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외부 부하에 따른 상지 관절 동작별 최대 수용 반복 빈도수 분석

Analysis of Maximum Acceptable Frequencies for Upper Extremity Motions with External Loads

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by

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ABSTRACT

Despite recent change into automation in many industries, the incidence of musculoskeletal disorders due to upper extremity intensive tasks is still significantly high. Repetitiveness (the extent of use of similar motions at work) has been identified as a major risk factor, along with force and posture, for work-related UEMSDs. However, there is very little experimental data available establishing acceptable exposure levels of repetitiveness. Therefore, research is needed to identify the acceptable exposure levels for repetitiveness of the upper extremities.

The purpose of this study is to identify acceptable exposure levels for repetitiveness of upper extremity (shoulder, elbow, wrist, and index finger) motions with external loads. The specific objectives are to survey and compare assessment methodologies and risk exposure levels for repetitiveness of upper extremity, to identify maximum acceptable frequencies (MAFs) for upper extremity (shoulder, elbow, wrist, and index finger) motions, and to analyze MAF characteristics and compare MAFs to repetitiveness risk levels.

First, this study compared various measures, measurement methods, analysis techniques, and risk levels that have been used to analyze the repetitiveness of upper extremity intensive tasks by reviewing 31 repetitiveness assessment studies (published between 1997 and 2002) and additional papers published before 1997. The measures were classified according to their dimensional types (cycle time and frequency) and analysis scopes (work cycle, body region, and force exertion). Based on the measure classification system, it was identified that frequency measures were more commonly used than cycle time measures and hand/wrist movement frequency was most commonly used. The measurement methods were classified into objective and subjective measurement methods, and the analysis techniques into statistical and spectral techniques. Results of the meta-analysis for repetitiveness risk levels of each upper extremity part indicated that mean values for the shoulder, elbow, wrist, and finger were

6.27, 8.15, 22.07, and 124.35 motions per minute, respectively.

Second, this study also identified MAFs using a psychophysical methodology for upper extremity motions with external loads. Seventeen right-handed males without any musculoskeletal or cardiovascular problems participated in the experiment. Independent variables were 4 upper extremity parts and 2 external load/force levels (1kg and 4kg for shoulder, elbow, and wrist; 0.25kg and 1kg for index finger). Dependent variables were MAF, working heart rate, work pulse, and rating of perceived exertion (RPE). MAF was determined as 'reasonable' for 8 hour of work by using the method of adjustment during the first 25 minutes of 30 minutes in length. Mean MAF levels for the shoulder, elbow, wrist, and index finger motions were 9.0, 19.7, 29.5, and 65.9 motions per minute at the high load/force level, and 24.1, 45.1, 56.3, and 128.5 motions per minute at the low load/force level, respectively. Mean working heart rates (work pulses), measured to identify the physiological level of functioning during the experiment for determining the MAF, for the shoulder, elbow, wrist, and index finger motions were 85.3(17.4), 79.7(12.3), 74.9(7.9), and 73.8(5.7) bpm at the high load/force level, and 79.6(12.0), 75.3(8.5), 73.0(6.5), and 70.9 (4.1) bpm at the low load/force level, respectively. For RPE, the subjects rated the perceived exertion ranging from level 1 (very weak) to level 3 (moderate) for the upper extremity regions involved in each motion.

Lastly, this study analyzed characteristics of MAFs, and compared MAFs to preliminary ergonomic guidelines of repetitiveness risk for each upper extremity part. The analysis results for reliability by using change in mean, retest correlation, and SEM proved that the MAF protocol was likely to be sufficiently reliable for measuring repetitiveness of the upper extremity. Regression analysis results showed that there were statistically significant linear relationships between MAF and MVC, and that the MAF of the shoulder decreased more with increasing load/force than the MAFs of the other parts. The comparison results between the MAF results and the meta-analysis results indicated that the repetitiveness risk levels might be set as 25th percentile values of the MAF results with high load (4 kg) in the shoulder, elbow, and wrist.

This study demonstrated the necessity of considering upper extremity part as well as load/force level when designing acceptable exposure levels for repetitiveness of upper extremity intensive tasks and also provided useful basic data to establish permissible exposure levels of repetitiveness for safe and acceptable work standards in industry.

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CHAPTER I.

Introduction

1.1 Problem statement

Despite recent change into automation in many industries, the incidence of musculoskeletal disorders due to upper extremity intensive tasks is still significantly high. In the US, the Bureau of Labor Statistics (2004) reported that, in 2002, the incidence rates of nonfatal occupational injuries and illnesses in manufacturing and construction industries (requiring upper extremity intensive tasks with a relatively high proportion) were 7.2 and 7.1 cases per 100 full-time workers (FTWs), respectively, while the industry-wide incidence rate of nonfatal occupational injuries and illnesses was 5.3 cases per 100 FTWs. In the Korea, the Korea Occupational Safety and Health Agency (2004) reported that, in 2003, claims in manufacturing industries accounts for 86% (2,498 cases) of all work-related musculoskeletal disorder claims (2,906 claims).

Upper extremity musculoskeletal disorders (UEMSDs) are a collective and descriptive term for symptoms developed in joints, muscles, tendons, and other soft tissues of the upper extremities due to upper extremity intensive tasks. These include cases of tendinitis, tenosynovitis, epicondylitis, carpal and cubital tunnel syndrome, and other nerve entrapments, as well as sprains, strains, and other conditions. Several epidemiologic reviews have concluded that there is evidence that certain work factors or combinations of factors appear to cause or significantly contribute to the manifestation of UEMSDs (Hales and Bernard, 1996; NIOSH, 1997; Stock, 1991).

Repetitiveness (the extent of use of similar motions at work) has been identified as a major risk factor for work-related UEMSDs. A number of factors have been identified as increasing the risk of sustaining UEMSDs, including repetitiveness, force, posture, and duration (Armstrong et al., 1986; Putz-Anderson, 1988; Moore et al., 1991). Among them, repetitiveness, force, and posture are regarded as three of the primary risk factors for work-related UEMSDs. Colombini (1998) and Silverstein et al. (1987) found that repetitiveness alone could increase the risk of UEMSDs in the workplace. In addition, Latko et al. (1999) showed that repetitiveness was associated with the clinical symptoms (such as pain, weakness, clumsiness, numbness, tingling, and nocturnal symptom aggravation) of the tendon and nerve disorders of the hand and wrist. Furthermore, NIOSH (1997) reported, based on a comprehensive review of previous findings, the evidence supported the existence of a causal relationship between repetitiveness and musculoskeletal disorders of the shoulder and hand/wrist.

However, although repetitiveness has been cited as a physical risk factor for UEMSDs, there is very little experimental data available establishing acceptable exposure levels of repetitiveness. That is to say, it is not known how fast is too fast. This information is necessary for developing guidelines or criteria that can be used for evaluating exposure to repetitive motion. Among four methodologies for establishing acceptable exposure levels of physical risk factors for UEMSDs, epidemiological methodology that examines the relationship between work and morbidity patterns requires excessive time and resources for data collection (Hennekens et al., 1987), biomechanical methodology cannot address repetitiveness and fatigue issues (Tracy, 1990; Armstrong and Chaffin, 1979), and physiological methodology is not as sensitive to upper extremity intensive tasks (e.g., Garg, 1983; Baidya and Stevenson, 1988). Alternatively, psychophysical methodology establishes acceptable exposure levels based on the worker's own feelings of pain, discomfort and fatigue (Garg and Saxena, 1982). The primary advantage of the psychophysical methodology is that it permits the realistic simulation of industrial work, allowing aspects such as workspace dimensions and task frequencies to be altered accordingly (Snook, 1985a). Krawczyk (1996) stated that this methodology was a consistent, reproducible, quick, inexpensive, and convenient way to assess the degree of physical strain on the human body.

Although psychophysical methodology can be used to establish acceptable exposure levels for repetitiveness of the upper extremity, few such studies have as yet been done. Marley and Fernandez (1995) established the maximum acceptable frequency under various wrist posture requirements and constant force and duration for a sheet metal drilling task which involves a potential risk of developing UEMSDs. Kim and Fernandez (1993) determined the maximum acceptable frequency for a simulated sheet metal drilling task at different applied forces and wrist flexion angles for females. Dahalan and Fernandez (1993) determined the maximum acceptable frequency for a simulated intermittent gripping task at different gripping forces and task durations. Klein and Fernandez (1997) determined the maximum acceptable frequency for males performing an intermittent isometric pinching task as a function of different pinch force levels, wrist postures, and task duration. However, there is very little experimental data available establishing acceptable exposure levels for repetitiveness of the upper extremities in normal conditions.

Therefore, research is needed to identify the acceptable exposure levels for repetitiveness of the upper extremities with moderate forces in moderate motion ranges. Acceptable exposure levels should be established for each joint (shoulder, elbow, wrist, and finger) for the sake of better application and evaluation of repetitiveness in the workplace. Also these exposure levels must be accompanied by a characterization of the psychophysical methodology and a comparison with previous results.

1.2 Objectives of the study

The present study is intended to identify acceptable exposure levels for repetitiveness of upper extremity (shoulder, elbow, wrist, and index finger) motions with external loads in moderate motion ranges in the sagittal plane. The detailed contents can be summarized as follows.

First, the present study surveys and compares assessment methodologies and risk exposure levels for repetitiveness of upper extremity intensive tasks. Various measures, measurement methods, and analysis techniques used in repetitiveness research are surveyed and then classified in a systematic manner. Furthermore, measures and measurement methods frequently employed for upper extremity intensive tasks are examined. Also, a meta-analysis is conducted to develop, on the basis of the published literature, preliminary ergonomic levels of repetitiveness risk for upper extremity intensive tasks.

Second, the present study identifies maximum acceptable frequencies (MAFs) for upper extremity (shoulder, elbow, wrist, and index finger) motions with external loads in moderate motion ranges in the sagittal plane. MAFs are determined as 'reasonable' for 8 hour of work by using the method of adjustment during the first 25 minutes of 30 minutes in length. Heart rate and rating of perceived exertion (RPE) are measured to identify the physiological and psychophysical level of functioning when the MAF is determined.

Lastly, the present study analyzes characteristics of MAFs in terms of reliability (reproducibility or repeatability) and the relationship between MAFs and maximal voluntary contraction (MVC), and compares MAF to preliminary ergonomic guidelines of repetitiveness risk for each upper extremity part (shoulder, elbow, wrist, and index finger).

The measures of reliability used in the present study are change in mean, retest correlation, and standard error of measurement (SEM). Regression models between MAFs and MVC are developed for each upper extremity part with load/force level. The MAFs identified in the present study are compared to preliminary ergonomic levels of repetitiveness risk developed through meta-analysis. The research flow diagram of the present study is depicted in Figure 1.1.

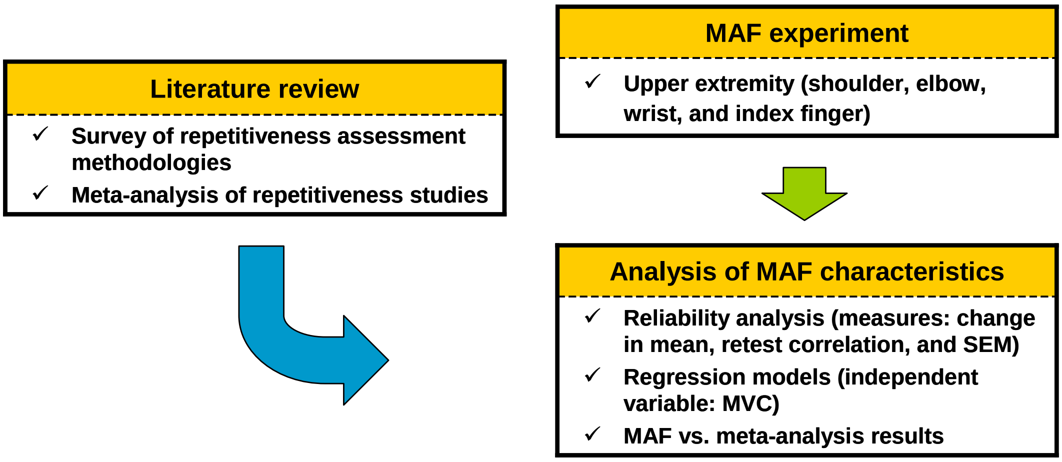


Figure 1.1 Research flow diagram

1.3 Significance of the study

The present study identifies and characterizes acceptable exposure levels for repetitiveness of the upper extremities, and compares them to risk exposure levels developed through the meta-analysis of previous repetitiveness studies. The specific significance of the present study can be summarized as follows.

First, the assessment methodologies for repetitiveness surveyed in the literature review are useful for evaluating repetitiveness in industry. As differences in assessment methodology often cause practitioners to be confused, a systematic comparison of the assessment methodologies is needed for better evaluation and control of repetitiveness in the workplace.

Second, a psychophysical measurement protocol for repetitiveness of the upper extremities is constructed to identify maximum acceptable exposure levels. This protocol is useful for determining maximum acceptable exposure levels considering various postures and forces, and for developing tables of maximum acceptable frequencies for upper extremity intensive tasks afterward.

Third, MAF results identified in the present study can be applied as useful basic data. As the present study identifies the acceptable exposure levels for repetitiveness of the upper extremities with moderate forces in moderate motion ranges, these results systematically establish permissible exposure levels for repetitiveness of the upper extremities.

Lastly, the physiological and psychophysical levels identified during the experiment for determining the MAF are supportive as references in establishing the acceptable workload levels. As the physiological and psychophysical results are identified during the task with a maximum acceptable workload, these results can be used as references to establish acceptable workload levels for physiological and psychophysical measures during upper extremity intensive tasks

1.4 Organization of the thesis

This thesis consists of 7 chapters, which are summarized as follows. Chapter 1 provides an overall perspective of the problem. In Chapter 2, the theoretical background of the present study is summarized through a literature review. The literature review focuses on upper-extremity musculoskeletal disorders (UEMSDs), and methodologies and psychophysical studies for exposure level establishment of upper-extremity intensive tasks.

Chapter 3 investigates assessment methodologies and risk exposure levels for repetitiveness of upper extremity intensive tasks through a comprehensive review of previous repetitiveness studies. Chapter 4 presents the identification of MAF for upper extremity (shoulder, elbow, wrist, and index finger) motions with external loads in moderate motion ranges in the sagittal plane. Chapter 5 describes the methods and results for the analysis of the reliability of MAF, the relationship between MAFs and MVC, and the comparison between MAFs and risk exposure levels for repetitiveness of upper extremities developed through meta-analysis. Chapter 6 discusses the implications and the limitations of the analysis results in the present study. Finally, Chapter 7 presents a thesis summary as the concluding remarks.

CHAPTER II.

Literature Review

2.1 Upper extremity musculoskeletal disorders (UEMSDs)

Upper extremity musculoskeletal disorder (UEMSD) is a collective and descriptive term for symptoms caused or aggravated by work and characterized by discomfort, impairment, disability, or persistent pain in joints, muscles, tendons, and other soft tissues of the upper extremity, with or without physical manifestations (Kroemer, 1989). Terms synonymous with musculoskeletal disorders (MSDs) have varied with the assumed causes, sites of injury, mechanisms of injury, or occupations. Terms identifying assumed causes are: cumulative trauma disorders (CTDs), mostly used in the USA; repetitive (or repetition) strain (or stress) injuries (RSI), mostly used in Australia and Canada; repetitive trauma disorders, or occupational overuse syndromes (OOS), mostly used in Australia. The terms identifying the site of injury include neck-shoulder syndromes, and occupational cervicobrachial disorders (OCDs), mostly used in Japan.

UEMSDs are classified into 5 categories by the sites of injury: tendon disorders, bursa disorders, muscle disorders, nerve disorders, and neurovascular disorders. Table 2.1 shows frequently noted disorders for each category. For example, one of the nerve disorders is carpal tunnel syndrome (CTS), the most common wrist mononeuropathy, which occurs due to localized compression to the median nerve in the carpal tunnel.

Table 2.1 Categories of UEMSDs

Category	Frequently noted disorders
1. Tendon disorders	Flexor/extensor tendinitis Lateral/medial epicondylitis Supraspinatus tendinitis (rotator cuff tendinitis) Flexor/extensor tenosynovitis Stenosing tenosynovitis crepitans (trigger finger)
2. Bursa disorders	Shoulder bursitis
3. Muscle disorders	Myalgia and myositis
4. Nerve disorders	Carpal tunnel syndrome Cubital tunnel syndrome Radial tunnel syndrome Pronator teres syndrome
5. Neurovascular Disorders	Thoracic outlet syndrome (brachial plexus neuritis, cervicobrachial disorder) Hand-arm vibration syndrome (white finger, Raynaud's disease)

Sources: Kroemer, 1989; Putz-Anderson, 1988

Common symptoms of UEMSDs are pain or soreness, discomfort, tenderness, weakness, fatigue or heaviness, swelling, clumsiness, numbness, tingling, and shooting or pulsing sensations. The onset of these symptoms can be gradual or sudden. To make things worse, these symptoms tend to aggravate nocturnally (Kroemer, 1989). With regard to the onset of the symptoms, three stages have been defined, as shown in Table 2.2 (Chatterjee, 1987). Treatment in the first stage is, of course, preferred. Often, the condition causing the symptom can be alleviated by ergonomic means. In more advanced stages, medical attention is necessary (Kroemer, 1989).

Table 2.2 Steps of UEMSDs and the characteristics (Chatterjee, 1987)

Step	Characteristics
Step 1	- Aches and 'tiredness' during the working hours - Settling of symptoms overnight and over days off work - No reduction in work performance - Persistence for weeks or months
Step 2	- Early start of symptoms in the work shift - Persistence of symptoms overnight, disturbing sleep - Reduction in performance of repetitive work - Persistence over months
Step 3	- Symptoms at rest, pain with non-repetitive movements - Sleep disturbance - Difficulties in performing even light duties - Duration of months or years

Based on the review of literature on classification of risk factors of UEMSDs, risk factors can be classified, as shown in Figure 2.1, into individual, physical, and psychosocial factors (You, 1999). It is known that physical and psychosocial factors constitute occupational factors, and individual factors are non-occupational factors. First, physical factors include task factors (such as body posture, repetitiveness, force, duration, mechanical stress, and angular velocity and acceleration), and environmental factors (such as vibration, temperature, ventilation). Second, psychosocial factors include physical demand factors (such as time pressure, monotony, and responsibility), organization factors (such as autonomy, job control, decision latitude, and job security), and social support factors (such as family or colleague relationship, and safety). Lastly, individual factors include sociodemographic factors (such as age, gender, heredity, exercise, and hobby), medical histories (such as acute trauma and chronic disease), and

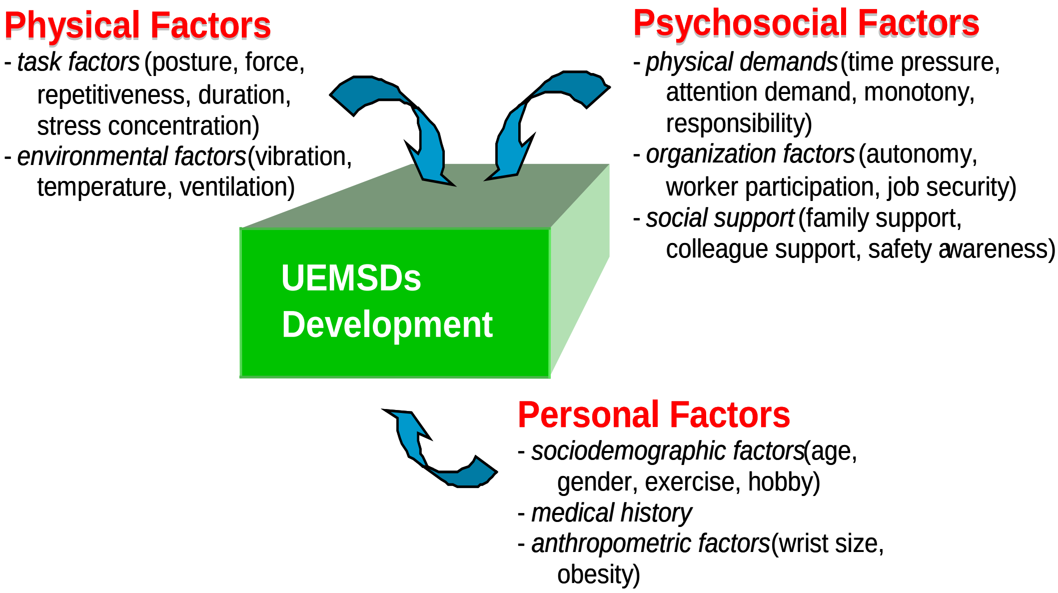


Figure 2.1 Risk factors of UEMSDs (adapted from You, 1999)

anthropometric factors (such as wrist size, spinal size, handedness, and obesity).

Control methods to prevent or reduce the risk factors for UEMSDs are usually categorized as engineering control methods and administrative control methods. On the basis of ergonomic principles, several qualitative guidelines of control methods to control UEMSDs are presented in Table 2.3 for each risk factor (You, 1999). Engineering control methods are methods (such as workstation design and tool redesign) of modifying the structure and dimensions as well as the temporal nature of the task and job design, whereas administrative control methods are methods (such as job rotation and rest breaks) of reducing either the magnitude or the duration of exposure to risk factors by management or personnel methods (Kuorinka and Forcier, 1995).

Table 2.3 Prevention methods for UEMSDs (You, 1999)

Risk Factors	Engineering and Administrative Solutions
Posture	1. Reorienting the work to maintain comfortable posture. 2. Redesigning tools or workstations by providing proper adjustability. 3. Relocating objects within a normal range of movements. 4. Eliminating static postures to reduce localized fatigue. 5. Using supports or rests.
Velocity/ Acceleration	1. Reducing of high-speed movements. 2. Eliminating or modifying piece-rate incentive pay system (payment based on the number of items completed).*
Forceful Exertion	1. Reducing the weight of an object held in the hand. 2. Having the worker lift with two hands rather than one. 3. Holding fewer objects at a time. 4. Enhancing the frictional quality of objects (e.g., tool handles). 5. Using of a power grip rather than a pinch grip. 6. Balancing weights that twist the hand. 7. Reducing the torque required to hold the tool using external torque-control devices. 8. Using mechanical aids (suspension devices or fixtures) to eliminate the need to hold objects.
Repetition	1. Automating or using mechanical aids. 2. Reducing work pace. 3. Allowing adequate rest time. 4. Using more workers to do a particular job.* 5. Rotating workers to jobs involving different motion patterns.* 6. Enlarging job content to include a wider variety of motion.* 7. Implementing a self-paced system (the worker controls the speed of work) rather than machine-paced system (a worker has little or no control over the work pace as in an assembly line).*
Vibration	1. Reducing the vibration magnitude of tool. 2. Reducing exposure time. 3. Isolating the operator from vibration source.
Cold Temperature	1. Maintaining proper body temperature (environmental air, tool exhaust air, and materials contacting with the worker' hands should not be colder than 70 deg. F for prolonged or repeated contact with the hand). 2. Directing exhaust air from power tools away from the hand. 3. Using gloves or mittens to help keep the hands warm.
Mechanical Stress Concentrations	1. Distributing forces over as large an area of the body as possible (rounding or padding all surfaces that come in contact with the body). 2. Using tool handles that are long enough to extend beyond the palm. 3. Using pliant materials. 4. Avoiding the use of the hand for pounding.
Glove Use	1. Fitting gloves well. 2. Avoiding unnecessary protection to the hand by the gloves (palm protection; finger protection).

Note: * administrative control methods

2.2 Methodologies for exposure level establishment of upper extremity intensive tasks

There are 4 types of methodologies (epidemiological, biomechanical, physiological, and psychophysical) for establishing exposure levels of upper extremity intensive tasks. Epidemiological methodology evaluates if a quantitative exposure-effect relationship exists between repetitiveness and UEMSDs by observing or surveying over a long time. Biomechanical methodology is used mainly to assess postural stresses with force loading. Physiological methodology assesses work stresses by using physiological equipments. Psychophysical methodology determines a maximum acceptable workload based on the worker's own feelings of pain, discomfort and fatigue.

Epidemiological methodology requires a lot of time and resources to assess the exposure level of upper extremity intensive tasks. There have been many epidemiological studies on UEMSDs (Silverstein et al., 1986, 1987; Winkel and Westgaard, 1992; Sommerich et al., 1993; NIOSH, 1997; You, 1999). Silverstein et al. (1986, 1987) systematically contrasted highly repetitive jobs with low repetitive jobs for a large range of industrial tasks, and then indicated an association between repetitiveness and UEMSDs. The NIOSH (1997) reviewed more than 600 epidemiological studies on UEMSDs of the shoulder, elbow, and hand/wrist, and then concluded that a large body of credible epidemiologic research showed a consistent relationship between UEMSDs and certain physical factors, especially at higher exposure levels. However, these studies were time-consuming. Other difficulties in establishing the exposure-effect relationship of UEMSDs, regardless of whether the risk factors occurred singly or with others, related to the varying responses of people to the same levels of exposure. Hennekens et al. (1987) also indicated that epidemiological methodology offered quantitative results of repetitiveness, but required a lot of time and resources for data collection.

Biomechanical methodology, which mainly assesses postural stresses with force loading, cannot address repetitiveness and fatigue issues on the musculoskeletal system. An advantage of the biomechanical methodology is that stresses on the body for some occupational activities can be estimated by using available biomechanical models, which are relatively easy to use and under constant refinement and update (Ayoub et al., 1980). On this account, biomechanical methodology has been mainly used in development of limits on load, and in estimation of mechanical stresses in terms of reactive forces and moments on the various joints of the musculoskeletal system for certain tasks. For example, Moore et al. (1991) presented several biomechanical models explaining the hand geometry, tendon pressure on surrounding tissue, tendon axial force, tendon excursion, and friction work factor. However, as the biomechanical methodology assumes infrequent tasks, the effect of repetitiveness and fatigue has been ignored (Ayoub, 1992; Tracy, 1990; Armstrong and Chaffin, 1979).

Physiological methodology is not as sensitive to upper extremity intensive tasks. This methodology to assess work stresses includes electromyography (EMG), heart rate, oxygen uptake, blood pressure (systolic, diastolic), and other techniques (Rohmert, 1973a, 1973b; Wilson and Corlett, 1995; Kumar and Mital, 1996; Li and Buckle, 1999). Among these, EMG and heart rate have been most widely used to evaluate work stress, while others have been used in a few particularly controlled studies. For each physiological parameter, a criterion is made as to the magnitude of change from resting or steady state conditions. For example, Rohmert (1973a, 1973b) concentrated on physiological methodology to establish safe levels of rest allowances. This methodology utilizing such quantifiable measures has, however, shown a lack of reliability, and is not sensitive enough to address the small muscle groups in upper extremity (e.g., Garg, 1983; Baidya and Stevenson, 1988).

Psychophysical methodology can be used to establish acceptable exposure levels under a variety of repetition, force, posture, and duration conditions. Psychophysics is the study of the relationship between sensations and their physical stimuli and relies on the assumption that subjects can identify exposure conditions that they perceive as having an acceptable level of stress for them, based on an integration of biomechanical and physiological sensory feedback (Potvin et al., 2000). Therefore, it can determine a maximum acceptable workload based on the worker's own feelings of pain, discomfort and fatigue (Garg and Saxena, 1982). The primary advantage of this methodology is that it permits the realistic simulation of industrial work, allowing aspects such as workspace dimensions and task frequencies to be altered accordingly (Snook, 1985a). Krawczyk (1996) stated that psychophysical methodology is a consistent, reproducible, quick, inexpensive, and convenient way to assess the degree of physical strain on the human body. Kim and Fernandez (1993), Dahalan and Fernandez (1993), and Marley and Fernandez (1995) showed that it was a reproducible and reliable method for establishing acceptable exposure levels in hand/wrist work, and then concluded that it was an acceptable technique for establishing acceptable exposure levels sensitive to changes in motion, frequency, duration, and hand grip type. However, Snook (1985a) indicated that psychophysical methodology was a subjective method that relies upon self report from subjects, and stated that it would probably be replaced when and if objective methods become available. Regardless, Putz-Anderson and Grant (1995) have concluded that "when carefully applied, psychophysical methods provide a practical means for achieving the goal of establishing safe levels of work.” In fact, psychophysical methodologies have been widely used to evaluate exposure stress independently or simultaneously with other objective methods such as EMG, because objective methods have reliably assessed exposure stresses. The detailed advantages and disadvantages of psychophysical methodology are shown in Table 2.4.

Table 2.4 Advantages and disadvantages of psychophysical methodology (Snook, 1985a)

	Description
Advantages	1) Psychophysics permits the realistic simulation of industrial tasks. For example, task frequency can be varied from very fast to very slow rates. 2) Psychophysics can be used to study the very intermittent tasks that are commonly found in industry. A physiologically steady state is not required. 3) Psychophysical results are consistent with the industrial engineering concept of a ‘fair day’s work for a fair day’s pay’. With the exception of very fast frequency tasks, psychophysical results are consistent with metabolic criteria of continuous or occupational work capacity. 4) Psychophysical results are very reproducible.
Disadvantages	1) Psychophysics is a subjective method that relies upon self-report from subjects. It will probably be replaced when and if more objective methods become available. 2) Psychophysical results from very fast frequency tasks are higher than recommended metabolic criteria.

2.3 Psychophysical studies for exposure level establishment of upper extremity intensive tasks

In recent years, psychophysical methodology has been used to establish acceptable exposure levels in upper extremity intensive tasks. One reason for its frequent use in the last few decades is the relative ease of obtaining data through this method. Alternate methodologies for establishing exposure levels or guidelines, such as the epidemiological, biomechanical and physiological methodologies, can take much longer and be more costly to perform. The psychophysical methodology is widely supported. Borg (1983) indicated that psychophysical methodologies might serve as a more sensitive indicator for the risk of the development of UEMSDs. Snook (1985b) noted that an application of psychophysical methodologies to hand intensive activities, such as those seen on an assembly line, would have reasonable results. Also, Putz-Anderson and Galinsky (1993) wrote that the only way to obtain a global assessment was to quantify the worker's perceptual experience of local fatigue sensations using psychophysical methodologies. Finally, Krawczyk (1996) stated that these psychophysical data could provide guidance in the analysis and design of repetitive manual work such as upper-extremity intensive tasks. Accordingly, psychophysical methodologies have been used to assess upper extremity intensive tasks and different hand tools, and to derive guidelines for the design of upper extremity intensive tasks (e.g., Putz-Anderson and Galinsky, 1993; Kim and Fernandez, 1993; Dahalan and Fernandez, 1993; Marley and Fernandez, 1995; Snook et al., 1995, 1997, and 1999; Potvin et al., 2000; Ciriello et al., 2001). These psychophysical studies for the upper extremity are grouped into maximum acceptable torque or force studies, maximum acceptable frequency studies, maximum acceptable duration studies, and maximum acceptable impact force studies, and summarized in Appendix A.

Snook and his colleges have recently used psychophysical methodologies to develop maximum acceptable torques or forces for upper extremity intensive tasks. Snook et al. (1995) used psychophysical methodology to measure maximum acceptable torques of repetitive wrist flexion with both a pinch and power grip, and extension with a power grip for various repetition rates (2, 5, 10, 15, and 20 motions per minute). These are motions used in lever operation and insertion tasks. Sixteen females were evaluated in a laboratory setting, performing the task for 8-hours on 2 days per week. Maximum acceptable torques significantly decreased with increasing repetition rates, and also varied consistently with type of hand motion and grip. The data were used to develop tables of maximum acceptable forces that may be converted by dividing each torque by the average length of the handle lever for various repetition rates. Snook et al. (1997) developed similar tables of maximum acceptable forces for repetitive ulnar deviation of the wrist with a power grip by using psychophysical methodology. Ulnar deviation is a motion commonly used in the meat packing industry when cutting and trimming meat products. Although maximum acceptable torques of ulnar deviation decreased with increasing repetition rate (15, 20, and 25 motions per minute), the differences were not statistically significant. Snook et al. (1999) developed maximum acceptable forces for repetitive wrist extension with a pinch grip, a motion commonly used during light assembly operations in manufacturing facilities and manual packaging operations in the food industry. Maximum acceptable torques of wrist extension with a pinch grip was lower than wrist flexion with a pinch grip, wrist flexion with a power grip or ulnar deviation. Recently, Ciriello et al. (2001) quantified maximum acceptable forces of six motions: wrist flexion with a power grip, wrist extension with a power grip, wrist flexion with a pinch grip, wrist extension with a pinch grip, ulnar deviation with a power grip, and a handgrip task (with a power grip), and compared them with maximum acceptable forces for wrist flexion with a power grip, wrist extension with a pinch grip, and ulnar deviation with a power grip from previous studies (Snook et al., 1995, 1997, 1999).

Several researchers have recently used psychophysical methodologies to develop maximum acceptable frequencies (MAFs) for upper extremity intensive tasks (Garg and Saxena, 1982; Kim and Fernandez, 1993; Dahalan and Fernandez, 1993; Marley and Fernandez, 1995). Garg and Saxena (1982) determined the MAFs of female workers for one-handed lifts in the horizontal plane and compared the results to psychophysical allowable workloads based on physiological fatigue criteria and methods-time measurement (MTM) analysis. Fernandez and his colleges have studied psychophysical applications of MAFs for upper extremity intensive tasks. In each of these studies, participants were asked to maintain a certain percent of their maximum voluntary contraction and arrive at an MAF at which they comfortably perform the task for 8-hours. It was noted that as force and duration increased, MAF generally decreased for both gripping and pinching tasks. Marley and Fernandez (1995) determined the MAF under various wrist posture requirements (combinations of flexion (0, 1/3, 2/3 ROM) and ulnar deviation (0, 1/3, 2/3 ROM)) and constant force (5.4 kg) and duration (1 sec) for a sheet metal drilling task which involves a potential risk of developing UEMSDs. This study indicated that wrist flexion angle was a significant factor for several dependent variables, but no significant relationships were found between any of the outcome variables and ulnar deviation. Kim and Fernandez (1993) used psychophysical methodology to determine the MAF of females for a simulated sheet metal drilling task at different applied forces (2.73, 5.45, 8.18, 10.91kg) and wrist flexion angles (0, 10, 20 deg). Force and angle were significant ($p < .01$) for the MAFs. Dahalan and Fernandez (1993) determined the MAF for a simulated intermittent gripping task at different gripping forces (20, 30, 50, 70% MVC) and task durations (1.5, 3, 5, 7 sec) using a psychophysical protocol. MAF in this study reduced significantly as gripping force and duration increased. Klein and Fernandez (1997) determined the MAF for males performing an intermittent isometric pinching task as a function of different pinch force levels, wrist postures, and task duration. This study showed that the MAF decreased with increased force, increased duration, and wrist deviation ($p < 0.05$).

Apart from maximum acceptable forces and frequencies, several studies have used psychophysical methodologies to establish acceptable exposure loads such as duration (Putz-Anderson and Galinsky, 1993; Wu and Wang, 2002) and impact severity (Potvin et al., 2000) for upper extremity intensive tasks. Putz-Anderson and Galinsky (1993) adopted a psychophysical approach to determine work durations for limiting shoulder-girdle fatigue in a set of experiments. They showed that psychophysically determined work durations significantly decreased as task loading variables, such as repetition rate, required force, tool weight, and reach height increased. Wu and Wang (2002) established the relationship between maximum acceptable work time and physical workload. Potvin et al. (2000) established acceptable impact severity levels for a simulated door trim panel installation process where the base of the hand was used to impact the door trim panel and drive plastic fastening push pins through holes in the metal door frames. Additionally, Kee and Karwowski (2001) proposed a postural classification scheme of the upper body based on perceived joint discomfort measured in a laboratory experiment using the magnitude estimation method.

CHAPTER III.

Comparison of Assessment Methodologies and Risk Exposure Levels for Repetitiveness of Upper Extremity Intensive Tasks

3.1 Repetitiveness assessment methodologies

To identify measures that have been used in repetitiveness research in a comprehensive manner, the present study reviewed 31 studies, published between 1997 and 2002. Scientific database systems utilized in the literature survey included ScienceDirect (www.sciencedirect.com), Ingenta Select (www.ingentaselect.com), and MEDLINE (www4.infotrieve.com). Keywords for the literature search were the combinations of terminologies for repetitiveness (such as repetition, repetitive, and repetitious), ones for upper extremity (such as finger, wrist, hand, forearm, elbow, arm, shoulder, manual, and upper limb), and ones for task (such as job, work, motion, and movement). By reviewing the abstracts of the resulting studies, 31 studies related to the repetitiveness assessment of upper extremity intensive tasks were selected for further analysis.

Then, from these 31 studies and additional papers published before 1997, repetitiveness measures were listed and then classified in terms of dimensional type and analysis scope, as shown in Table 3.1. At the top level of the measure classification table, two types of dimensions were identified: cycle time (the length of time for the completion of a work cycle) and frequency (the number of work cycles, movements, or force exertions per unit time). Then, at the second level of the table, under the frequency category, three types of analysis scopes were further identified: work cycle, body part, and force exertion.

Next, based on the measure classification system, the surveyed repetitiveness measures were summarized in group, as shown on the last column of Table 3.1. First, under the work cycle time category, two measures (overall work cycle time and fundamental work cycle time) are listed. Note that a work cycle can be subdivided into several fundamental work cycles (Kilbom, 1994); for example, a door assembly task can be decomposed into several fundamental work cycles such as driving a screw, drilling, stapling, laminating, and lifting the door. Second, under the work cycle frequency category, frequency measures which correspond to overall work cycle time and fundamental work cycle time are listed. Note that the work cycle time and work cycle frequency measures are convertible to each other by Equation 1.

$$f = \frac{L - R}{W} \tag{1}$$

where, *f* = frequency of overall (or fundamental) work cycle

L = length of a time period

W = overall (or fundamental) work cycle time

R = rest time between overall (or fundamental) work cycles

Third, under the body part frequency category, four types of movement frequency measures involving different parts of the upper extremity are listed: fingers, hand/wrist, forearm/elbow, and arm/shoulder movement frequencies. Lastly, under the force exertion frequency category, two types of hand force exertion frequency measures are listed: power and pinch force exertion frequencies.

Table 3.1 Classification of repetitiveness measures for upper extremity intensive tasks

Dimension	Analysis scope	Measure
Cycle time	Work cycle	Overall work cycle time
		Fundamental work cycle time
Frequency	Work cycle	Overall work cycle frequency
		Fundamental work cycle frequency
	Body part	Finger movement frequency
		Hand/wrist movement frequency
		Forearm/elbow movement frequency
		Arm/shoulder movement frequency
	Force exertion	Power force exertion frequency
		Pinch force exertion frequency

Then, based on the measure classification system, the 31 studies were summarized as displayed in Table 3.2, which indicates a dominant use of frequency measures in repetitiveness research. Among these studies, the frequency measures have been employed 4.7 times more frequently than the time measures and hand/wrist movement frequency has been most frequently used (42%) in repetitiveness assessment. Notice that none of the studies employed fundamental work cycle time.

Table 3.2 Application of repetitiveness measures (from 1997 to 2002)

Measure			Study (No. studies)	
Cycle time	Work cycle	Overall work cycle time	BK, CD, CH1, KR, LW-2, SP, TF, JB-2, YT-2, YT-3	(10)
		Fundamental work cycle time		(0)
Fre-quency	Work cycle	Overall work cycle frequency	CD, YT-1, YT-2	(3)
		Fundamental work cycle frequency	CD, HM	(2)
	Body region	Finger movement frequency	LW-1, LW-2, YM-1, YM-2	(4)
		Hand/wrist movement frequency	AT, BK, CE, CH2, CV, HG1, HS, JB-1, JB-2, KR, LM-1, LM-2, LM-3, LT, LW-1, LW-2, MJ, SE, SM, SP, YM-1, YT-1, YT-2, YT-3	(24)
		Forearm/elbow movement frequency	HS, LW-1, YT-1, YT-2, YT-3	(5)
		Arm/shoulder movement frequency	HS, YT-1, YT-2, YT-3	(4)
	Force exertion	Power force exertion frequency	CV, LW-2, MJ, PJ	(4)
		Pinch force exertion frequency	KM	(1)
Total				(57)

AT: Armstrong et al. (2002)
BK: Babski-Reeves and Crumtpon-Young (2002)
CD: Colombini (1998)
CE: Carey and Gallwey (2002)
CH1: Christensen et al. (2000)
CH2: Coury et al. (2000)
CV: Ciriello et al. (2001)
HG1: Hansson et al. (2000)
HS: Hignett and McAtamney (2000)
HM: Häkkänen et al. (1997)
JB-1: Juul-Kristensen et al. (2002)
JB-2: Juul-Kristensen et al. (2001)
KM: Klein and Fernandez (1997)
KR: Ketola et al. (2001)
LM-1: Lin and Radwin (1998a)
LM-2: Lin and Radwin (1998b)
LM-3: Lin et al. (1997)
LT: Leskinen et al. (1997)
LW-1: Latko et al. (1999)
LW-2: Latko et al. (1997)
MJ: Malchaire et al. (1997)
PJ: Potvin et al. (2000)
SE: Serina et al. (1999)
SM: Stål et al. (1999)
SP: Spieholz et al. (2001)
TF: Treveltan and Haslam (2001)
YM-1: Yun and Kwon (2002)
YM-2: Yun et al. (2002)
YT-1: Yen and Radwin (2002)
YT-2: Yen and Radwin (2000)
YT-3: Yen and Radwin (1999)

In the literature survey in the present study, measurement methods and analysis techniques used for repetitiveness assessment were also identified. The measurement methods were classified into objective methods and subjective methods depending on the involvement of subjective judgment. Table 3.3 summarizes the measurement methods

Table 3.3 Application of measurement methods (studies from 1997 to 2002)

Measurement method		Studies (number of studies)
Objective method	Stopwatch	BK, KR (2)
	Video	BK, CD, HM, JB-2, KR, LT, LW-1, LW-2, SP, TF, YT-1, YT-2, YT-3 (13)
	Electrogoniometer	CE, CH2, HG, JB-1, JB-2, LM-1, LM-2, LM-3, MJ, SE, SM, SP, YT-1, YT-2, YT-3 (15)
	Cyberglove	YM-1, YM-2 (2)
	Electromyography (EMG)	MJ (1)
	Force gauge	CV, KM, PJ (3)
Subjective method	Categorical scale	HS (1)
	Visual analog scale	AT, LW-1, LW-2, SP (4)

AT: Armstrong et al. (2002)
BK: Babski-Reeves and Crumtpon-Young (2002)
CD: Colombini (1998)
CE: Carey and Gallwey (2002)
CH1: Christensen et al. (2000)
CH2: Coury et al. (2000)
CV: Ciriello et al. (2001)
HG: Hansson et al. (2000)
HS: Hignett and McAtamney (2000)
HM: Häkkänen et al. (1997)
JB-1: Juul-Kristensen et al. (2002)
JB-2: Juul-Kristensen et al. (2001)
KM: Klein and Fernandez (1997)
KR: Ketola et al. (2001)
LM-1: Lin and Radwin (1998a)
LM-2: Lin and Radwin (1998b)
LM-3: Lin et al. (1997)
LT: Leskinen et al. (1997)
LW-1: Latko et al. (1999)
LW-2: Latko et al. (1997)
MJ: Malchaire et al. (1997)
PJ: Potvin et al. (2000)
SE: Serina et al. (1999)
SM: Stål et al. (1999)
SP: Spieholz et al. (2001)
TF: Treveltan and Haslam (2001)
YM-1: Yun and Kwon (2001)
YM-2: Yun et al. (2002)
YT-1: Yen and Radwin (2002)
YT-2: Yen and Radwin (2000)
YT-3: Yen and Radwin (1999)

employed in the surveyed studies, indicating that electrogoniometer, video system, and visual analog scale have been used more frequently in repetitiveness research.

Lastly, two types of techniques have been applied to analysis of repetitiveness measurements: statistical and spectral techniques. While most studies have summarized measurement results by using statistical measures (such as mean and standard deviation), some studies such as Juul-Kristensen et al., (2001), Hansson et al. (2000), and Yen and Radwin (1999, 2000) have utilized spectral analysis for repetitiveness assessment. Radwin and Lin (1993) first applied spectral analysis to quantify the repetitiveness of joint motions by calculating mean power frequency (average frequency weighted by power) through conversion of angular measurements from an electrogoniometer at the joint along time to power data along frequency. Hansson et al. (1996) supported the utility of spectral analysis for the repetitiveness assessment of complex and/or irregular joint motions.

3.2 Meta-analysis for repetitiveness risk levels

To conduct a meta-analysis of the repetitiveness risk levels that had been determined in repetitiveness research, the present study used the 31 studies used in the repetitiveness assessment methodologies survey. Then, based on the 31 studies, additional papers published from 1980 to 1996 were included in the meta-analysis. The objective of the meta-analysis is to develop, on the basis of the published literature, preliminary ergonomic levels for repetitiveness risk of upper extremity intensive tasks. Here, the influence on the levels of repetitiveness for personal factors such as body mass, age, and gender as well as physical factors such as posture, force, and duration was not taken into consideration. The meta-analysis allowed the development of statistics (such as means) based on the results of many studies of various researchers.

Studies included in the meta-analysis were selected from the various repetitiveness studies previously mentioned after a comprehensive review. Studies eligible for inclusion were scrutinized using 4 exclusion criteria; (1) lack of quantitative values for repetitiveness risk level for upper extremity intensive tasks, (2) absence of reference data, i.e. absence of reference studies or, absence of analysis process, (3) lack of a clear definition for upper extremity part (such as shoulder, elbow, wrist, and finger), and (4) repetitiveness not by motion, but by force at a static posture.

Results of the meta-analysis are summarized in Table 3.4. Altogether 7 studies (comprising 1 prospective study, 1 cross-sectional study, 1 case-referent study, and 4 review studies) on repetitiveness risk levels were selected. Although a considerable number of repetitiveness studies investigated the wrist, repetitiveness studies on the shoulder, elbow, and finger were limited. Repetitiveness risk levels in the studies selected were expressed as a single value of the number of motions per minute. When a range of values was reported rather than a single value, the highest value was used as a representative risk level. The number of motions per hour was converted to the number of motions per minute based on an 8-h working day including two 15-min breaks (Genaidy et al., 1993). Lastly, for each upper extremity part, the mean number of motions per minute was computed across all studies.

Table 3.4 Repetitiveness risk level for upper extremity

Part	Study	Criterion (motions/min)	Remark
Shoulder	Kilbom (1994)	2.50	-
	Genaidy et al. (1993)	6.30	-
	Colombini (1998)	10.00	20~60°
	Mean	6.27	
Elbow	Genaidy et al. (1993)	6.30	-
	Kilbom (1994)	10.00	-
	Mean	8.15	
Wrist	Kilbom (1994)	10.00	-
	Malchaire et al. (1996)	15.10	F/E*: 60 %ROM R/U**: 50 % ROM
	Malchaire et al. (1997)	16.20	F/E: 60 %ROM R/U: 50 % ROM
	Genaidy et al. (1993)	26.00	-
	Hansson et al. (2000)	31.80	-
	Wick (1994)	33.30	-
	Mean	22.07	
Finger	Genaidy et al. (1993)	48.70	-
	Kilbom (1994)	200.00	-
	Mean	124.35	

* F/E: flexion/extension, ** R/U: radial/ulnar deviation

CHAPTER IV.

Identification of Maximum Acceptable Frequencies for Upper Extremity Motions with External Loads

4.1 Methods

4.1.1 Subjects

Seventeen right-handed male adults selected from the student population at POSTECH participated in the experiment. The mean age of the subjects was 25 years with a standard deviation of 1.32 and a range of 23 to 27 years. All the subjects were screened for previous upper extremity injuries prior to selection. All the subjects were judged to be in good physical health and claimed to have never had any musculoskeletal or cardiovascular problem. Each subject was required to report a medical history.

Fourteen anthropometric measurements were made to characterize the subject population. The anthropometric measures taken included height, weight, shoulder-elbow length, upper arm circumference, elbow-wrist length, elbow-grip length, elbow breadth, forearm circumference, hand length, palm length, wrist breadth, hand breadth, wrist circumference, and hand circumference. Detailed descriptions of these measures are shown in Appendix B. These anthropometric measures were assessed with a anthropometric kit including a tapeline and Vernier calipers (Figure 4.1). Table 4.1 contains means and standard deviations of selected upper extremity and whole body anthropometrics. All anthropometric measures of the upper extremity were performed using the subject's right hand and arm.

Figure 4.1 Anthropometric kit

Table 4.1 Descriptive statistics of the subjects' characteristics

Measure	Mean	Std Dev	Max	Min
Age (year)	25.0	1.32	27.0	23.0
Height (cm)	175.6	5.16	183.0	167.0
Weight (kg)	71.7	8.51	85.0	55.0
Shoulder-Elbow Length (cm)	32.3	1.62	35.0	29.9
Upper Arm Circumference (cm)	30.1	3.07	34.1	24.5
Elbow-Wrist Length (cm)	25.1	1.35	27.4	23.3
Elbow-Grip Length (cm)	31.9	1.62	34.5	29.6
Elbow Breadth (cm)	8.6	0.45	9.3	7.8
Forearm Circumference (cm)	27.2	1.46	30.0	24.8
Hand Length (cm)	19.0	0.50	19.9	18.0
Palm Length (cm)	11.2	0.42	11.8	10.5
Wrist Breadth (cm)	5.6	0.25	6.0	5.1
Hand Breadth (cm)	8.3	0.26	8.8	7.6
Wrist Circumference (cm)	16.8	0.51	17.7	16.1
Hand Circumference (cm)	19.9	0.83	22.0	18.3

4.1.2 Experimental design

A two-factor (4×2) within-subject design was used in the experiment. Independent variables of the experiment were 4 upper extremity parts (shoulder, elbow, wrist, and index finger) and 2 external load/force levels (low and high). External load levels for the shoulder, elbow, and wrist were 1kg and 4kg, and external force levels for the index finger were 0.25kg and 1kg. Although no consensus exists on how to standardize external load/force, these load/force levels have been recognized as moderate force levels by Silverstein et al. (1986, 1987), Stetson et al. (1991), and Li and Buckle (1998).

Control variables were motion range for each upper extremity part and motion speed. Motion ranges for the shoulder, elbow, and wrist were 40° (50 ~ 90°), 30° (90 ~ 120°), and 20° (0 ~ 20°) respectively (see Figure 4.2) to avoid awkward postures in each motion in the sagittal plane. Since consensus on non-awkward motion ranges is lacking, the present study chose moderate motion ranges for the shoulder, elbow, and wrist based on the studies by Stetson et al. (1991) and Kee and Karwowski (2001). However, the motion range for the index finger was not controlled. Here, subjects were instructed that motion speed should be constant at a acceptable speed during the experimental session. Figure 4.2 shows standard postures and motion ranges for shoulder, elbow, and wrist motions.

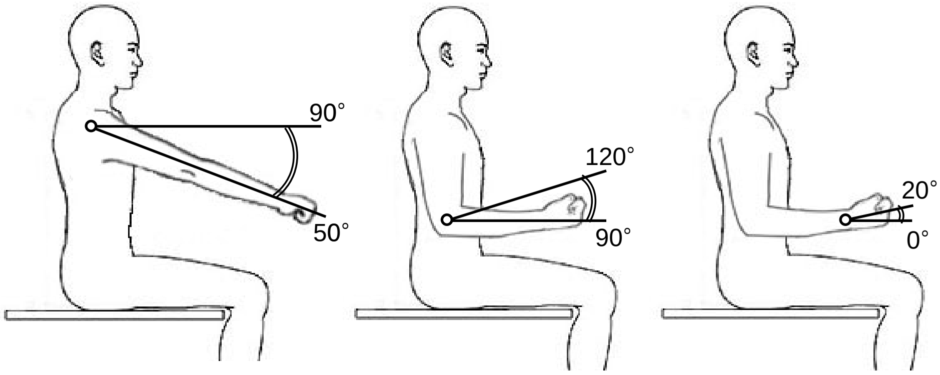


Figure 4.2 Motion ranges for shoulder, elbow, and wrist motion

Dependent variables were maximum acceptable frequency (MAF), work pulse (change in heart rate), working heart rate, and rating of perceived exertion (RPE). Heart rate and RPE were measured to identify the physiological and psychophysical level of functioning during the experiment for determining the MAF. RPE were collected at the shoulder, upper arm, elbow, forearm, wrist, palm, and fingers regions of right upper extremity.

4.1.3 Apparatus

Experimental setup

The workstation was set up to simulate upper extremity (such as shoulder, elbow, wrist, and index finger) motions as depicted in Figure 4.3. The workstation was constructed with an adjustable chair, a table, and a desktop computer as a beep generator. The desktop computer was used to display a color bar graph, and emit a beep to prompt the subject to perform the task. The monitor was situated in front of the subject at a distance of approximately 70cm.The top side of the table was covered with a mouse pad to minimize noise generated due to impact of the load with the table top. All experiments were performed under approximately constant environmental conditions at or near normal room temperature.

The load/force levels of the task were controlled by dumbbells and a pinch dynamometer (NK pinch-grip™, NK Biotechnical Co.). Loads used in the experiment of shoulder, elbow, and wrist motions were two dumbbells of different weights (1kg and 4kg) with a center grasping diameter of 2.8cm. The pinch device used in the experiment of index finger motion is a pinch grip dynamometer (NK Biotechnical Corporation). When index finger motion applied force to the pinch gauge, colored signal lamps (comprising white, green, and red lamps) provided feedback to the subject. A green lamp represented the target force or the level of force required (± 0.05 kg). A white lamp indicated that subject was not exerting enough force and a red lamp indicated that more force was exerted than required.

The frequency of the task used in the experiment was controlled with a program which offered an auditory cue and a visual cue. The program (using Visual Basic 6.0) was designed such that it provided no quantitative feedback to the subject except for the direction arrow keys of keyboard indicating frequency "increase" or "decrease." The auditory output from the program served as a cue for the subject to begin the motion. The initial frequency was randomly determined in 1 to 100 (motions per minute) for the shoulder, elbow, and wrist motions, and 1 to 300 (motions per minute) for the index finger motion.

Figure 4.3 Workstation plan

Physiological and psychophysical measures

Maximal voluntary contractions (MVCs) of upper extremity parts (shoulder, elbow, wrist, and index finger) for each subject were measured using a digital force gauge with a remote load cell (Chatillon® DFGS-R-500, AMETEK®) or a pinch dynamometer (NK pinch-grip™, NK Biotechnical Co.) as depicted in Figure 4.4. The digital force gauge was used to measure the MVC of the shoulder, elbow, and wrist, and the pinch dynamometer to measure the MVC of the index finger. The load cell was operated with a 0 to 250 kg range, and the pinch dynamometer with a 0 to 20 kg range.

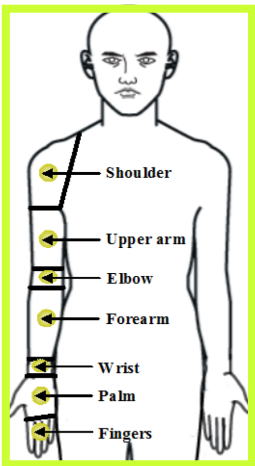
(a) Force gauge

(b) Pinch dynamometer

Figure 4.4 MVC measurement devices

Heart rate was monitored with a ‘Polar Accurex Plus™’ heart rate monitor system (POLAR®) with transmitter and wrist receiver. The polar coded transmitter was attached below the chest muscles. Heart rate data was monitored every 5 seconds. Kroemer and Grandjean (1997) noted that measuring heart rate was the most useful way of assessing the workload because it could be done so easily. Kroemer et al. (1990) indicated that equipment used to measure and record heart rate was relatively simple and inexpensive.

The Borg category ratio 10 (CR-10) scale (Borg, 1998) was used to collect ratings of perceived exertion (RPE) for upper extremity regions: shoulder (area of joint rotation), upper arm, elbow (area of joint rotation), forearm, wrist (area of joint rotation), palm, and fingers. The Borg CR-10 scale is a one dimensional scale from 0 to 10 with verbal anchors. It is a 10-point category rating scale with ratio properties which yields psychophysical functions similar to those found with magnitude estimation methods (Putz-Anderson and Galinsky, 1993). The scale used in the present study has been widely used to obtain RPE in fatigue research, along with the visual analog scale (VAS). A VAS which consists of a horizontal 10cm line with verbal anchors or descriptions at the endpoints has been used for the evaluation of upper-extremity intensive tasks (e.g., Ulin et al, 1990). Harms-Ringdahl et al. (1986) compared Borg’s category scale and a 10-cm VAS and found no significant difference between the two scales. Moreover, some studies have correlated Borg subjective ratings to other objective measures (e.g., Dedering et al., 1999; Gorman et al., 1999; Yun and Kwon, 2001; Wikstrom, 1993). Figure 4.5 shows the upper extremity regions and Borg’s CR-10 scale presented to subjects for report of RPE.



0	Nothing at all	"No P"
0.3		
0.5	Extremely weak	Just noticeable
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	**Extremely strong**	**"Max P"**
11		
∞		
●	Absolute maximum	Highest possible

Figure 4.5 Upper extremity regions and Borg's CR-10 scale used in collecting RPE

4.1.4 Experimental procedure

Maximal voluntary contraction (MVC)

Each subject performed four different maximal voluntary contraction (MVC) tests involving shoulder flexion, elbow flexion, wrist flexion, and index finger press. MVC were collected while the subject was sitting on a chair with upper arm hanging down naturally, elbow flexed at 90°, forearm supinated, and wrist in neutral position for shoulder flexion, elbow flexion, and wrist flexion (see Figure 4.7). A cuff was placed just proximal to the right upper extremity and connected to a load cell (Chatillon® DFGS-R-500, AMETEK®) at a right angle with a cable. A Velcro strap was wrapped around the seatback and trunk, the trunk and upper arm of the working hand (just above the elbow), and the armrest and forearm to restrain the arm during the performance of the test for shoulder, elbow, and wrist flexions respectively, thus assuring the proper shoulder, elbow, and wrist flexions. MVC for index finger press was recorded with upper arm hanging down naturally, elbow flexed at 90°, and forearm parallel to the floor. Then, the forearm and wrist were in a position such that the palm was down and the index finger was in line with the straight wrist.

The Caldwell regime (Caldwell et al., 1974), which requires a total of five seconds for a ramp-up, hold, ramp-down cycle, was used to measure MVC in the present study. The subject was instructed to build up the force over 1 second, thereafter keep pressure for about 3 seconds and then lower the force to zero. The subject received verbal instructions and motivation during each MVC test. At least two MVC trials were performed to ensure that the force recorded was representative of a subject's maximum effort. If there was a difference greater than 10 % between the first two MVC values, additional trials were performed as needed. A 2-min rest period was allowed between MVC measurements. These MVC measurements were performed with the training on the first day.

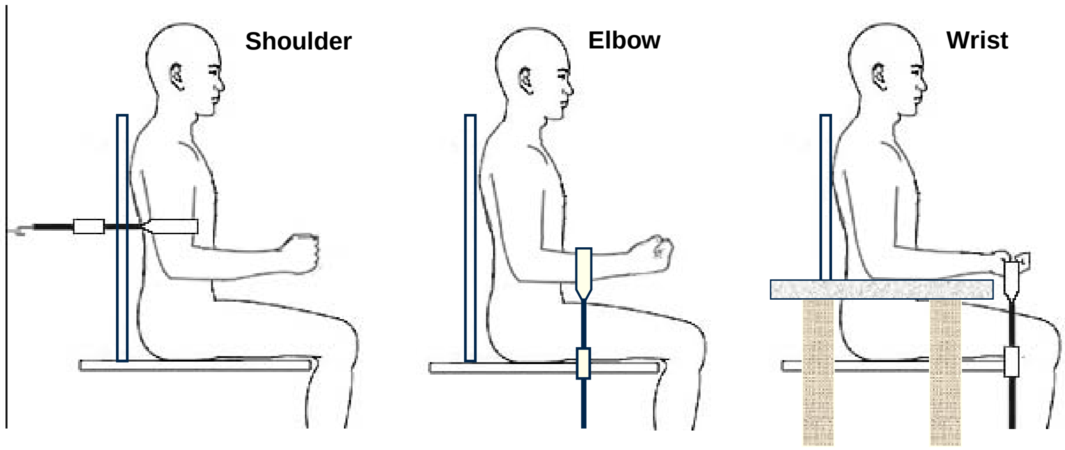


Figure 4.6 Standard postures for measuring MVC of shoulder, elbow, and wrist flexion

Training

Each subject was allowed to become familiar with the experimental method including instructions regarding the psychophysical method of adjustment and training for the 8 treatment tasks. A training session was conducted for a minimum of forty minutes (5 minute session for each task) in one day. No data were collected during the training session. The training session was used to only familiarize the subjects with the psychophysical methodology and with the consequences of the selected workload.

Experiment

Before the experiment, physiological measure was taken while the subjects were sitting at rest. Resting heart rate was monitored for one minute prior to any physical activity. The subjects were then asked to remain seated without moving, drinking coffee or smoking for a further 1 hour.

Subjects sat at the workstation, and placed their right forearm horizontally on the table. The experiments were done on the right arm only in a seated position. The standard neutral posture (referred to as the starting position) was assumed to be sitting, upper arm hanging down naturally, 90° elbow flexion, forearm parallel to floor and mid-supinated or mid-pronated with wrist at a neutral angle (see Figure 4.2). The standard posture was controlled by adjusting the height of the chair for each subject. The tasks were one-handed lifting and lowering of a dumbbell in the sagittal plane for the shoulder, elbow, and wrist motions, and index pulp pressing for the index finger motion. In the shoulder motion, the subject sat by the side of a 70cm high work table to perform upper extremity motions, and they were required to grasp a dumbbell located in front of them with their right hand (palm down and mid-pronated). In the elbow and wrist motions, the subject sat by the side of a 70cm high work table to perform upper extremity motions, and they were required to grasp a dumbbell located in front of them with their right hand (palm up and mid-supinated). Moreover, in the elbow and wrist motions, elbow and wrist parts were supported by the table to restrict a movement of the other upper extremity parts during a motion. In the index finger motion, the subjects sat by the side of the same table, and they were required to pose for the index pulp pressing task (palm down and mid-pronated).

The subjects were first allowed to warm-up by performing the task for 5 minutes. No data was collected during the warm-up period. The warm-up period was used only to familiarize the subjects with the corresponding task and with the psychophysical methodology. In the warm-up period, the subjects were also given control of the task frequency to determine maximum acceptable frequency to them for the corresponding task if working a normal 8-hour workday.

A psychophysically adjusted frequency was determined using the method of adjustment for each of the 8 treatment tasks according to upper extremity parts and load/force levels. Each treatment session was 30 minutes in length. Adjustment of the task frequency was allowed during the first 25 minutes of the session. The final 5-minute period was maintained at the final frequency selected as ‘reasonable’ for 8 hour of work. This frequency was labeled the maximum acceptable frequency (MAF). That is to say, the frequency selected after 25 minutes of adjustment was then considered to be the maximum acceptable frequency (MAF). During the final minute of a session (30th minute overall), the working heart rate was measured. The working heart rate was the average heart rate during the last minute.

Subjects were instructed to work as if they were on an incentive basis, getting paid for the amount of work they performed. They were asked to work as hard as they could without developing unusual discomfort in upper extremity regions such as shoulder, upper arm, elbow, forearm, wrist, palm, and fingers. A detailed instruction for adjustment given to subject was adapted from the instruction used by Snook et al. (1999), as shown in Appendix D. The subjects had no feedback on the task frequency at which they were performing.

During a treatment task, 4 types of interventions were conducted. First, the instructions were reviewed. Secondly, the subject was informed that he was not following the instructions for adjusting the task frequency. Next, at the 24th minute the subject was informed that frequency adjustment was no longer allowed. Finally, heart rate was monitored during the final minute.

After the experiment, psychophysical measure was measured. Immediately after an experiment, a subjective rating of perceived exertion (RPE) using a Borg CR-10 scale was noted for every upper extremity region: shoulder, upper arm, elbow, forearm, wrist, palm, and fingers. The Borg CR-10 scale was shown at the sitting eye height on the left side.

No more than one session was performed in a day. The 8 treatment tasks were given to the subjects in random order. Each subject completed 9 days of experiment. The first day consisted of training sessions, where subjects were gradually exposed to all 8 treatments. All treatment sessions were performed using the same procedures.

Analysis

Statistical analyses such as analysis of variance (ANOVA), simple main effects analysis, and the Student Newman-Keuls (SNK) test were conducted to investigate characteristics of interesting variables using the SAS software (version 8.2, SAS Institute Inc.). Descriptive statistics were used to summarize the variables of interest including MAF, work pulse, working heart rate, and RPE for each upper extremity region. The level of significance chosen for all tests was 0.05. All dependent variables were analyzed through the procedure shown in Figure 4.7.

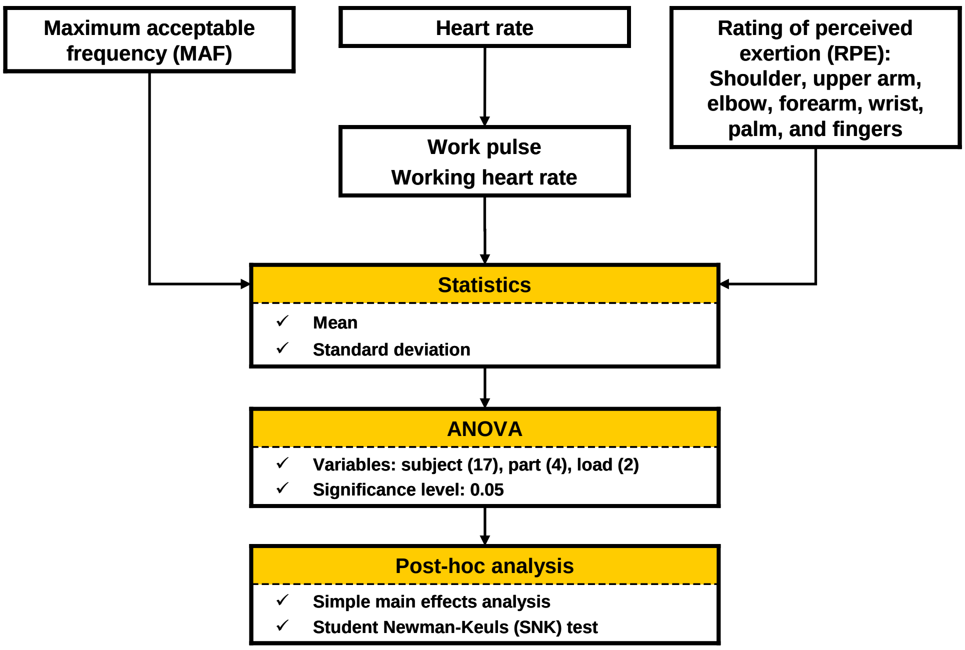


Figure 4.7 Analysis procedure

4.2 Results

4.2.1 Maximal voluntary contraction (MVC)

Table 4.2 provides descriptive statistics of maximal voluntary contractions (MVCs) for shoulder, elbow, wrist, and index finger. While the mean MVC for shoulder was similar to that for elbow, the standard deviation was relatively large. Mean MVC values were 42.65, 42.86, 15.21, and 5.02 kg for shoulder, elbow, wrist, and index finger, respectively. The MVC data for each subject were used to analyze MAF characteristics.

Table 4.2 Descriptive statistics for maximal voluntary contraction of upper extremity (kg)

Measure	Mean	Std Dev	Max	Min
MVC for shoulder	42.65	6.19	54.28	32.65
MVC for elbow	42.86	2.85	46.43	37.91
MVC for wrist	15.21	2.14	18.23	11.50
MVC for index finger	5.02	0.69	6.39	4.08

4.2.2 Maximum acceptable frequency (MAF)

As can be seen in Table 4.3, maximum acceptable frequencies (MAF) were measured on the upper extremity parts with 2 load/force levels. The MAF increased for the shoulder, elbow, wrist, and index finger motions in order. These results show that the larger movement regions have smaller MAF. Moreover, these results indicate that MAF for tasks with low load/force are larger than those with high load/force. For example, the mean (S.D) MAF of the shoulder motion with 4 kg load, having the smallest repetitiveness, is 9.00 (4.73) motions per minute, and the mean (S.D) MAF of the index finger motion with 0.25 kg force, having the largest repetitiveness, is 128.47 (58.10) motions per minute.

ANOVA results indicate that main effects of upper extremity part (shoulder, elbow, wrist, and index finger) and load/force level (low and high) of each, as well as their interaction effect, have significant effects on the MAF ($p<0.0001$). Table 4.4 provides the ANOVA results for the effects of upper extremity part and load/force level on the MAF. To investigate the interaction effect in detail, MAF results for upper extremity parts with 2 load/force levels were plotted (Figure 4.8), and analyzed using a simple main effects

Table 4.3 Summary of maximum acceptable frequency (motions/min)

	Load			
	1 kg (0.25 kg in index finger)		4 kg (1 kg in index finger)	
Part	Mean	Std Dev	Mean	Std Dev
Shoulder	24.12	9.70	9.00	4.73
Elbow	45.06	18.64	19.71	8.56
Wrist	56.29	24.71	29.53	13.28
Index finger	128.47	58.10	65.88	27.97

analysis (Table 4.5). As seen in Figure 4.8, the slope of MAF in low load/force level was steeper than that in high load/force level. Analysis results of simple main effects showed that all the effects were statistically significant, as displayed in Table 4.5. The Student-Newman-Keuls (SNK) test for MAFs of the upper extremity parts for each load/force level showed that, only the difference between the MAFs of elbow and wrist motions at low load/force level were not significant statistically. MAF results at high load/force level showed significant increases for shoulder, elbow, wrist, and index finger in order. Figure 4.9 shows the results of the SNK test for MAF of the upper extremity part for each load/force level.

Table 4.4 ANOVA table for maximum acceptable frequency

Source	DF	Sum of Square	Mean Square	F	*p*
Part (P)	3	124931.90	41643.97	70.46	<.0001*
Load (L)	1	35815.07	35815.07	70.03	<.0001*
P x L	3	10977.02	3659.01	15.24	<.0001*
Subject (S)	16	39634.37	2477.15	-	-
P x S	48	28368.22	591.00	-	-
L x S	16	8182.31	511.39	-	-
P x L x S	48	11525.10	240.11	-	-
Total	135	259433.99			

* indicates that the effect is significant at alpha = 0.05

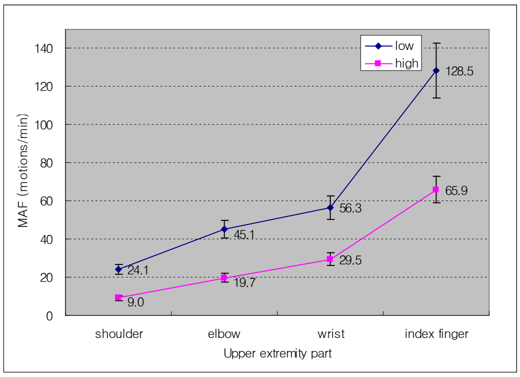
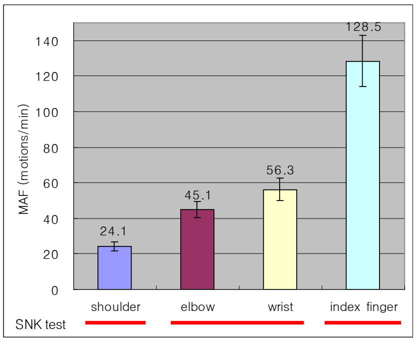


Figure 4.8 MAF result for upper extremity parts

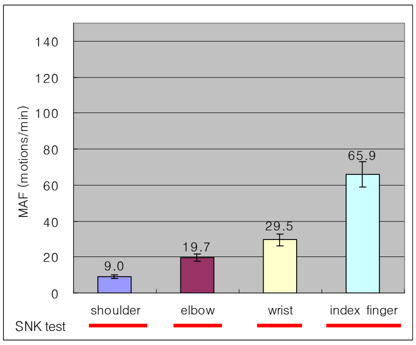
Table 4.5 Analysis results of simple main effects for maximum acceptable frequency

Source	DF	Sum of Square	Mean Square	F	*p*
Load at shoulder	1	1942.62	1942.62	71.47	<.0001*
Load at elbow	1	5463.56	5463.56	59.67	<.0001*
Load at wrist	1	6088.97	6088.97	45.34	<.0001*
Load at index finger	1	33296.94	33296.94	34.02	<.0001*
Part at low load	3	104790.51	34930.17	54.57	<.0001*
Part at high load	3	31118.41	10372.80	54.30	<.0001*

* indicates that the effect is significant at alpha = 0.05



(a) MAF results at low load/force level



(b) MAF results at high load/force level

Figure 4.9 Results of SNK test for MAF of upper extremity part for each load/force level

4.2.3 Heart rate (HR)

Two kinds of heart rate variables were analyzed: work pulse (WP) and working heart rate (WHR). Descriptive statistics of the heart rate variables are summarized in Table 4.6. Work pulse is the difference between the resting and working heart rate, and working heart rate is an average heart rate during the work. Both variables had the largest values (WP, 17.39 bpm; WHR, 85.34 bpm) in the shoulder motion with 4 kg load, and the smallest ones (WP, 4.15 bpm; WHR, 70.91 bpm) in the index finger motion with 0.25 kg force.

ANOVA results (Table 4.7) for the heart rate variables show that main effects of upper extremity part and load/force level are significant on the work pulse and working heart rate. Besides, an interaction effect of the upper extremity part and load/force level for the work pulse was significant at the 0.05 level of alpha. However, an interaction effect

Table 4.6 Summary of heart rate variables (bpm)

		Load			
		1 kg (0.25 kg in index finger)		4 kg (1 kg in index finger)	
Part	Variable	Mean	Std Dev	Mean	Std Dev
Shoulder	Work pulse	11.98	2.72	17.38	5.69
	Working heart rate	79.61	12.39	85.34	13.10
Elbow	Work pulse	8.46	3.26	12.34	5.51
	Working heart rate	75.28	11.86	79.74	10.46
Wrist	Work pulse	6.53	3.24	7.86	3.16
	Working heart rate	73.00	10.23	74.91	9.75
Index finger	Work pulse	4.15	1.92	5.72	2.03
	Working heart rate	70.91	10.35	73.83	11.82

for the working heart rate was not significant (at α= 0.05). Detailed ANOVA results of each variable are shown in Appendix D. As shown in Figure 4.10, a Student-Newman-Keuls (SNK) test result of the upper extremity part for the working heart rate indicates that working heart rate decreased significantly from the shoulder, to the elbow, to the wrist motions, but working heart rate between the wrist and index finger motions is not significant.

Table 4.7 Summary of *p*-value from ANOVAs for heart rate variables

Variable	part	load	part*load
Work pulse	<.0001*	0.0001*	0.0066*
Working heart rate	<.0001*	0.0027*	0.2465

* indicates that the effect is significant at alpha = 0.05

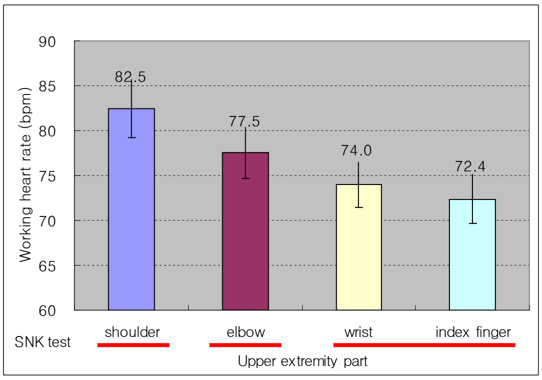


Figure 4.10 Results of SNK test of upper extremity part for WHR

To investigate the interaction effect for the work pulse in detail, work pulse results for upper extremity parts with 2 load/force levels were plotted (Figure 4.11), and analyzed using a simple main effects analysis (Table 4.8). As seen in Figure 4.11, the slope of work pulse at the high load/force level was steeper than that at the low load/force level. Analysis results of simple main effects showed that all the effects except the load/force effect for the wrist were statistically significant, as displayed in Table 4.5. SNK test results for work pulse of the upper extremity part for each load/force level showed that only work pulse between wrist and index finger motions at high load/force levels was not significant statistically. Work pulse results for the shoulder, elbow, wrist, and index finger motions decreased significantly at the low load/force level as the moving part became more distant. Figure 4.12 shows the results of the SNK test for work pulse of the upper extremity part for each load/force level.

Table 4.8 Results of simple main effects for work pulse

Source	DF	Sum of Square	Mean Square	F	*p*
Load at shoulder	1	248.02	248.02	15.09	0.0013*
Load at elbow	1	127.81	127.81	16.84	0.0008*
Load at wrist	1	15.00	15.00	2.75	0.1168
Load at index finger	1	20.94	20.94	5.66	0.0301*
Part at low load	3	557.94	185.98	25.15	<.0001*
Part at high load	3	1361.75	453.92	28.11	<.0001*

* indicates that the effect is significant at alpha = 0.05

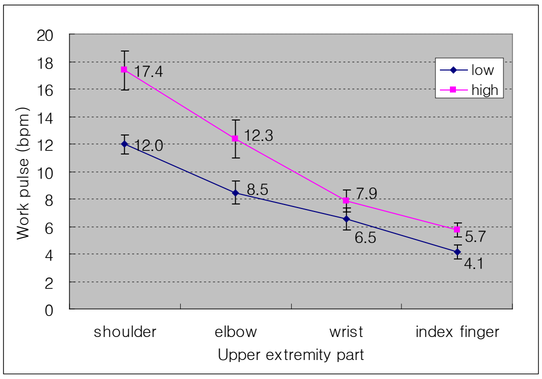
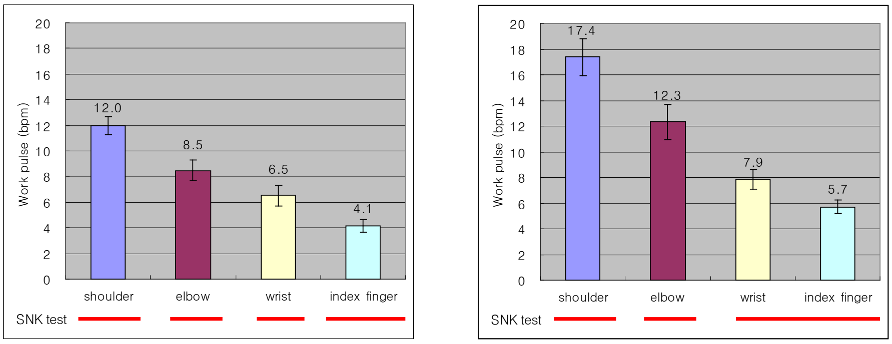


Figure 4.11 Work pulse results for upper extremity parts



(a) WP results at low load/force level (b) WP results at high load/force level

Figure 4.12 Results of SNK test for WP of upper extremity part for each load/force level

4.2.4 Rating of perceived exertion (RPE)

Rating of perceived exertion (RPE) using Borg CR-10 scale for 7 upper extremity regions (shoulder, upper arm, elbow, forearm, wrist, palm, and fingers) were also analyzed for effects of upper extremity part and load/force level. Table 4.9 summarizes the descriptive statistics of the RPE analysis. These results show that the RPE of shoulder region in the shoulder motion with 4 kg load, the RPE of forearm region in the elbow motion with 4 kg load, and the RPE of wrist region in the wrist motion with 4 kg load are over level 3, which would be associated with ‘moderate’ on the Borg CR-10 scale. In addition to this, subjects perceived the greatest exertion in the shoulder, forearm, wrist, and fingers regions for the shoulder, elbow, wrist, and index finger motions, respectively.

ANOVA results show that main effect of load/force level is significant. However, no significant differences were found on main effect of upper extremity part and the interaction at the 0.05 level of alpha. For ANOVA, RPE values in the shoulder, forearm, wrist, and fingers regions were used for the shoulder, elbow, wrist, and index finger motions, respectively. The shoulder, forearm, wrist, and fingers regions had the highest RPE values for the shoulder, elbow, wrist, and index finger motions, respectively. Table 4.10 provides the ANOVA results for the effects of upper extremity part and load/force level on the RPE. Then, Figure 4.13 indicates that RPE in the high load/force level is significantly higher than that in the low load/force level.

Table 4.9 Summary of RPE variables

		Load			
		1 kg (0.25 kg in index finger)		4 kg (1 kg in index finger)	
Part	Variable	Mean	Std Dev	Mean	Std Dev
Shoulder	Shoulder RPE	2.71	1.18	3.09	1.79
	Upper arm RPE	2.12	0.94	2.34	1.31
	Elbow RPE	2.26	1.13	2.34	1.63
	Forearm RPE	2.44	1.51	2.97	1.15
	Wrist RPE	1.44	1.06	2.39	1.37
	Palm RPE	1.26	0.97	1.98	1.07
	Fingers RPE	1.43	1.24	2.33	1.37
Elbow	Shoulder RPE	0.69	0.64	0.83	1.15
	Upper arm RPE	1.78	1.20	1.88	1.18
	Elbow RPE	1.13	0.82	1.74	1.41
	Forearm RPE	2.55	1.26	3.03	1.40
	Wrist RPE	1.86	1.08	2.32	1.13
	Palm RPE	1.24	0.71	1.71	1.16
	Fingers RPE	0.97	0.75	1.60	1.54
Wrist	Shoulder RPE	0.31	0.48	0.48	0.70
	Upper arm RPE	0.45	0.65	0.66	0.86
	Elbow RPE	0.68	0.78	0.90	1.07
	Forearm RPE	1.72	1.37	2.43	1.24
	Wrist RPE	2.55	1.44	3.06	0.90
	Palm RPE	1.55	1.13	2.33	1.32
	Fingers RPE	1.32	1.30	2.10	1.36
Index finger	Shoulder RPE	0.31	0.42	0.51	0.69
	Upper arm RPE	0.30	0.42	0.46	0.44
	Elbow RPE	0.32	0.29	0.43	0.46
	Forearm RPE	0.91	0.90	1.05	0.77
	Wrist RPE	0.95	0.78	0.97	0.94
	Palm RPE	0.75	0.65	1.05	1.23
	Fingers RPE	2.09	1.03	2.74	1.28

Table 4.10 ANOVA table for RPE

Source	DF	Sum of Square	Mean Square	F	*p*
Part (P)	3	4.72	1.57	0.75	0.5296
Load (L)	1	8.75	8.75	16.93	0.0008*
P x L	3	0.29	0.10	0.13	0.9396
Subject (S)	16	75.51	4.72	-	-
P x S	48	101.12	2.11	-	-
L x S	16	8.27	0.52	-	-
P x L x S	48	34.97	0.73	-	-
Total	135	233.64			

* indicates that the effect is significant at alpha = 0.05

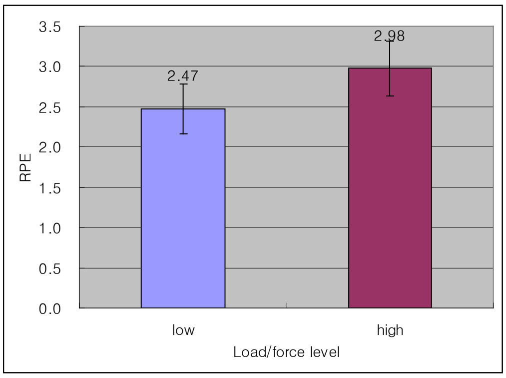


Figure 4.13 RPE result for load/force level

CHAPTER V.

Analysis of Maximum Acceptable Frequency Characteristics

5.1 Reliability of maximum acceptable frequency

Reliability analysis for maximum acceptable frequency (MAF) was performed in the wrist motion with 1 kg and the index finger motion with 0.25 kg. Reliability in the present study means retest reliability, which refers to the reproducibility or repeatability of values of a measurement in repeated trials on the same subjects. The retest reliability was analyzed by checking the agreement on MAF results of each subject. The data used in the reliability analysis were MAF results for 10 randomly selected subjects (of the total 17 subjects) who participated twice with a gap of at least one month between tests.

The three measures of reliability used in the present study were change in mean, retest correlation, and standard error of measurement (SEM). First, the change in mean is the difference between the means for two tests. The value subtracted the mean of all the subjects for trial 1 from that for trial 2 is the change in mean. A simple way to evaluate difference of the change in mean is to do a paired t test between the pairs of trials.

Second, the retest correlation represents how closely the values of trial 1 track the values of trial 2. Retest correlation is known as a good measure of reliability (Hopkins, 2000). A correlation of 1.00 represents perfect agreement between tests, whereas 0.00 represents no agreement whatever. In the present study, the Pearson correlation coefficient and intraclass correlation coefficient (ICC) were used to calculate the retest correlation. It is known that the usual Pearson correlation coefficient is acceptable for two tests, but it overestimates the true correlation for small sample sizes (less than 15). A better measure of the retest correlation is the intraclass correlation coefficient. It does not have this bias with small samples. Strictly speaking, the *r* should be the intraclass correlation coefficient, but there is so little difference between the Pearson correlation coefficient and the ICC, even for as few as 10 subjects, that it doesn't matter. The ICC may be conceptualized as the ratio of within-group variance to between-groups variance, as shown in Equation 2 (Shrout and Fleiss, 1979).

$$\text{ICC} = \frac{SD_{between}^2 - SD_{within}^2}{SD_{between}^2} \qquad (2)$$

where, $SD_{between}$ = SD for between-subjects variation (between-subjects SD)

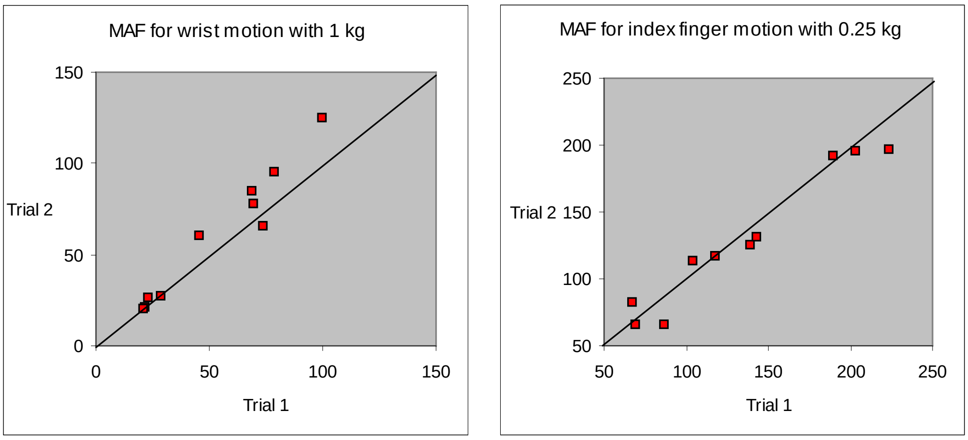
SD_{within} = SD for within-subject variation (within-subject SD)

Lastly, standard error of measurement (SEM) is the likely standard deviation of the error made in predicting a true score of an individual measurement. When examining reliability, both a relative and an absolute measurement are recommended (Bruton et al, 2000; Larsson et al., 2003). Where ICC is a relative and dimensionless variable, SEM can be used to estimate an absolute measure of reliability. It is derived from the square root of the error variance and has the same unit as the original tested variable, as shown in Equation 3 (Norkin and White, 1995). The smaller the SEM value, the better the reliability.

$$\text{SEM} = SD_{between}\sqrt{1-r} \qquad (3)$$

where, $SD_{between}$ = SD for between-subjects variation (between-subjects SD)

r = Pearson product moment correlation coefficient



(a) MAF data for wrist with 1 kg (b) MAF data for index finger with 0.25 kg

Figure 5.1 Scatter plot of test-retest results for MAF

The relationship between MAF data from trial 1 and trial 2 is shown in Figure 5.1 for the wrist motion with 1 kg and the index finger motion with 0.25 kg respectively. These plots show that subjects tended to have higher MAFs in trial 2 for the wrist motion, but lower MAFs for the index finger motion.

Retest reliability results are summarized in Table 5.1. First, change in mean did not have statistical differences at the 0.05 level of alpha for either motion. The change in mean for the wrist MAF was 6.9 motions per minute, and that for the index finger motion was -6.1 motions per minute. These results indicated that MAF in the wrist motion were up a bit in the second test, and those in the index finger motion were down a bit in the second test. Second, Person correlation coefficient (*r*) results were more or less the same, and significant statistically for either motion. The Person correlation coefficient (*r*) for the wrist motion was 0.973, and that of the index finger motion was 0.974. Third, the ICC results for MAFs were 0.928 for the wrist motion and 0.966 for the index finger motion, and showed acceptable reliability. These results showed that the MAF of the index finger motion was relatively better than that of the wrist motion in terms of ICC. Lastly, the standard error of measurement (SEM) was 5.29 motions per minute for the wrist motion and 8.66 motions per minute for the index finger motion.

Table 5.1 Retest reliability of MAF for wrist motion with 1 kg and index finger motion with 0.25 kg

	Change in mean (Pr > |t|)	Pearson r (Pr > |r|)	ICC*	SEM**
Wrist motion with 1 kg	6.90 (0.07)	0.973 (<0.0001)	0.928	5.29
Index finger motion with 0.25 kg	-6.10 (0.18)	0.974 (<0.0001)	0.966	8.66

* ICC: intraclass correlation coefficient

** SEM: standard error of measurement

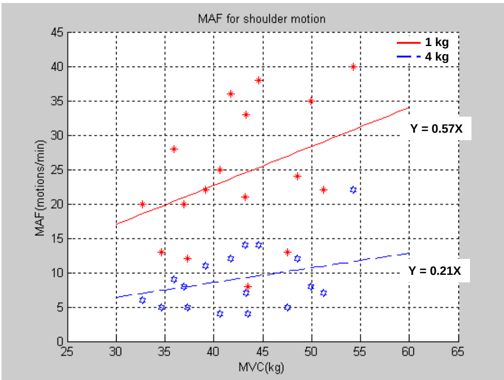
5.2 Relationship between maximal voluntary contraction and maximum acceptable frequency

Regression analysis was conducted to describe the relationship between maximal voluntary contraction (MVC) and maximum acceptable frequency (MAF) for each upper extremity part using the SAS software. Dependent variables were MAFs for the 4 upper extremity motions with 2 load/force levels. Independent variables were MVC for each upper extremity part. In the present study, an intercept parameter was not included in all the regression models, since that was meaningless in these models.

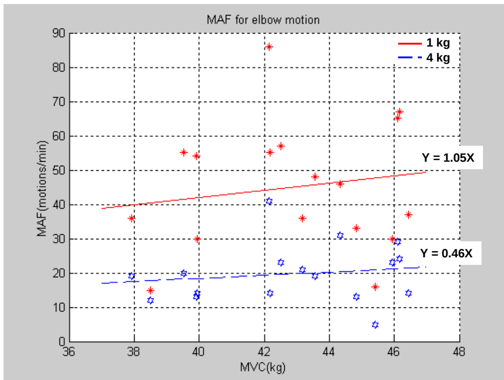
Regression models for MAFs of the 4 upper extremity motions with 2 load/force levels are summarized in Table 5.2. The slopes of the regression models were 0.57, 1.05, 3.65, and 25.17 at low load/force level, and 0.21, 0.46, 1.96, and 12.84 at high load/force level for the shoulder, elbow, wrist, and index finger motions, respectively. The coefficients of determinant (R^2) were 0.89, 0.86, 0.84, and 0.82 at low load/force level, and 0.83, 0.85, 0.87, and 0.83 at high load/force level, respectively. And the adjusted R^2 values were 0.88, 0.85, 0.83, and 0.81 at low load/force level, and 0.82, 0.84, 0.86, and 0.82 at high load/force level, respectively. Moreover, all the regression models were statistically significant ($p<0.001$). Detailed ANOVA tables of the regression models are shown in Appendix E. Figure 5.2 shows the regression models of 2 load/force levels for each upper extremity part. These plots indicate that the slopes of regression models at low load/force were steeper than those at high load/force.

Table 5.2 Regression models for MAF of upper extremity

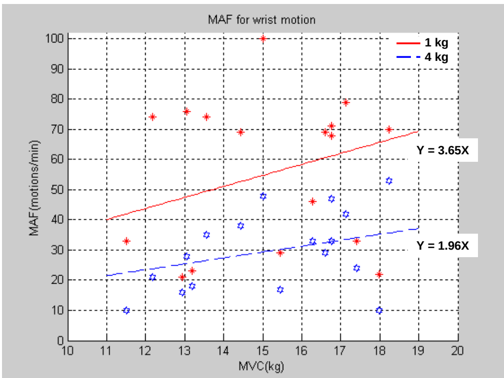
Part	Load/force					
	1 kg (0.25 kg in index finger)			4 kg (1 kg in index finger)		
	Slope	R^2	adj-R^2	Slope	R^2	adj-R^2
Shoulder	0.57	0.89	0.88	0.21	0.83	0.82
Elbow	1.05	0.86	0.85	0.46	0.85	0.84
Wrist	3.65	0.84	0.83	1.96	0.87	0.86
Index finger	25.17	0.82	0.81	12.84	0.83	0.82



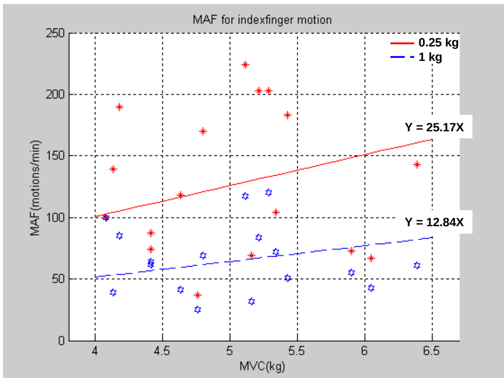
(a) Shoulder motion



(b) Elbow notion



(c) Wrist motion



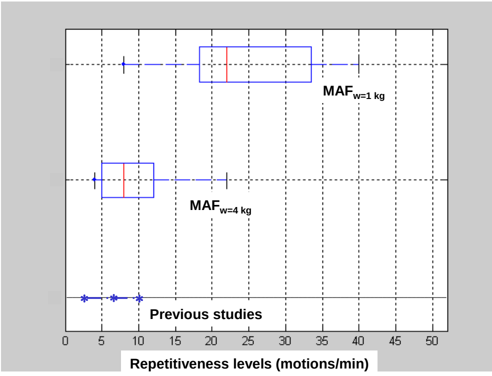
(d) Index finger motion

Figure 5.2 Regression models for MAF of upper extremity with external load/force

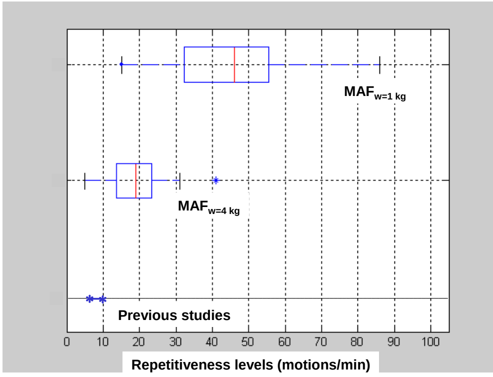
5.3 Comparison between maximum acceptable frequency and meta-analysis result

To compare maximum acceptable frequency (MAF) to preliminary ergonomic levels of repetitiveness risk developed through meta-analysis, MAF and meta-analysis results for each upper extremity part were displayed with a box and whisker plot. As a box and whisker plot (consisting of the median, the quartiles, the most extreme data of the whiskers, and outliers) is a visual representation of how the data is spread out and how much variation there is, it is useful to explore data and to draw informal conclusions when two or more variables are present.

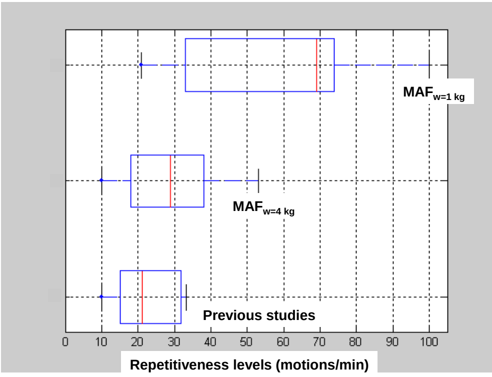
Repetitiveness risk levels developed through meta-analysis were similar to or slightly smaller than MAF results with high load (4 kg) in the shoulder, elbow, and wrist. Figure 5.3 shows box and whisker plots of MAF results with external load/force level and meta-analysis results for each upper extremity part. These plots indicate that meta-analysis results for the shoulder and wrist are similar to MAF results with 4 kg, and that the elbow result is slightly smaller than MAF results with 4 kg. However, meta-analysis results for the finger is similar not to high force MAF results, but to MAF results with low force (0.25 kg). The asterisk in the 4 kg data set in the elbow plot represents an outlier that falls well outside the range of the other values.



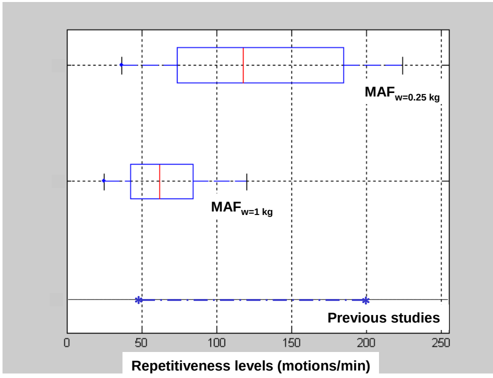
(a) Shoulder motion



(b) Elbow motion



(c) Wrist motion



(d) Finger motion

Figure 5.3 Comparison for repetitiveness risk level of upper extremity

CHAPTER VI.

Discussion

6.1 Comparison of assessment methodologies and risk exposure levels for repetitiveness

The present study provided a comprehensive survey of repetitiveness assessment methodology, classifying repetitiveness measures, measurement methods, and analysis techniques. It was found that various repetitiveness measures could be classified according to their dimensional characteristics (cycle time and frequency) and analysis scopes (work cycle, body region, and force exertion). By using the time-frequency conversion formula (see Equation 1), repetitiveness evaluation results in cycle time could be converted into those in frequency and vice versa. While cycle time and frequency measures exist for work cycle, only frequency measures exist for body region and force exertion because it is difficult and/or impractical to measure and analyze times of individual motions and force exertions. Next, two categories of measurement methods (objective and subjective methods) and two types of analysis techniques (statistical and spectral techniques) that have been employed in repetitiveness assessment were summarized. The survey information of repetitiveness assessment methodology can be utilized to facilitate effective integration of findings of repetitiveness research and help practitioners select the appropriate methodology in repetitiveness assessment.

The analysis of the 31 repetitiveness studies, based on the repetitiveness measure nomenclature, showed that frequency measures have been more frequently used than cycle time measures and hand/wrist movement frequency has been the most popular for the assessment of repetitiveness of upper extremity intensive tasks. Since cycle time measures are less practical for the analysis of rapid, individual motions involved in a task (explained in previous paragraph), frequency measures, which document the number of movements of the body parts selected, have been more readily utilized. Next, the most frequent use of hand/wrist movement frequency may be due to the dominant concern with musculoskeletal disorders at the hand/wrist (such as carpal tunnel syndrome and tendinitis) among the upper extremity musculoskeletal disorders.

The analysis of the 31 studies also indicated that, of the measurement methods, electrogoniometer, video system, and visual analog scale have been most frequently employed in repetitiveness assessment. As for electrogoniometer (which measures angular movements at the joint of interest), Moore et al. (1991) reported measurement error of up to 11% with a Penny & Giles biaxial electrogoniometer due to the cross-talk effect of the instrument, but Coury et al. (2000) asserted that this cross-talk problem would not affect the validity of analysis results in frequency by using angular measurements because the angular measurement errors due to the cross-talk effect would be balanced out throughout all experimental conditions. Next, regarding visual analogue scale in repetitiveness assessment, Latko et al. (1999) used a 10-point scale consisting of a line with numbers and verbal anchors such as 0 for hands idle most of the time and 10 for rapid steady motion with a speed difficult to keep up.

On the basis of existing data from various studies published in the last two decades, preliminary ergonomic levels for repetitiveness risk of each upper extremity part were summarized through meta-analysis. The selection of studies published since 1980 in the English language was arbitrary to some extent, but presumably did not cause a significant bias in any particular direction. Exclusion criteria were aimed at the selection of quantitative information on risk repetitiveness, and exclusion of studies that were highly susceptible to misclassification. First of all, 18 publications that provided quantitative data on repetitiveness risk were selected as displayed in Appendix F. Next, to compare with MAF identified in the present study, 7 publications which studied motion repetitiveness for each upper extremity part were put over in the end. The procedure of retrieving potentially relevant studies and the subsequent selection for this review may have caused the exclusion of some studies, but there is no reason to assume that the results were biased in a particular direction because of these procedures.

Most of the studies selected in meta-analysis showed differences in repetitiveness risk levels for each upper extremity part. This is probably because the values of repetitiveness risk depend on many other factors (e.g., posture, force, and duration), or because the studies were conducted in different industries. Thus, there may be differences according to personal or other physical factors, or variances from industry to industry in terms of repetitiveness risk levels. However, in the present study, the influence of these factors on repetitiveness values was not taken into consideration. Although data from well-designed studies should be polled into the meta-analysis in order to obtain combined repetitiveness risk levels, the selected studies were too heterogeneous with regard to the values of repetitiveness risk to be aggregated in the meta-analysis.

6.2 Maximum acceptable frequency for upper extremity motions

The present study also identified MAF for upper extremity (shoulder, elbow, wrist, and index finger) motions with moderate loads in moderate motion ranges at a seated position. In occupational settings, repetitiveness of upper extremity intensive tasks depends on the motion range, force exerted, and the time of force exertion. However, in the present study, moderate forces and moderate motion range for each upper extremity motion were used to minimize effects of other risk factors. Accordingly, mean MAF levels for the shoulder, elbow, wrist, and index finger motions were 9.0, 19.7, 29.5, and 65.9 motions per minute at the high load/force level, and 24.1, 45.1, 56.3, and 128.5 motions per minute at the low load/force level, respectively. These MAF levels had significant effects on the upper extremity part and the load/force level. First, the MAF level of the shoulder motion was significantly lower than those of the other upper extremity motions, and MAF level of the index finger motion was significantly higher than those of the others. The MAF level of the elbow motion was lower than that of the wrist motion, but not statistically significant. These results were similar to Kilbom (1994)'s indication that risk levels of repetitiveness increased from shoulder, to elbow, to wrist, to finger. Next, the MAF levels for each upper extremity motion were relatively high at the low load/force levels. The observation that MAF level was negatively correlated with exposure load/force level was consistent with previous psychophysical studies for upper extremity intensive tasks (Kim and Fernandez, 1993; Dahalan and Fernandez, 1993; Klein and Fernandez, 1997; Snook et al., 1995, 1997, 1999; Ciriello et al., 2001). Thus, MAF results from the present study should be considered together with load/force level.

However, MAF results identified the present study may be slightly overestimated due to several limitations. First of all, all the experiments of the present study were performed in a seated position to minimize effects of other risk factors. But, considering that most repetitive industrial tasks are performed in a standing position, MAF results may be slightly overestimated. Next, in the experiment for the elbow and wrist motions, elbow and wrist parts were supported by the table to restrict a movement of the other upper extremity parts. But, considering that most tasks in the workplace are performed in an unsupported state, MAF results in the elbow and wrist motions may be slightly overestimated. Lastly, Subjects participated in the experiment were seventeen male adults ranged from 23 to 27 years. It means that MAF data are collected from a small and homogeneous group. Thus, it is difficult that MAF results identified in the present study are generalized.

Based on subjective estimates of physical fatigue, working heart rate and work pulse levels for the upper extremity motions decreased from shoulder, to elbow, to wrist, to index finger. First, the working heart rate level for the upper extremity motions was the highest in the shoulder motion, and the lowest in the index finger motion for each load/force level. The working heart rate in the shoulder, elbow, wrist, and index finger motions at the low load/force level were 79.6, 75.3, 73.0, and 70.9 bpm, and those at high load/force level were 85.3, 79.7, 74.9, and 73.8 bpm respectively. As an acceptable level for working heart rate, Snook and Irvine (1969) recommended that it should not exceed 99 bpm for arm work, and Garg and Saxena (1982) suggested 101 bpm. Generally, it is believed that it should not exceed 110 bpm for an 8-hour workday. In the previous psychophysical studies for upper extremity intensive tasks, Marley and Fernandez (1995) reported that working heart rate for establishing the MAF under various wrist postures requirements for a drilling task ranged from 96.99 to 104.49 bpm, Kim and Fernandez

(1993) stated that working heart rate ranged from 91.23 to 110.36 bpm in determining the MAF at different applied forces and wrist flexion angles for a drilling task, and Dahalan and Fernandez (1993) found working heart rate ranged from 78.0 to 85.9 bpm when determining the MAF at different gripping forces and task durations for a gripping task. Second, the levels of a work pulse for the upper extremity motions also decreased for each load/force level. The work pulse in the shoulder, elbow, wrist, and index finger motions at the low load/force level were 12.0, 8.5, 6.5, and 4.1 bpm, and those at high load/force level were 17.4, 12.3, 7.9, and 5.7 bpm respectively. These results indicated that the work pulse decreased as the motion part became more distant. Marley and Fernandez (1995) reported that work pulse for establishing the MAF under various wrist postures requirements for a drilling task ranged from 25.41 to 32.91 bpm. Kroemer and Grandjean (1997) suggested a work pulse of 35 bpm for men and a work pulse of 30 bpm for women as the acceptable level for continuous performance throughout an 8-h working day, taking the resting pulse in a seated position. However, the present study performed in a seated position should be distinguished from the studies performed in a standing position. Therefore, the present results can provide useful basic data to establish the permissible level for acceptable workload of heart rate. Lastly, both working heart rate and work pulse had significant effect on the load/force level in the experiment of the present study. In the previous studies, Kim and Fernandez (1993) indicated that drilling force was the significant factor on heart rate response for a drilling task, and Klein and Fernandez (1997) said that pinching force was the significant factor on heart rate response for a pinching task. However, Dahalan and Fernandez (1993) showed that gripping force was not significant on the change in heart rate from the resting state.

For RPE, the subjects rated the perceived exertion ranging from level 1 (very weak) to level 3 (moderate) for the upper extremity regions involved in each motion. Moreover, RPE values for each upper extremity motion reflected upper body regions involved in each upper extremity motion. For example, while the shoulder region was not involved in the other upper extremity motions except the shoulder motion, the forearm region was involved in all the upper extremity motions. Upper body regions having the highest RPE values for each upper extremity motion were shoulder, forearm, wrist, and fingers regions for the shoulder, elbow, wrist, and index finger motions respectively. Garg and Saxena (1982) reported that the RPE range for determining the MAF of one-handed lifts in the horizontal plane was 'fairly light' (10.6) to 'somewhat hard' (13.2). Marley and Fernandez (1995) reported that the mean RPE of upper body regions for establishing the MAF under various wrist postures requirements ranged from 9.92 (very light) to 14.42 (somewhat hard). Kim and Fernandez (1993) reported that the mean RPE of upper body regions for determining the MAF at different applied forces and wrist flexion angles ranged from 8.13 (extremely light) to 16.07 (hard). Dahalan and Fernandez (1993) indicated that the mean RPE of upper body regions for determining the MAF at different gripping forces and task durations ranged from 1.29 (very weak) to 6.57 (strong). For determining an acceptable workload from RPE, no reference in the literature could be found which would indicate what level of RPE is fatigue-generating. However, Klein and Fernandez (1997) suggested level 3 (moderate) as the criterion of RPE for acceptability of an intermittent isometric pinching task. In contrast, Putz-Anderson and Galinsky (1993) used level 4 (somewhat strong) as the criterion of RPE for determining work duration to limit shoulder girdle fatigue, indicating that the method of regulating work durations using a perceived fatigue criterion provided an empirical means for evaluating the influence of various task factors on fatigue. Therefore, systematic research establishing a RPE reference is still needed for reliable psychophysical study.

Furthermore, further research is needed for generalization of the research findings and effective application to industry. First, considering that most repetitive industrial tasks are performed by females, a MAF study for females is necessary. It is for this reason that previous studies have indicated a difference for gender in repetitive work. Potvin et al. (2000) indicated that males were more sensitive than females to the effects of increased impact frequency for repetitive hand impact tasks. Coury et al. (2002) showed that female workers presented more symptoms than male workers doing the same repetitive industrial tasks. Putz-Anderson and Galinsky (1993) indicated that there was some tendency for the overall work duration of males to be longer than that of females, although work durations produced by males and females were not affected differentially by any of the task factors studied. Generally, this evidence indicates that perceived exertion grows faster in females than in males when their work demand is objectively equivalent. Second, it is necessary to identify MAF for each upper extremity part using various tasks or motion ranges. MAFs may be different according to task or motion range. Tasks used in the present study were the flexion/extension motions in the sagittal plane. These motion ranges were selected to be moderate motion ranges based on previous studies. However, there was little consensus on definitions for moderate motion ranges. For example, regarding wrist flexion, Stetson et al. (1991) indicated that cut-point of the extreme posture for wrist flexion was 30° based on increases in intra-carpal tunnel pressure. A postural classification scheme of the upper extremity, developed by Kee and Karwowski (2001), using the magnitude estimation method, a psychophysical scaling method, showed that the wrist flexion motion range having relatively low discomfort for wrist flexion was 0~20°. Finally, a study for maximum frequency is also needed to normalize MAFs. While MAF is the frequency selected as ‘reasonable’ for 8 hour of work, maximum frequency is the highest frequency that a subject can maintain for a period of 4 minutes. Garg and Saxena (1982) determined the MAF of female workers for one-handed lifts in the horizontal plane, and indicated that the average ratio of MAF to maximum frequency was 51.3 % (ranging from 47 to 56.4 %).

6.3 Characteristics of maximum acceptable frequency

The analysis results for retest reliability suggested that the MAF protocol used in the present study was likely to be sufficiently reliable for measuring repetitiveness of the upper extremity. First, the changes in mean were not statistically different at the 0.05 level of alpha. Secondly, the relative reliability indexes, the retest correlation coefficients (Pearson correlation coefficient and ICC) were acceptable. For example, ICC results for MAF showed acceptable reliability as 0.928 and 0.966 for the wrist motion with 1 kg and the index finger motion with 0.25 kg respectively. Criteria for acceptability of ICC have been suggested by many researchers. Fleiss (1986) suggested that $ICC<0.4$ demonstrates poor, $0.4<ICC<0.75$ fair to good, and $ICC>0.75$ excellent reliability. Currier (1990) has suggested that an ICC value >0.8 is acceptable for clinical work. Sleivert and Wenger (1994) have characterized ICC as follows: good reproducibility: 0.80~1.0, fair reproducibility: 0.60~0.79 and poor reproducibility: <0.60. Lastly, the absolute index, SEM, also showed low values. Therefore, this protocol is likely to be useful for researchers who want to measure a repetitiveness level using a psychophysical method.

The retest reliability for MAF of the index finger motion with 0.25 kg was better than that of the wrist motion with 1 kg. In the change in mean analysis, the *p*-value (0.18) of the index finger motion was relatively larger than that (0.07) of the wrist motion. Besides, the wrist motion result was statistically significant at the 0.10 level of alpha. The results of the retest correlations indicated that coefficients for the index finger motion were higher than those for the wrist motion. Although the result of SEM for the index finger motion was relatively higher than that for the wrist motion, it might be because the values of MAF for the index finger motion were higher than those for the wrist motion.

Regression analysis results showed that there was a statistically significant linear relationship between MAF and MVC. All regression models for the upper extremity with external load/force level developed were statistically significant ($p<0.001$). The coefficients of determinant (R^2) of selected regression models were considerably large: 0.89, 0.86, 0.84, and 0.82 at low load/force level, and 0.83, 0.85, 0.87, and 0.83 at high load/force level for the shoulder, elbow, wrist, and index finger motions respectively. These results indicate that the larger the MVC, the higher the MAF. Therefore, the regression models developed will be used to predict MAF level with load/force level for MVC of each upper extremity part.

The MAF of the shoulder decreased more with increasing load/force than the MAFs of the other parts. Table 6.1 shows slope results according to load/force level in the regression model for each upper extremity part. The ratios of the slope with low load/force to the slope with high load/force were 2.65, 2.28, 1.87, and 1.96 for the shoulder, elbow, wrist, and index finger motions, respectively. These results indicate that load/force levels for distal part motions of the upper extremity except for the index finger motion give a smaller effect on the repetitiveness level.

Table 6.1 Comparison of slope according to load/force level in the regression model

Part	Load/force		Ratio
	1 kg (0.25 kg in index finger)	4 kg (1 kg in index finger)	
Shoulder	0.57	0.21	2.65
Elbow	1.05	0.46	2.28
Wrist	3.65	1.96	1.87
Index finger	25.17	12.84	1.96

Comparison between the MAF results and the meta-analysis results indicated that the repetitiveness risk levels might be set as 25th percentile values of the MAF results with high load (4 kg) in the shoulder, elbow, and wrist. The 25th percentile values have been proposed by Snook (1978) and Potvin et al. (2000) as reasonable levels to set acceptable levels for exposure to occupational workloads. Snook (1978) established a threshold limit value at the 75th percentile for both males and females based on insurance data indicating that the risk of low-back injury was three times higher if a lifting task was acceptable to less than 75% of the working population. However, a difference in repetitiveness risk for the finger may be related to the number of fingers involved in finger motions. For example, Kilbom (1994) reviewed some studies conducted in different types of repetitive finger motions, but didn't give a concrete description identifying repetitiveness risk levels. Anyway, in a similar manner, the repetitiveness risk levels for the finger may be set as 25th percentile values of the MAF results with high load (1 kg). Table 6.2 shows the repetitiveness risk levels in the present study (25th percentile values) and previous studies (mean values).

Table 6.2 Repetitiveness risk levels in the present study and previous studies

	Load level in the present study		Mean risk level
	1 kg (0.25 kg in finger)	4 kg (1 kg in finger)	in the previous studies
Shoulder	20	5	6.27
Elbow	33	14	8.15
Wrist	33	18	22.07
Finger	74	43	124.35

CHAPTER VII.

Conclusions

The main objective of this study was to identify acceptable exposure levels for repetitiveness of upper extremity (shoulder, elbow, wrist, and index finger) motions with external loads in moderate motion ranges in the sagittal plane. The detailed objectives were threefold: to survey and compare assessment methodologies and risk exposure levels for repetitiveness of upper extremities, to identify maximum acceptable frequencies (MAFs) for upper extremity (shoulder, elbow, wrist, and index finger) motions, and to analyze MAF characteristics and compare MAFs to preliminary risk levels.

To begin with, this study compared the measures, measurement methods, analysis techniques, and risk levels that have been used to analyze the repetitiveness of upper extremity intensive tasks. The repetitiveness measures were classified according to their dimensional types (cycle time and frequency) and analysis scopes (work cycle, body region, and force exertion). By summarizing 31 repetitiveness assessment studies (published between 1997 and 2002) based on the measure classification system, it was identified that frequency measures were 4.7 times more commonly used than cycle time measures and hand/wrist movement frequency was most commonly used (42%). The measurement methods were classified into objective and subjective measurement methods and the analysis techniques into statistical and spectral techniques. Electrogoniometer, video system, and visual analog scale of the measurement methods have been most frequently employed in repetitiveness assessment. Lastly, results of the meta-analysis for repetitiveness risk levels of each upper extremity part indicated that mean values of repetitiveness risk level for the shoulder, elbow, wrist, and finger were

6.27, 8.15, 22.07, and 124.35 motions per minute, respectively.

This study also identified MAFs for upper extremity (shoulder, elbow, wrist, and index finger) motions with external loads in moderate motion ranges. Mean MAF levels for the shoulder, elbow, wrist, and index finger motions were 9.0, 19.7, 29.5, and 65.9 motions per minute at the high load/force level, and 24.1, 45.1, 56.3, and 128.5 motions per minute at the low load/force level, respectively. These MAF results indicated that repetitiveness level should be considered together with load/force levels. Mean working heart rates (work pulses), measured to identify the physiological level of functioning during the experiment for determining the MAF, for the shoulder, elbow, wrist, and index finger motions were 85.3(17.4), 79.7(12.3), 74.9(7.9), and 73.8(5.7) bpm at the high load/force level, and 79.6(12.0), 75.3(8.5), 73.0(6.5), and 70.9 (4.1) bpm at the low load/force level, respectively. These heart rate results also showed that acceptable heart rate level should be considered together with load/force levels. For RPE, the subjects rated the perceived exertion ranging from level 1 (very weak) to level 3 (moderate) for the upper extremity regions involved in each motion. Upper body regions having the highest RPE values for each upper extremity motion were shoulder, forearm, wrist, and fingers regions for the shoulder, elbow, wrist, and index finger motions, respectively.

Then, this study analyzed characteristics of MAFs, and compared MAFs to preliminary ergonomic guidelines of repetitiveness risk for each upper extremity part. The analysis results for reliability by using change in mean, retest correlation, and SEM proved that the MAF protocol was likely to be sufficiently reliable for measuring repetitiveness of the upper extremity. Regression analysis results by using stepwise procedure showed that there were statistically significant linear relationships between MAF and MVC, and that the MAF of the shoulder decreased more with increasing load/force than the MAFs of the other parts. Lastly, the comparison results between the MAF results and the meta-analysis results indicated that the repetitiveness risk levels might be set as 25th percentile values of the MAF results with high load (4 kg) in shoulder, elbow, and wrist.

This study demonstrated the necessity of considering upper extremity part as well as load/force level when designing acceptable exposure levels for repetitiveness of upper extremity intensive tasks and also the need for safe and acceptable work standards in industry today. The MAF levels for each upper extremity part identified can be applied as useful basic data to establish permissible exposure levels for repetitiveness of upper extremity intensive tasks. What is more, the physiological and psychophysical levels identified during the task with MAF are supportive in establishing acceptable workload levels.

요 약 문

산업의 자동화에도 불구하고, 상지 근골격계 질환(upper extremity musculoskeletal disorders; UEMSDs)은 상지 작업이 수행되는 산업현장에서 여전히 높은 비율을 차지하고 있다. UEMSDs 은 상지 작업으로 인해 상지의 근골격 부위에 발생하는 모든 증상들을 의미하는 집합적인 용어이다. 상지 작업의 반복성은 부자연스러운 자세, 과다한 힘과 더불어 UEMSDs 의 주요 유해 요인으로 알려져 있음에도 불구하고, 반복성 평가에 필요한 객관적인 기준에 대한 연구는 부족한 실정이다. 따라서, 상지 작업의 반복성에 대한 객관적인 기준을 설정하기 위하여 체계적인 실험 data 를 구축하는 것이 필요하다.

본 연구에서는 상지 작업에 사용되는 상지 관절별(어깨, 팔꿈치, 손목, 검지 손가락) 반복성의 수용 기준을 결정하였다. 이를 위해 본 연구에서는 기존 반복성 연구들의 평가 방법론과 반복성 유해 기준들을 분석하였으며, 심물리학적인 방법을 이용하여 상지 작업에 사용되는 힘에 따른 상지 관절별 최대 수용 반복빈도수(maximum acceptable frequency; MAF)를 파악하였다. 그리고, 파악된 MAF 의 특성을 분석하고 상지 관절별로 기존 반복성 연구에서의 반복성 유해 기준들과 비교하였다.

기존 반복성 연구들에 근거하여 반복성의 평가 방법론과 유해 기준들을 분석하였다. 반복성 평가 척도들은 크게 시간과 빈도수 측면에서, 세부적으로는 척도들의 분석 대상의 유형에 따라 분류되었다. 반복성 척도의 분류 체계를 기준으로 하여 최근 발표된 논문들을 중심으로 적용 사례를 분석한 결과, 반복성 평가 시 빈도수 차원의 척도들이 시간 차원의 척도들에 비해 많이 사용되고 있었으며, 반복성 평가 연구에서 사용된 다양한 척도 중 손목 동작의 빈도수가 가장 많이 사용되고 있었다. 관련된 측정 방법들은 주관적 측정법과 객관적 측정법으로 구분되었으며, 분석 방법들은 통계적 분석법과 스펙트럴(spectral) 분석법으로 구분되었다. 또한, 반복성 측정에는 electrogoniometer 와 video 가 가장 많이 사용되고 있었다. 그리고, 메타분석을 통해 도출된 7 개 연구에 근거한 상지 관절별 반복성 유해 기준의 평균은 어깨, 팔꿈치, 손목, 손가락 관절에 대해 각각 6.27, 8.15, 22.07, 124.35 로 분석되었다.

심물리학적 방법을 이용하여 상지 작업에 사용되는 힘에 따른 상지 관절별 최대 수용 반복빈도수가 파악되었다. 피실험자는 상지 부위에 근골격계 질환 병력이 없는 평균 25 세의 성인 남성 17 명으로 구성되었다. 실험은 상지 관절(어깨, 팔꿈치, 손목, 검지 손가락)과 힘을 독립변수로 하는 4×2 within-subject design 으로 설계되었으며, 힘은 어깨, 팔꿈치, 손목 관절의 경우 1kg 과 4kg, 검지 손가락 관절의 경우 0.25kg 과 1kg 이 사용되었다. 실험의 종속변수는 MAF, 심박수, 그리고 주관적 불편

도(RPE)였다. 상지 관절과 힘에 따른 총 8 개의 실험 작업은 피실험자마다 임의의 순서로 하루에 한 작업씩 총 8 일에 걸쳐 수행되었다. 각 실험 작업 시간은 30 분이었으며, 피실험자는 처음 25 분 동안 8 시간 작업에 적합한 반복 빈도수를 심물리학적으로 선정하였다. 마지막 5 분 동안 유지된 반복 빈도수가 MAF 로 정의되었다. 실험에 앞서 휴식 중 심박수가 측정되었으며, 실험 중 마지막 1 분 동안 작업 중 심박수가 측정되었다. 그리고, 실험이 끝난 직후 7 개 상지 부위에 대한 RPE 가 측정되었다.

상지 관절별 평균 MAF 는 어깨, 팔꿈치, 손목, 검지 손가락 관절에 대해 높은 힘에서 분당 9.0, 19.7, 29.5, 65.9 회, 낮은 힘에서 분당 24.1, 45.1, 56.3, 128.5 회로 각각 파악되었다. MAF 결과는 상지 관절과 힘 수준에 유의한 효과를 보였으며, 상지 작업에 사용되는 상지 부위가 작을수록, 힘이 작을수록 상대적으로 큰 MAF 를 나타냈다. 그리고, 상지 관절별 MAF 작업동안 평균 작업 심박수(심박수 변화량)는 어깨, 팔꿈치, 손목, 검지 손가락 관절에 대해 높은 힘에서 85.3(17.4), 79.7(12.3), 74.9(7.9), 73.8(5.7) bpm, 낮은 힘에서 79.6(12.0), 75.3(8.5), 73.0(6.5), 70.9(4.1) bpm 으로 각각 분석되었다. 작업 심박수(심박수 변화량)는 움직이는 부위가 클수록, 심장에 가까울수록 유의하게 커지는 것으로 파악되었다. 마지막으로 RPE 는 각 관절 동작에 사용되지 않은 부위(예: 팔꿈치, 손목, 손가락 동작에서의 어깨 부위)를 제외하고 수준 1(very weak)에서 수준 3(moderate)의 범위인 것으로 분석되었다. 또한, RPE 결과는 어깨, 팔꿈치, 손목, 검지 손가락 관절 동작에 대해 각각 어깨, 전완, 손목, 손가락 부위가 다른 부위들에 비해 상대적으로 큰 것으로 분석되었다.

실험에서 파악된 MAF 는 신뢰도 특성과 MVC 와의 관계 특성에 대해 분석되었으며, 메타분석을 통해 도출된 반복성 유해 기준과도 비교되었다. 평균 변화량, 상관 관계, 측정 표준 오차를 이용하여 분석된 MAF 의 신뢰도는 충분히 신뢰할 수 있는 것으로 분석되었으며, 상지 관절별 MAF 는 상지 관절별 MVC 와 유의한 선형관계가 있는 것으로 분석되었다. 또한, 어깨 관절의 MAF 는 다른 관절들에 비해 힘 수준의 차이에 더 민감한 경향을 보였다. 그리고, 상지 관절별 MAF 와 메타분석을 통해 파악된 반복성 유해 기준간의 비교에서는 어깨, 팔꿈치, 손목 관절들의 기존 반복성 유해 기준은 4kg 의 힘을 사용한 각 관절의 MAF 결과에 대한 25th percentile 값과 유사한 것으로 분석되었다.

본 연구의 결과는 상지 작업에 대한 상지 관절별 반복성의 허용기준을 수립하는 데 유용한 기초 자료로 사용될 수 있을 것이다. 뿐만 아니라, 본 연구에서 측정된 심박수와 근전도 및 주관적 불편도의 결과들도 상지 관절별 상지 작업의 부하에 대한 생리적/심리적 허용기준을 수립하는 데 유용하게 사용될 수 있을 것이다.

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Appendices

Appendix A. Psychophysical studies of upper extremity intensive tasks

Study	Subjects	Task Type(s)	Independent Variable(s)	Dependent Variable(s)	Results
Ciriello et al.(2001)	31 females	• Wrist flexion with a power grip • Wrist extension with a power grip • Wrist flexion with a pinch grip • Wrist extension with a pinch grip • Ulnar deviation with a power grip • Handgrip task (with a power grip)	• Repetition (15, 20, 25/min) • Motion • Hour of day (hours 1-7)	• MAT • Symptom rate (0-3 scale)	• MAT ranged from 11 to 19% of maximum isometric torque depending on frequency and motion. • MATs were significantly higher for the low repetition rate ($p < 0.001$). • The overall symptom rate was 1.1% (96% of them were the lowest intensity).
Snook et al. (1999)	20 females	• Wrist extension with a pinch grip	• Repetition (15, 20, 25/min) • Day of week (days 1-5) • Hour of day (hours 1-7)	• MAT • Duration of force • Error rate • Symptom rate (0-3 scale)	• MAT was 0.87 Nm (22.2% max isometric strength). • Mean (S.D.) duration of force was 0.60 (0.24) sec. • Mean error rate was 1.08%. • The overall symptom rate was 0.86% (81% of them were the lowest intensity). • MAT of wrist extension with a pinch grip is lower than wrist flexion with a pinch grip, wrist flexion with a power grip or ulnar deviation.
Snook et al. (1997)	<Exp. 1> 13/16 females	• Ulnar deviation with a power grip	• Repetition (15 & 20/min) • Day of week (days 1-5) • Hour of day (hours 1-7)	• MAT • Max isometric strength • Tactile sensitivity • Duration of force • Error rate • Symptom rate	• Mean (S.D.) MATs were 1.81 (0.89) Nm (30.3% max isometric strength) for 15/min and 1.81 (0.95) Nm (28.8% max isometric strength) for 20/min. • Mean (S.D.) max isometric strengths were 5.98 (3.04) Nm for 15/min and 6.28 (3.09) Nm for 20/min. • Mean (S.D.) tactile sensitivities were 1.21 (0.22) for 15/min and 1.28 (0.36) for 20/min. • Mean (S.D.) durations of force were 0.82 (0.31) sec for 15/min and 0.47 (0.09) sec for 20/min. • Mean error rates were 0.51% for 15/min and 0.86% for 20/min. • Mean symptom rates 5.7% for 15/min and 5.3% for 20/min. • Only duration of force showed a statistically significant difference in repetition rate.

	<Exp. 2> 11/12 females	● Ulnar deviation with a power grip	● Repetition (15, 20, 25/min) ● Day of week (days 1-5) ● Hour of day (hours 1-7)	● MAT ● Max isometric strength ● Tactile sensitivity ● Duration of force ● Error rate ● Symptom rate	● Mean (S.D.) MATs were 2.14 (1.00) Nm (27.2% max isometric strength) for 15/min, 2.11 (1.21) Nm (25.8% max isometric strength) for 20/min, and 1.89 (1.01) Nm (23.2% max isometric strength) for 25/min. ● Mean (S.D.) max isometric strengths were 7.88 (2.64) Nm for 15/min, 8.17 (2.94) Nm for 20/min, and 8.16 (3.24) Nm for 25/min. ● Mean (S.D.) tactile sensitivities were 1.28 (0.33) for 15/min, 1.34 (0.30) for 20/min, and 1.35 (0.32) for 25/min. ● Mean (S.D.) durations of force were 1.12 (0.36) sec for 15/min, 1.05 (0.42) sec for 20/min, and 1.08 (0.41) sec for 25/min. ● Mean error rates were 1.04% for 15/min, 0.77% for 20/min, and 1.18% for 25/min. ● Mean symptom rates 2.0% for 15/min, 2.6% for 20/min, and 2.5% for 25/min. ● Although MAT decreased with increasing repetition rate, the differences were not statistically significant.
Snook et al. (1995)	<Exp. 1> 15/16 females	● Wrist flexion with a power grip ● Wrist extension with a power grip ● Wrist flexion with a pinch grip	● Repetition (2, 5, 10, 15, 20/min) ● Motion	● MAT ● Max isometric strength ● Tactile sensitivity ● Symptoms	● Mean (S.D.) MATs were 3.59 (1.80), 3.20 (1.72), and 2.07 (0.98) Nm for flexion with a power grip, flexion with a pinch grip and extension with a power grip respectively. ● Mean (S.D.) max isometric strengths were 7.24 (2.99), 6.15 (2.40), and 5.18 (1.72) Nm for flexion with a power grip, flexion with a pinch grip and extension with a power grip respectively. ● Mean (S.D.) tactile sensitivities were 0.75 (0.32), 0.77 (0.35), and 0.76 (0.31) for flexion with a power grip, flexion with a pinch grip and extension with a power grip respectively. ● Overall symptoms were 5.7% (1,613 reports out of 28,350 opportunities). ● MATs significantly decreased with increasing repetition rates, and also varied consistently with type of hand motion and grip..
	<Exp. 2> 14/16 females	● Wrist flexion with a power grip	● Day of exposure (days 5-23)	● MAT ● Max isometric strength ● Tactile sensitivity ● Duration of force ● Performance errors ● Symptoms	● Mean (S.D.) MAT was 2.11 (0.89) Nm. ● Mean (S.D.) max isometric strength was 6.82 (2.89) Nm. ● Mean (S.D.) tactile sensitivity was 1.35 (0.48). ● Mean (S.D.) duration of force was 0.81 (0.24) sec. ● Overall symptoms were 5.4% (108 symptoms). ● Mean error rate was 0.46 errors per 100 motions. ● There was very little variation and no significant difference in MAT from day to day during the experiment.

Dahalan and Fernandez (1993)	12 females	• Gripping task	• Force (20, 30, 50, 70% MVC) • Duration (1.5, 3, 5, 7 sec)	• MAF • Heart rate • Blood pressure • RPE (Borg's CR10 scale) • EMG	• Highest (lowest) MAF was 9.55 (1.93) grips/min. at 20% (70%) MVC and 1.5 (7.0) sec. duration. • MAF was significantly reduced as force and duration increased. • As force and duration increased, EMG and RPE were increased significantly. • The gripping task at 70% MVC was at an unacceptable level and should be avoided in industrial tasks. • Mean heart rate ranged from 78.0 to 85.9 bpm. • Mean systolic (diastolic) BP ranged from 107.1 (74.7) to 122.6 (79.1) mmHg. • Mean RPE of upper body regions at acceptable levels ranged from 1.29 (very weak) to 6.57 (Strong). • Mean RMS of flexor (extensor) EMG at acceptable levels ranged from 56.3 (61.7) to 135.2 (119.2) mV.
Kim and Fernandez (1993)	15 females	• Drilling task	• Wrist flexion (0, 10, 20°) • Force (2.73, 5.45, 8.18, 10.91kg)	• MAF • Heart rate • Blood pressure • RPE (Borg's RPE scale) • EMG	• Highest (lowest) MAF was 10.30 (3.79) grips/min. at 2.73 (10.91) kg and 0° (20°) wrist flexion. • As force and wrist flexion increased, EMG and RPE were increased significantly with associated reduction in MAF. • Mean heart rate ranged from 91.23 to 110.36 bpm. • Mean systolic (diastolic) BP ranged from 102.27 (76.10) to 122.86 (79.60) mmHg. • Mean RPE of upper body regions ranged from 8.13 (extremely light) to 16.07 (hard). • Mean RMS of flexor (extensor) EMG ranged from 203.35 (615.65) to 500.15 (2618.83) mV.
Marley and Fernandez (1995)	12 females	• Drilling task	• Wrist flexion (0, 1/3, 2/3 ROM) • Wrist ulnar deviation (N, 1/3, 2/3 ROM)	• MAF • Heart rate • Blood pressure • RPE (Borg's RPE scale) • EMG	• Highest (lowest) MAF was 11.33 (7.67) grips/min. at neutral wrist flexion posture (2/3 ROM wrist flexion) and 1/3 ROM ulnar deviation. • There was no significant effect of ulnar deviation posture upon any of the dependent variables. • MAF for one-third (25°) and two-third (50°) flexion were 88% and 73%, respectively, of those selected in the neutral posture. • Mean heart rate (work pulse) ranged from 96.99 (25.41) to 104.49 (32.91) bpm. • Mean systolic (diastolic) BP ranged from 110.00 (75.81) to 118.55 (83.82) mmHg. • Mean RPE of upper body regions ranged from 9.92 to 14.42. • Mean RMS of flexor (extensor) EMG ranged from 138.50 (336.42) to 379.50 (578.33) mV.

Klein and Fernandez (1997)	12 males	• Lateral pinch task	• Force (15, 30, 50% MVC) • Wrist flexion (0, 2/3 ROM) • Task duration (1, 3, 7 sec)	• MAF • Heart rate • Blood pressure • RPE (Borg's CR10 scale) • EMG • Body discomfort	• Highest (lowest) MAF was 11.3 (2.03) pinches/min. at 15% (50%) MVC, 1 (7) sec. duration and neutral (2/3 ROM) wrist flexion. • RPE values were negatively correlated with MAF value and positively correlated with the EMG RMS activity. • As wrist flexion, force, and task duration increased, RPE and EMG RMS activity increased significantly while the MAF decreased (exponentially, not linearly) significantly. • For mean heart rate, force was the only significant factor.
Potvin et al. (2000)	<Exp. 1> 29 subjects (17 males/ 12 females; 6 workers/ 23 students)	• Hand impact	• Gender • Skill level (skilled, unskilled) • Impact location (high-close, high-far, low-close, low-far)	(Of both the force and the acceleration) • Peak • Time to peak • Load rate • Impulse	• The location of the impact surface, relative to the body, did not appear to influence the acceptable impact severity. • None of independent variables showed any effects of skill or gender. • Mean (S.D.) first peak force was 235.2 (60.8) N. • Mean (S.D.) time to first peak was 5.39 (1.14) ms. • Mean (S.D.) rate of loading was 81.1 (37.9) N/ms. • Mean (S.D.) force impulse was 3.50 (1.03) PSI. • Mean (S.D.) peak accel was 490.4 (119) m/s^2) • Mean (S.D.) time to peak accel was 4.77 (1.07) ms. • Mean (S.D.) rate of accel was 189.6 (72.4) $m/s^2/ms$. • Mean (S.D.) accel impulse was 4.23 (0.78) m/s.
	<Exp. 2> 16 subjects (8 males & 8 females)	• Hand impact	• Gender • Frequency (2, 5, 8/min)	• Peak force • Time to peak force • Load rate • Force impulse	• Frequency had a significant effect on peak force, load rate, and impulse. • Male impulse values were significantly higher than female values. • Mean peak force ranged from 581.5 (8/min) to 739.4 N (2/min). • Mean (S.D.) time to peak was 4.89 (0.93) ms. • Mean rate of loading ranged from 189.8 (8/min) to 287.9 N/ms (2/min). • Mean impulse ranged from 2.95 (8/min) to 3.25 Ns (2/min). • The limits ranged from 181 N and 2.53 Ns (females, 8/min) to 259 N and 3.52 Ns (males, 2/min) for the peak force and force impulse variables, respectively.
Putz-Anderson and Galinsky (1993)	<Exp. 1> 18 subjects (8 males & 10 females)	• Shoulder elevation	• Discomfort criteria (level 3, 4, 5) • Force (10, 20, 30% MVC) • Work session (session 1-4)	• Work duration	• The mean work durations for work sessions 1-4 decreased significantly (mean= 77, 71, 66, 66 sec.). • As the discomfort criterion was raised from 3 to 4 to 5, there was a significant increment in work duration (mean= 47.91, 66.62, 93.63 sec.) • Increases in the force from 10 to 20 to 30 % MVC produced significant decreases in work duration (mean= 88.02, 69.31, 52.83 sec.).

	<Exp. 2> 18 subjects (8 males & 9 females)	● Shoulder elevation	● Repetition rate (20, 24, 35/min) ● Force (10, 20, 30% MVC) ● Work session (session 1-4)	● Work duration	● The mean work durations decreased significantly as time progressed from work session 1 to 3 (mean= 92, 84, 77 sec.). ● Work duration varied inversely with each of force and repetition rate, significantly. ● Force accounted for 21% of variance and repetition rate accounted for 39% of the variance for work duration. ● Repetition rate and force of movement had the largest effects on work duration.
	<Exp. 3> 18 subjects (8 males & 9 females)	● Shoulder elevation	● Repetition rate (20, 24, 35/min) ● Tool weight (2136, 2506, 3039 gm) ● Work session (session 1-4)	● Work duration	● An insignificant decrease in mean work duration was observed as time progressed form work session 1 (73 sec.) to 2 (68 sec.) to 3 (65 sec.). ● Increases in tool weight led to minor significant reductions in mean work duration, accounting for only 2% of the variance. ● Increases in repetition rate led to pronounced significant reductions in mean work duration which accounted for 45% of the variance.
	<Exp. 4> 18 subjects (8 males & 9 females)	● Shoulder elevation	● Repetition rate (20, 24, 35/min) ● Reach height (109, 120, 131cm) ● Work session (session 1-4)	● Work duration	● The mean work durations for work sessions 1-3 decreased significantly (mean= 100, 85, 85 sec.). ● Work duration had significant inverse relationships with each of repetition rate and reach height. ● Repetition rate was the more powerful variable, accounting for 43% of the variance as compared to only 4% accounted for by reach height.
Garg and Saxena (1982)	10 females	● One-handed lifting	● Distance (38.1, 63.5cm) ● Force (2.3, 4.5, 5.7kg for 38.1cm; 1.1, 2.3, 4.5kg for 63.5cm)	● MAF ● Heart rate ● RPE (Borg's RPE scale)	● Both the load and reach distance had a significant effect on MAF. ● MAF ranged from 12.7/min. at 4.5kg for 63.5cm distance to 18.8/min. at 2.3kg for 38.1cm distance. ● The percentage of MAF to the maximum frequency that the subject could maintain for a 4 minutes ranged from 47 to 56.4% (mean= 51.3%). ● Mean heart rate was 101 bpm (ranged from 98 to 105 bpm). ● RPE ranged from 10.6 (fairly light) to 13.2 (somewhat hard), and mean RPE was approximately 12. ● Based on MTM analysis, the 100% performance ranged from 13.9 to 19.7/min. ● Performance based on MTM analysis ranged from 11% below to 32% above the MAF.

Appendix B. Descriptions for anthropometric variables

Region	Dimension	Variable	Definition
Whole body	-	Height (cm):	The distance from the top of the head to the ground.
	-	Weight (kg):	The lightly clothed weight (no shoes).
Upper Arm/ Shoulder	Length	Shoulder-Elbow Length	The distance from the top of the acromion process to the bottom of the elbow. The subject sits erect with his upper arm vertical and forearms and hands extended forward horizontally.
	Circumference	Upper Arm Circumference	The circumference of the arm measured high in the armpit.
Forearm / Elbow	Length	Elbow-Wrist Length	The distance from the tip of the elbow to the tip of the styloid process of the radius.
		Elbow-Grip Length	The distance from the tip of the bent elbow to the center of the clenched fist.
	Width	Elbow Breadth	The distance between the medial and lateral epicondyles of the humerus measured with the flesh compressed.
	Circumference	Forearm Circumference	The circumference of the arm at the level of the forearm landmark. The subject stands with his upper arm raised so that its long axis is horizontal, elbow flexed 90 degrees and fist tightly clenched.
Hand/ Wrist	Length	Hand Length	The distance from the base of the hand to the top of the middle finger measured along the long axis of the hand. The subject sits with the hand flat on a table, palm up, with fingers together and straight.
		Palm Length	The distance from the base of the hand to the furrow where the middle finger folds upon the palm.
	Width	Wrist Breadth	The distance between the radial and ulnar styloid prominences of the wrist measured with the flesh compressed.
		Hand Breadth	The breadth of the hand between metacarpal-phalangeal joints II and V. The subject sits with the hand flat on a table, palm down, with fingers together and straight.
	Circumference	Wrist Circumference	The circumference of the wrist at the level of the tip of the styloid process of the radius. The subject sits with the hand flat on a table, palm up, with fingers together and straight.
		Hand Circumference	The circumference of the hand passing over the metacarpal-phalangeal joints II and V. The subject sits with the hand flat on a table, palm down, fingers extended, and thumb abducted.

Appendix C. Subject instructions

YOUR JOB IS TO MOVE THE MOTION REQUIRED EVERY TIME YOU HEAR THE BEEP, AND TO ADJUST THE WORK PACE ACCORDING TO THE GUIDELINES BELOW:

Move the motion smoothly and at a moderate pace - not too fast and not too slow.
Move the motion only once per beep, and at the range of movement required.
Do not apply pressure between movements.
You are permitted to talk with each other, but do not talk about the experiment, or about how your hand, wrist, forearm, and upper arm are feeling.
You are not permitted to read, because we want you to concentrate on adjusting the work pace.
We depend upon you for successful results, and greatly appreciate your participation!

Instructions for Adjusting Work Pace

We want you to imagine that you are on piece work getting paid for the amount of work that you do, but working an eight hour shift that allows you to go home without unusual discomfort in the hand, wrist, forearm, and upper arm.
In other words, we want you to work as hard as you can without straining your hand, wrist, forearm, or upper arm.

YOU WILL ADJUST YOUR OWN WORK PACE. You will work only at the sound of the beep. Your job will be to adjust the pace; that is, to adjust the arrow key, which controls the amount of task frequency.

Adjusting your own work pace is not an easy task. Only you know how you feel.

IF YOU FEEL YOU ARE WORKING TOO HARD, reduce the pace by pushing the arrow key downward.
HOWEVER, WE DON'T WANT YOU WORKING TOO LIGHTLY EITHER. If you feel that you can work harder, as you might on piece work, push the arrow key upward.

DON'T BE AFRAID TO MAKE ADJUSTMENTS. You have to make enough adjustments so that you get a good feeling for what is too hard and what is too easy.
You can never make too many adjustments - but you can make too few.
REMEMBER . . . THIS IS NOT A CONTEST.
EVERYONE IS NOT EXPECTED TO DO THE SAME AMOUNT OF WORK.

WE WANT YOUR JUDGMENT ON HOW HARD YOU CAN WORK WITHOUT DEVELOPING UNUSUAL DISCOMFORT IN THE HAND, WRIST, FOREARM, OR UPPER ARM.

Appendix D. ANOVA tables in MAF experiment

Table D.1 ANOVA table for work pulse

Source	DF	Sum of Square	Mean Square	F	*p*
Part (P)	3	1823.03	607.68	36.75	<.0001
Load (L)	1	315.10	315.10	25.92	0.0001
P × L	3	96.66	32.22	4.60	0.0066
Subject (S)	16	419.72	26.23	-	-
P × S	48	793.69	16.54	-	-
L × S	16	194.54	12.16	-	-
P × L × S	48	336.40	7.01	-	-
Total	135	3979.14			

Table D.2 ANOVA table for working heart rate

Source	DF	Sum of Square	Mean Square	F	*p*
Part (P)	3	2048.10	682.70	21.22	<.0001
Load (L)	1	480.08	480.08	12.61	0.0027
P × L	3	72.29	24.10	1.43	0.2465
Subject (S)	16	13383.18	836.45	-	-
P × S	48	1544.23	32.17	-	-
L × S	16	609.05	38.07	-	-
P × L × S	48	810.69	16.89	-	-
Total	135	18947.62			

Appendix E. Regression models for MAF of upper extremity

Table E.1 Regression model for MAF of shoulder motion with 1 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	10139.00	10139.00	129.29	<.0001
Error	16	1254.77	78.42		
Total	17	11394.00			

Table E.2 Regression model for MAF of shoulder motion with 4 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	1443.35	1443.35	79.18	<.0001
Error	16	291.65	18.23		
Total	17	1735.00			

Table E.3 Regression model for MAF of elbow motion with 1 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	34549.00	34549.00	100.01	<.0001
Error	16	5527.42	345.46		
Total	17	40076.00			

Table E.4 Regression model for MAF of elbow motion with 4 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	6628.84	6628.84	92.54	<.0001
Error	16	1146.16	71.63		
Total	17	7775.00			

Table E.5 Regression model for MAF of wrist motion with 1 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	53400.00	53400.00	83.4	<.0001
Error	16	10245.00	640.32		
Total	17	63645.00			

Table E.6 Regression model for MAF of wrist motion with 4 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	15315.00	15315.00	105.19	<.0001
Error	16	2329.40	145.59		
Total	17	17644.00			

Table E.7 Regression model for MAF of index finger motion with 0.25 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	275728.00	275728.00	74.95	<.0001
Error	16	58858.00	3678.61		
Total	17	334586.00			

Table E.8 Regression model for MAF of index finger motion with 1 kg

Source	DF	Sum of Square	Mean Square	F	*p*
Model	1	71817.00	71817.00	79.33	<.0001
Error	16	14485.00	905.33		
Total	17	86302.00			

Appendix F. Meta-analysis results of repetitiveness studies

Study	Design or method	Population (gender-n)	Task	Measure	Repetitiveness definition	Repetitiveness criterion	Note
Genaidy et al. (1993)	Review	-	-	Finger movement	# of motions per day	MPL: 21,936 motions/day	48.7 motions/min
				Wrist movement	# of motions per day	MPL: 11,706 motions/day	26 motions/min
				Elbow movement	# of motions per day	MPL: 2,838 motions/day	6.3 motions/min
				Shoulder movement	# of motions per day	MPL: 2,838 motions/day	6.3 motions/min
Kilbom (1994)	Review	-	-	Finger movement	# of motions per minute	200 motions/min	
				Wrist movement	# of motions per minute	10 motions/min	
				Elbow movement	# of motions per minute	10 motions/min	
				Shoulder movement	# of motions per minute	2.5 motions/min	
Wick (1994)	Review	-	-	Wrist movement	# of hand movements per hour	2,000 hand movements/h	33.3 motions/min
Malchaire et al. (1997)	Prospective	Workers (184)	14 industrial tasks in 10 workplaces	Wrist movement	# of motions per minute	16.2 motions/min	
Malchaire et al. (1996)	Cross-sectional	Workers (335)	12 industrial tasks in 9 workplaces	Wrist movement	# of motions per minute	15.1 motions/min	
Colombini (1998)	Review	-	-	Shoulder movement	# of motions per minute	10 motions/min	
Hansson et al. (2000)	Case-referent	Workers (F-169)	Industrial work	Wrist movement	Mean power frequency (MPF)	0.53 Hz	31.8 motions/min
Garg and Saxena (1982)	Psychophysical	Students (F-10)	One-handed lifting	Shoulder or elbow movement	# of lifts per minute	12.7 lifts/min (4.5 kg for 63.5 cm distance) ~ 18.8 lifts/min (2.3 kg for 38.1 cm distance)	IV.: 2.3, 4.5, 5.7 kg for 38.1 cm distance; 1.1, 2.3, 4.5 kg for 63.5 cm distance

Silverstein et al. (1986)	Cross-sectional	Workers (574)	34 industrial work in 6 workplaces	Cycle time	cycle time and % of cycle time performing the same fundamental cycle	< 30 sec or > 50 % of fundamental cycle	
Silverstein et al. (1987)	Cross-sectional	Workers (652)	39 industrial tasks in 7 workplaces	Cycle time	cycle time and % of cycle time performing the same fundamental cycle	< 30 sec or > 50 % of fundamental cycle	
Killough and Crumpton (1996)	Review	-	-	Cycle time	Cycle time	< 30sec	
Hansson et al. (1996)	Observational	Workers (F-32)	12 fish processing	Fundamental cycle time	Fundamental cycle time	< 2 sec	
Dahalan and Fernandez (1993)	Psychophysical	Students (F-12)	Gripping	Power exertion	# of grips per minute	1.93 grips/min (70% MVC and 7.0 sec. duration) ~ 9.55 grips/min (20% MVC and 1.5 sec. duration)	IV.: force (20, 30, 50, 70% MVC); duration (1.5, 3, 5, 7 sec)
Kim and Fernandez (1993)	Psychophysical	Students (F-15)	Drilling	Power exertion	# of grips per minute	3.79 grips/min (10.91 kg and 20° WF) ~ 10.30 grips/min (2.73 kg and WN)	IV.: WF (0, 10, 20°); force (2.73, 5.45, 8.18, 10.91kg)
Marley and Fernandez (1995)	Psychophysical	Students (F-12)	Drilling	Power exertion	# of grips per minute	7.67 grips/min (2/3 ROM WF and 1/3 ROM WUD) ~ 11.33 grips/min (neutral WF and 1/3 ROM WUD)	IV.: WF (0, 1/3, 2/3 ROM); WUD (0, 1/3, 2/3 ROM)
Klein and Fernandez (1997)	Psychophysical	Students (M-12)	Lateral pinching	Pinch exertion	# of pinchs per minute	2.03 pinches/min (50% MVC, 7 sec. duration and 2/3 ROM WF) ~ 11.3 pinches/min (15% MVC, 1 sec. duration and WN)	IV.: force (15, 30, 50% MVC); WF (0, 2/3 ROM); duration (1, 3, 7 sec)
Moore and Garg (1995)	Review	-	-	Power exertion	# of exertions per minute	20 exertions/min	Strain index
Carey and Gallwey (2002)	Review	-	-	Power exertion	# of exertions per minute	20 exertions/min	