Stevens JC, Cain WS: Effort in isometric muscular contractions related to force level and duration. *Perception and Psychophysics* 1970;8:240–244.
14. Stevens JC, Krimsley AS: Build up of fatigue in static work: Role of blood flow, in Borg G (ed): *Physical Work and Effort.* Oxford, UK, Pergamon Press, 1977, pp 145–155.
15. deVries HA: Method for evaluation of muscle fatigue and endurance from electromyographic fatigue curves. *Am J Phys Med* 1968;47:125–135.
16. Hosman J: Adaptation to muscular effort. Stockholm, Sweden, University of Stockholm, 1967.
17. Eason RG: Electromyographic study of local and generalized muscular impairment. *J Appl Physiol* 1960;15:479–482.
18. Lloyd AJ, Voor JH, Thieman TJ: Subjective and electromyographic assessment of isometric muscle contractions. *Ergonomics* 1970;13:685–691.
19. Caldwell LS, Smith RP: Pain and endurance of isometric muscle contractions. *J Eng Physiol* 1966;5:25–32.
20. Park SR, Rodbard S: Effects of load and duration of tension on pain induced by muscular contraction. *Am J Physiol* 1962;203:735–738.
21. Tanii K, Sadoyama T, Sanjo Y, et al: Appearance of effort-depending changes in static local fatigue. *J Hum Ergol* 1973;2:31–45.
22. Corlett EN, Bishop RP: A technique for assessing postural discomfort. *Ergonomics* 1976;19:175–182.
23. Corlett EN, Manenica I: The effects and measurement of working postures. *Appl Ergonomics* 1980;11:7–16.
24. Pandolf KB: Influence of local and central factors in dominating rated perceived exertion during physical work. *Percept Mot Skills* 1978;46:683–698.
25. Borg GA: Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982; 14:377–381.
26. Borg G: Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med* 1970;2:92–98.

27. Borg G: Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* 1990:16 (suppl 1):55–58.
28. Yonda RA: An investigation of the human ability to replicate task-produced forces on a load cell: A method for determining the magnitude of forces exerted by workers engaged in manual materials handling activities. Buffalo, NY, State University of New York at Buffalo, 1986. Unpublished thesis.
29. Deeb JM, Drury CG, Pendergast DR: An exponential model of isometric muscular fatigue as a function of age and muscle groups. *Ergonomics* 1992;35:899–918.
30. Jones LA, Hunter IW: The relation of muscle force and EMG to perceived force in human finger flexors. *Eur J Appl Physiol* 1982;50:125–131.
31. Hogan JC, Fleishman EA: An index of physical effort required in human task performance. *J Appl Psychol* 1979;64:197–204.
32. Hogan JC, Ogden GD, Gebhardt DL, et al: Reliability and validity of methods for evaluating perceived physical effort. *J Appl Psychol* 1980;65:672–679.
33. Snook SH, Irvine CH, Bass SF: Maximum weights and work loads acceptable to male industrial workers: A study of lifting, lowering, pushing, pulling and walking tasks. *Am Ind Hyg Assoc J* 1970 31:579–586.
34. Chaffin DB, Andersson GBJ: *Occupational Biomechanics.* New York, NY, Wiley & Sons, 1991.
35. Poulton EC: Bias in ergonomic experiments. *Appl Erg* 1973;4:17–18.
36. Poulton EC: Qualitative subjective assessments are almost always biased, sometimes completely misleading. *Br J Psychol* 1977;68:409–425.
37. Snook SH, Irvine CH: Maximum frequency of lift acceptable to male industrial workers. *Am Ind Hyg Assoc J* 1968;29:531–536.
38. Snook SH, Irvine CH: Psychophysical studies of physiological fatigue criteria. *Hum Factors* 1969;11:291–300.
39. Garg A, Saxena U: Maximum frequency acceptable to female workers for one-handed lifts in the horizontal plane. *Ergonomics* 1982;25:839–853.
40. Genaidy AM, Houshyar A, Asfour SS: Physiological and psychophysical responses to static, dynamic and combined arm tasks. *Appl Ergonomics* 1990;2:63–67.
41. Marley RJ, Fernandez JE: Psychophysical frequency and sustained exertion at varying wrist posture for a drilling task. *Ergonomics* 1995;38:303–325.
42. Kim CH, Fernandez JE: Psychophysical frequency for a drilling task. *Int J Indust Ergonomics* 1993;12:209–218.
43. Dahalan JB, Fernandez JE: Psychophysical frequency for a gripping task. *Int J Indust Ergonomics* 1993;12:219–230.
44. Krawczyk S: Psychophysical determination of work design guidelines for repetitive upper extremity transfer tasks over an eight hour workday. Ann Arbor, MI, University of Michigan, 1993. Unpublished dissertation.
45. Ulin SS, Armstrong TJ, Snook SH, et al: Examination of the effect of tool mass and work postures on perceived exertion for a screw driving task. *Int J Indust Ergonomics* 1993;12:105–116.
46. Grant KA, Habes DJ, Putz-Anderson V: Psychophysical and EMG correlates of force exertion in manual work. *Int J Indust Ergonomics* 1994;13:31–39.
47. Harber P, Hsu P, Pena L: Subject-based rating of hand-wrist stressors. *J Med* 1994;36:84–89.
48. Putz-Anderson V, Galinsky T: Psychophysically determined work durations for limiting shoulder girdle fatigue from elevated manual work. *Int J Indust Ergonomics* 1993;11:19–28.
49. Snook SH, Vaillancourt DR, Ciriello VM, et al: Psychophysical studies of repetitive wrist motion: Part I: Two day per week exposure. *Ergonomics,* in press.
50. Ulin SS, Armstrong TJ, Snook SH, et al: Perceived exertion and discomfort associated with driving screws at various work locations and at different work frequencies. *Ergonomics* 1993;36:833–846.
51. Putz-Anderson V: *Cumulative Trauma Disorders: A Manual for Musculoskeletal Disorders of the Upper Limbs.* London, UK, Taylor and Francis, 1988, pp 61–64.
52. Armstrong TJ, Punnett L, Ketner P: Subjective worker assessments of hand tools used in automobile assembly. *Am Ind Hyg Assoc J* 1989;50:639–645.

53. Ulin SS, Snook SH, Armstrong TJ, et al: Preferred tool shapes for various horizontal and vertical work locations. *Appl Occup Environ Hyg* 1992;7:327–337.
54. Ulin SS, Armstrong TJ, Snook SH, et al: Effect of tool shape and work location on perceived exertion for work on horizontal surfaces. *Am Ind Hyg Assoc J* 1993;54:383–391.
55. Sanders MS, McCormick EJ (eds): *Human Factors in Engineering and Design*. New York, NY, McGraw-Hill, 1987.
56. Snook SH, Vaillancourt DR, Ciriello VM, et al: Psychophysical studies of repetitive wrist motion: Part II. Five day per week exposure. *Ergonomics*, in press.
57. Dember WN, Jenkins JJ, Teyler TJ: *General Psychology*, ed 2. Hillsdale, NJ, L Erlbaum Associates, 1984.
58. Theorell T, Harms-Ringdahl K, Ahlberg-Hulten G, et al: Psychomotor job factors and symptoms from the locomotor system: A multicausal analysis. *Scand J Rehabil Med* 1991;23:165–173.
59. Snook SH, Campanelli RA, Hart JW: A study of three preventive approaches to low back injury. *JOM* 1978;20:478–481.
60. Hammarskjöld E, Harms-Ringdahl K, Ekholm J: Shoulder-arm muscular activity and reproducibility in carpenters' work. *Clin Biomech* 1990;5:81–87.
61. Garg A, Beller D: One-handed hynamic pulling strength with special reference to speed, handle height and angles of pulling. *Int J Indust Ergonomics* 1990;6:231–240.
62. Park D, Yun MH, Freivalds A: Knife replacement studies at an automobile carpet manufacturing plant. Proceedings of the Human Factors Society 35th Annual Meeting, San Francisco, CA, 1991, pp 848–852.