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RELIABILITY OF A PSYCHOPHYSICAL METHOD FOR EVALUATING REPETITIVE POWER HAND GRASPS OF FEMALES

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RELIABILITY OF A PSYCHOPHYSICAL METHOD FOR EVALUATING

REPETITIVE POWER HAND GRASPS OF FEMALES

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ABSTRACT

Several researchers have used the psychophysical method of adjustment to study hand grasping tasks. However, these studies have not reported the effect of elapsed time upon the recorded psychophysical values. The objectives of this study were (1) to investigate the test-retest reliability of psychophysical evaluations of subjects using the psychophysical method of adjustment for a repetitive power hand grasping task, (2) to verify a methodology for studying and quantifying the exposure limits to CTD occupational risk factors for hand-wrist repetitive tasks as proposed by Abu-Ali (1993), and (3) to determine psychophysically the effect of exertion time on the subject-determined flexion grasping frequency and rest time.

Sixteen female subjects performed a simulated industrial hand grasping task in twenty-minute sessions conducted over four weeks. Each subject was required to exert a grasping force of 30% of her MVC for five seconds. Travel distance was 0.25 inch to simulate activating the trigger on a power tool. The subject then relaxed her grip for a rest period whose length could be adjusted at two-minute intervals. These subject-determined rest intervals were recorded at the end of the twenty-minute test session. Test sessions were conducted at seven-day intervals.

Test-retest reliability of subject-determined rest times revealed a high correlation (0.92) between the first and second experimental session. Test-retest correlations of rest time were 0.94 for the wrist neutral condition and 0.88 for the 45° wrist flexion

condition. Sensitivity analysis of the correlation values revealed that the correlations were stable across the entire sixteen subject population. Analysis of the mean MVC data showed that the mean MVC increased from Session 1 to Session 4 with no statistically significant difference among Sessions 1, 2 and 3, and Session 1, 3, and 4. Mean pre-session MVC data were found to be greater than mean post-session MVC values and this difference was statistically significant. Analysis of rest time data revealed that wrist angle and subjects were significant. The 45° wrist flexion condition produced greater mean rest times than the wrist neutral posture. Maximum acceptable frequency (MAF) was significantly affected by wrist angle and individual subject differences. Subjective difficulty ratings were not statistically significant.

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RELIABILITY OF A PSYCHOPHYSICAL METHOD FOR EVALUATING REPETITIVE POWER HAND GRASPS OF FEMALES

CHAPTER 1

INTRODUCTION

Cumulative trauma disorders (CTD) and carpal tunnel syndrome (CTS) have been described as common problems of the hand in the United States (Amadio, 1992). As early as the 1800's a condition known as *acroparesthesia* was known and diagnosed in the United States. The term *carpal tunnel syndrome* was coined in the 1950's. At present, cumulative trauma disorders (CTD) are among the most serious and frequent complaints in the workplace. The term CTD refers to a group of conditions of discomfort, impairment, disability, or persistent pain that occur in the musculonervous system that may or may not be accompanied by physical manifestation (Kroemer, 1989; NOHSC, 1987). Carpal tunnel syndrome (CTS) is a CTD that occurs as a result of compression of the median nerve at the wrist. CTS symptoms occur mostly during the night and include pain, numbness, tingling, and loss of sensation in most of the palmar side of the hand, thumb, index finger, middle finger, and ring finger (Kroemer, 1989;

Meagher, 1986; Tayyari and Sohrabi, 1990). CTD's were recognized as occupational diseases in 1960 by the International Labor Office (ILO, 1960).

Today CTS has been identified as one of the most expensive occupational illnesses in the United States. The Bureau of Labor Statistics showed that in 1991, 61% of all workplace illnesses were attributed to CTS (CTD News, 1993a). The state of Oklahoma reported 1993 incident rates of 6.7 and 17.8 per 100 employees for CTS and repetitive motion injuries, respectively (Oklahoma Department of Labor, 1995). Costs associated with CTD's were set at $26.6 million for federal employees in 1991 (CTD News, 1993b). Estimates of individual costs of CTD's range from $10,000 to $30,000 per person. As an occupational illness, the burden of relief and recovery of this illness has fallen on the employers and the workers compensation system. With the large amounts of money associated with this illness, a large effort has been undertaken to investigate the illness and develop strategies to relieve workplace stress and occupational factors that may lead to the occurrence of CTS.

The prevalence of CTS diagnoses and claims resulting from the workplace has continued to rise over the last decades. An Urban Institute study in 1991 found that CTD's had the highest total average workers compensation case cost of $14,726. Blue Cross found that the cost of CTS can run as high as $100,000 in medical and administrative expenses and lost productivity (CTD News, 1994). Research has identified several occupational factors as contributing to CTS over the last four decades (Gordon, Lubbers and McCosker, 1992). Silverstein, Fine and Armstrong (1987) found that high force-high repetition jobs presented a significantly greater risk for CTS than low force-low repetition jobs. Gordon et al. (1992) reported increased CTS symptoms when employees performed repetitive tasks, whether at work or as a hobby.

There has been some question in the literature of whether CTS is a genetic or an occupational disease. Generally, most of the research has focused on the occupational aspect of the illness and the work place factors that lead to the onset of CTS. Personal hobbies are not considered by employers and it is the occupational setting that is the focus of ergonomic analyses due to privacy issues for employees [personal communication, Dr. Ila Elson, Battelle Memorial Institute]. However, there has been some indication that people may be genetically predisposed to developing CTS. Several authors have defined familial occurrence of CTS in subsequent generations of the same family (Radecki, 1994; Danta, 1975; Braddom, 1985; Leifer, Cros, Halperin, Gallico, Pierce and Shalini, 1992; Michaud, Hays, Dudgeon and Kropp, 1990). Carpal tunnel syndrome seems prevalent in people with medical conditions of rheumatoid arthritis, hypothyroidism, diabetes mellitus, gout, hemophilia, pregnancy, amyloidosis, obesity and the use of oral contraceptives (Gordon et al., 1992; Stevens, Beard, O'Fallon, and Kurland, 1992). Anthropomorphic characteristics such as wrist size and shape have been linked to CTS as well (Johnson, Gatens, Poindexter, and Bowers, 1981).

1.1 Problem Statement

CTD injuries in the workplace are caused or aggravated by factors usually categorized as occupational risk factors or genetic risk factors. Occupational factors include repetitive movements, forceful exertions, sustained or constrained postures, vibration, low temperature, and mechanical stress (Gordon et al., 1992; Silverstein et al., 1987; Calisto, Jiang and Cheng, 1986; Cannon, Benacki, and Walter, 1981; Lifshitz and Armstrong, 1986; Turner, Buckle and Stubbs, 1990). In addition to these risk factors, task parameters such as exertion time and work duration have been reported as occupational risk factors (Abu-Ali, 1993).

Even though these occupational risk factors have been identified, current literature research revealed that acceptable safety limits of exposure to these factors have not been established (Armstrong, Radwin, and Hansen, 1986; Bishu, Manjunath, and Hallbeck, 1990; Kim, 1991; Kroemer, 1989), nor have acceptable methods to study, investigate, and determine these acceptable limits. OSHA has promulgated guidelines for controlling CTD's in the meat packing industry, but to date it has no guidelines or regulations to address CTD hazards in other industries. OSHA, in 1992, initiated an advanced notice of proposed rule making for all industries, but by 1995 this effort was withdrawn (OSHA, 1992).

Several authors have used the psychophysical method in hand grasping research. Marley (1990), Kim (1991) and Abu-Ali (1993) used the method to investigate work-rest grasping cycles that were acceptable to subjects. Wiker and Fuerlinger (1994) and Jeng, Radwin, and Rodriquez (1994) used the psychophysical method to investigate pinch grasping. Bishu, Hallbeck, King and Kennedy (1995) investigated the stability of MVC. They found that the coefficient of variation among subjects was around 8%. Jeng et al. (1994) reported a high reliability using the psychophysical method. However, systematic bias was introduced as a result of the order of testing, which may have affected the reliability score. It appears that no hand study using the psychophysical method has included a test-retest evaluation. Test-retest reliability is an important question if the psychophysical method is to be used for future hand and pinch grasp psychophysical research.

1.2 Objectives

The objectives of this dissertation were to:

1. investigate the test-retest reliability of psychophysical evaluations of subjects using the psychophysical method of adjustment upon a repetitive power hand grasping task,
2. verify a methodology for studying and quantifying the exposure limits to CTD occupational risk factors for hand-wrist repetitive tasks (Abu-Ali, 1993), and
3. determine psychophysically the effect of exertion time on subject-determined rest time and the resulting grasping frequency.

The related research on CTD's is reviewed in Chapter 2. This information provides the background for the study. Chapter 3 contains the research methodology, and the experimental design used in the study as well as analysis of the pilot study data. Chapter 4 contains the results and analysis from the principal study and Chapter 5 presents conclusions and recommendations resulting from the research.

CHAPTER 2

LITERATURE REVIEW

2.1 Carpal Tunnel Syndrome

Repetitive strain injuries (RSI) or CTD's have been the recent focus of governmental regulation (OSHA, 1992) and occupational research. Morse (1986) stated that the corporate cost of CTD's may be as high as $30,000 per case. Chatterjee (1987) indicated that up to 66% of Canadian supermarket cashiers experienced some musculo-skeletal problems. Hiltz (1990) stated that the average direct cost of a CTD case was $3,500 with total disability costs ranging from $30,000 to $60,000.

Carpal tunnel syndrome (CTS) is a result of damage to the median nerve. Symptoms include numbness, pain and decreased motor function of the hand. The median nerve provides sensory distribution to the palmar surface of the hand, which includes the thumb, index finger, middle finger and half of the ring finger. The median nerve also supplies motor function to the thenar muscles at the base of the thumb and partial motor function to the lumbrical muscles in the fingers (Morse, 1986). Rapid repetitive motion, especially movements involving flexion of the wrist during pinch or power grasps, may compress the median nerve against the carpal ligament and cause a low-grade inflammation of the flexor tendons (Smith, Sonstegard, and Anderson, 1977;

Chatterjee, 1987; Browne, Nolan, and Faithfull, 1984). There are three stages of clinical aspects of CTS as identified by Browne et al. (1984):

> **Stage 1**: Aching and tiredness of the affected limb which occurs during the work shift, but subside overnight and on days off from work. There is no significant reduction of work performance nor any physical signs. This condition can persist for weeks or months and is reversible.
>
> **Stage 2**: Recurrent aching and tiredness which increasingly occur earlier in the work shift and persist longer. Symptoms fail to subside overnight, cause disturbances of sleep and are associated with a reduced capacity for repetitive work. Physical signs may be present and this condition may last for months.
>
> **Stage 3**: Aching, fatigue and weakness persist at rest and pain occurs with non-repetitive movement. The symptoms cause disturbance of sleep. The patient is unable to perform light duties and experiences difficulty with non-occupational tasks. Physical signs are present and the condition may last for months to years.

Hymovich and Lindholm (1966) investigated handgrip injuries at a company in Connecticut. They found no correlation between handgrip strength and the development of CTD's. They stated that injuries primarily consisted of sprains of the muscles of the forearm with or without accompanying tenosynovitis of the wrist tendons. This suggests that muscle pain or changes in muscle strength were not good correlates of the presence of a CTD.

Goldstein, Armstrong, Chaffin and Matthews (1987) postulated that viscoelastic creep responses of the tendons or tendon sheaths is an important etiological factor in the development of CTD's. The authors believed that CTD's were the response to cumulative strain developed in the tendons, tendon sheaths or the retaining ligaments that form the anatomical belt and pulley described by Armstrong and Chaffin (1979). They found that shear traction forces were significantly higher in wrist flexion and extension than when the wrist was in a neutral position. Additionally, the shear forces were greater in flexion than in extension. The authors noted that significant stresses exist at the tendon, tendon sheath and the retinacula and these forces increase significantly with increasing wrist deviation. The authors found that the tendons crept in response to loads. They found that there was an initial shearing of the viscoelastic gel at low strains as the tendon fibers straightened out and a transition of the gel to a gradual linear region of fibrillar creep. They found this creep strain to be significantly related to gender and wrist position and modeled it with the equation:

$$\varepsilon_{creep} = K(t)^{0.409}, \tag{1}$$

where K is a constant based upon gender and wrist position. They also found that for a given load, the strain response of a female tendon was less than that of the typical male. This implies that the female tendons were stiffer than the male tendons. If there is an inflammatory process in the tendons and tendon sheaths, then this would increase the pressure on the tendons and restrict tendon gliding. This finding implies that female tendons would be impacted to a greater degree than male tendons. The authors also found that the shear interactions were not caused by degeneration of the cadaver tissues or a loss of lubrication as tendons demonstrated non-linear elastic and visco-elastic properties. This finding suggests that the functional interactions between the tendons and the biomechanical pulley system are significant.

The following facts are known about CTS:

1. Flexion at the wrist reduces the carpal tunnel size, and the tensions applied to the wrist are greater in flexion than in any other deviation.

2. There seems to be a physiologic limit above which smooth gliding of the tendon through the tendon sheath is impaired.

3. Movement associated with industrial assembly lines and other repetitive, forceful movements may strain the tendon beyond its physiological limit.

4. There are three stages of clinical aspects of CTS in which people may experience increasing symptoms and decreasing recovery ability.

5. In addition to the reduction in size of the carpal tunnel during wrist deviation, inflammation of the tendon and tendon sheaths increases the mechanical compression of the median nerve, leading to loss of sensation and grip strength in the hand region.

Several researchers have shown that muscular contractions in the forearm, over 30% MVC begin to occlude the blood flow into the forearm and this reduces the ability of the body to remove metabolites from the muscle area. Chaffin (1973) stated that when a contraction is sustained, the active muscle fibers can lose their tension producing capability. Additional motor units are then needed to maintain the total tension state of the muscle. The body, in response to this, increases the number of motor units that are firing to augment the automatic central nervous system (CNS) feedback that occurs when the spindle sensory system is stretched. Chaffin proposed the following theory to account for the research data:

1. Moderate exertion of the muscle above 15% MVC for a prolonged period of time results in decreased tension capabilities of the extrafusal motor units.

2. Spindle sensory organs are stretched as the muscle stretches when the muscle fails to produce the required tension.

3. Increased stimulation of the spindle sensory system increases the bias on these organs. This increases the feedback to the CNS caused by the muscle stretch.

4. This increase in feedback causes the CNS to recruit more extrafusal motor units. This produces a low frequency shift in EMG recordings and increased tremor.

5. The increased facilitation in the spindle system accounts for the tendency to judge light forces as being heavier and to overshoot an intended target during fast hand movements.

These actions would seem to account for the observation that under certain work cycles, certain people develop pain symptomology at different intervals and can work through the pain. It appears that pain is not necessarily a limiting factor, but that people lose the ability to support a load (Chaffin, 1973). He states that the pain mechanism is probably separate from the mechanisms that physiologically limit the tension in the motor units.

This would seem to explain the differences between whole body lifting (manual material lifting) and localized muscle contraction during hand gripping. Research on whole body lifting indicates that the psychophysical methodology may be protective at low to moderate lifting frequencies (Ciriello, Snook, Blick, and Wilkinson, 1990; Fernandez, Ayoub, and Smith, 1991). This seems to agree with Caldwell and Lyddan (1971), who state that one cannot deny the importance of the circulatory state of the muscles on energy production and utilization, the contribution of central factors such as motivation, instructional set and pain tolerance. As this type of activity involves many muscle groups, the mechanism of muscle fatigue and pain may be self-limiting. While people can and do work through the pain, when the muscle metabolites saturate the ability of the circulatory system to remove them, the physiologic aspect of the pain may cause people to cease a particular activity. In contrast, the localized muscle activity of the forearm during contractions occludes blood flow from the forearm, preventing muscle metabolites from being removed from the area. The physiologic response to the fatigue and pain may limit a person in performing a hand grip activity, but there is no evidence there is a connection between the physiological muscle limit and the biomechanical limit of the tendons and tendon sheaths in their action in the carpal tunnel. The pain response of CTS generally occurs after many years of repetitive movements of the hand and forearm. This implies the physiologic pain response of the local muscles is not protective with regards to CTS development. If this were the case, then, as people stop performing the particular activity and recover from the muscle stress, they should also recover from any physiologic damage that occurs to the tendons.

2.2 The Psychophysical Paradigm

Psychophysics is a scientific method that has been used to study the relation between a stimulus and a sensation. This paradigm has largely been used in psychological experiments since Fechner published the work *Elements in Psychophysics* in 1860 (Gescheider, 1985). Measurement of both stimulus and sensation are required in order to use psychophysical laws. The problem in using this methodology is that sensations are a subjective measurement of a particular individual and that the measure used cannot be directly seen or interpreted by the observer. The researcher must determine the magnitude of the sensations by using some subjective measurement of the sensation (Gescheider, 1985). Five different psychophysical methods have been described that have been used to develop psychophysical functions. These five are the *method of adjustment, method of limits, method of constant stimuli, method of paired comparison*, and the *method of ratio scaling* (Gescheider, 1985).

2.2.1 Method of Adjustment

This method has been applied to measuring difference thresholds and to measuring absolute sensitivity. Gescheider (1985) defines a threshold as a point where 50% of the trials are detected. The stimulus with the weakest intensity should almost never be detected while the strongest intensity stimulus should almost always be detected. This method requires the subject to continually adjust the stimulus until it is just perceptible or disappears (absolute threshold) or until a comparison stimulus appears to be equal to a standard stimulus (difference threshold). These methods require the subject to make changes across a wide range of stimulus intensity and over many trials. However, this method fails when the stimuli are not continuously variable or cannot be presented simultaneously. Another failing of this method is that the subject has control of the stimulus, making it difficult to maintain constant conditions throughout the experiment (Gescheider, 1985).

2.2.2 Method of Limits

This method is used to determine sensory thresholds. Absolute thresholds are determined by presenting a stimulus far above or far below the threshold and at each presentation, the stimulus intensity is changed by a small amount until a boundary of sensation is reached. The stimulus is moved in either an ascending or descending series. Since the stimulus is changed in the direction of the threshold over trials, this may lead to *errors of habituation*, where the subject incorrectly moves the level of the threshold in the direction of movement of the stimulus. The other error that is possible is the *error of expectation*, where the subject falsely reports a stimulus before the threshold is reached (Gescheider, 1985). This method may also be used to measure difference thresholds. This requires the experimenter to pair a standard stimulus with a comparison stimuli. A series of pairs are presented from which an upper and lower limen (L_u and L_l) are established (Gescheider, 1985). The object is for the subject, if determining an upper limen, to determine the point where the stimulus changes from being greater than the standard stimulus to being equal. Similarly, if determining a lower limen, the subject would look for the point of transition of the stimulus from being less than the standard to being equal to it.

2.2.3 Method of Constant Stimuli

The method of constant stimuli is a procedure which repeatedly uses the same stimuli throughout the experiment. The experimenter usually uses five to nine different values of stimuli. The responses are recorded and the proportion of yes responses is computed and a psychometric function graph is developed. If enough measurements are collected, then the psychometric function follows an ogive or S-shaped pattern. This method may also be used to measure difference thresholds. The observer is asked to evaluate a pair of stimuli and determine the signal with the greater magnitude (Gescheider, 1985).

2.2.4 Method of Paired Comparison

This is the most commonly applied psychophysical method used to collect data for constructing psychophysical scales. It is based upon comparative judgements in which a standard stimulus is compared to a comparison stimulus (Gescheider, 1985). Similarly to the method of adjustment, this method requires the subject to make comparative judgements for all possible pairs of stimuli. Here each stimulus serves as the standard in a series of comparative judgements with the other stimuli.

2.2.5 Method of Ratio Scaling

Ratio scaling requires the subject to make judgements of the ratio between the magnitudes of stimuli. Use of this method depends upon the ability of the subject to consistently construct their own sensory scale. Construction of a sensory scale requires a knowledge of the ratios between sensations at several points along the sensory dimension (Gescheider, 1985). Use of this method requires tests of internal consistency in order to evaluate the subject's performance.

2.3 Psychophysics

2.3.1 Psychophysics in Physical Ergonomics

Several authors have used this paradigm as the basis in performing human performance research since the early 1960s. Most notable of these authors include Snook and Irvine (1967, 1968), Snook and Ciriello (1974), Garg and Saxena (1979), Garg, Mital, and Asfour (1980), Mital (1983), Karwowski and Yates (1986), Karwowski (1991), and Drury, Deeb, Hartman, Woolley, Drury, and Gallagher (1989). This research paradigm has been used to develop human performance criteria in defining manual material handling (MMH) or lifting limits that the worker can perform generally in an eight hour work day. There is a lack of psychophysical research on the hand. Most of the hand related research has investigated physiological or biomechanical aspects of the hand. Only recently have researchers used the psychophysical method in hand-related research.

The psychophysical method was first used in ergonomics by Snook and Irvine of Liberty Mutual Insurance Company in 1967. This study was to determine the maximum acceptable weight which 90% of the male industrial population should lift. Nine subjects with a mean age of 30.1 years (range 25-37) made a total of 18 weight judgements. They stated that a 50 pound weight was the maximum weight of a compact object that should be lifted by an unselected adult male worker. This study was the first study that used instructions that emphasized in the amount of weight that could be lifted "comfortably and without strain". Snook and Irvine in 1968 followed up their previous work by investigating the maximum frequency of lift using psychophysical principles. The authors note that the subjects in this study selected mean frequencies that were 10 to 30% lower than the mean frequencies obtained in an earlier study. In a continuation of the two previous studies, Snook and Ciriello (1974) investigated the maximum weight and work loads acceptable to female workers. They were interested in the maximum acceptable weight of lift, the maximum work load and the heart rate of the subjects. The results of this study showed that there were differences in the amount of weight that could be lifted by sex and that women had less variability in adjusting object weight.

Garg and Saxena (1979) studied the effects of lifting frequency and technique upon the acceptable work load. They also were interested in comparing the physiological workload criteria of 5 kcal min^{-1} with the psychophysical fatigue criteria. They also found that the subjects did not adjust the weight of the load to produce a uniform metabolic rate over the different levels of frequency and technique. They found that the maximum acceptable weights found in this study were considerably lower than those found previously.

Mital (1983) sought to verify the psychophysical method in determining lifting capabilities. He stated that the psychophysical method was the only approach available to researchers to determine acceptable levels at which individuals perform frequent or infrequent lifting tasks. He further stated that this method identifies a "comfortable" limit, not capacity. He was critical of the supposition that the 25-minute adjustment period would not change if the subject continued to work for eight hours. This study was undertaken to investigate this assumption. He found that males lifted only 65% of the pre-experimental estimated lift weight and females lifted 84%. When the study was expanded to twelve hours, men lifted 77% and women lifted 70% of the estimated weight. It was evident that the metabolic energy expenditure decreased significantly over time as loads were reduced, but that heart rates remained fairly constant. It seemed that subjects were sensitive to their physiological state and adjusted those measures to maintain a steady state cardiovascular load. Mital stated at the conclusion of this study that the psychophysical method would overestimate the maximum acceptable weight of lift.

Karwowski and Yates (1986) studied seven female subjects that investigated psychophysical limits of a lift for four different lift frequencies. This study also recorded physiological as well as subjective measures in addition to the weight of the lift. They were interested in verifying the amount of weight selected after a 40 minute evaluation period actually reflected the amount of weight that was lifted for 8 hours. They found that after setting the weight for the four frequencies (1,3,6 and 12 lifts min^{-1}) they did not differ from the 4 hour values found for each frequency. They found that the physiological measure of oxygen consumption remained steady and unchanged over time as per the frequency (19, 25, 35 and 45.5% VO_2 max). They conclude that the psychophysical method as applied and used in their study should not be used to set lifting standards at frequencies higher than 6 lifts/min. Karwowski (1991) studied subjective perceptions of load heaviness and maximal acceptable weights of lift. This study investigated 10 female college students and used the psychophysical method to determine an acceptable 8 hour lift weight. He found that the loads selected as maximal acceptable weights for an 8 hour shift were judged more-than-moderate or heavy. He also stated that females were better capable or more realistic with respect to load heaviness perception than were males.

2.3.2 Criticisms of Psychophysics

It is clear based upon the research that the psychophysical methodology as applied to manual lifting studies has its drawbacks. It may not be the absolute research paradigm as suggested by Snook. However, Snook (1985) offered these arguments for the methodology:

(1) Psychophysics permits the realistic simulation of industrial work. Task frequency can be varied from very fast to very slow rates.
(2) Psychophysics can be used to study intermittent tasks found in industry, physiological steady state is not required.
(3) Psychophysical results are consistent with metabolic criteria of continuous or occupational work capacity.
(4) Psychophysical results are reproducible.
(5) Psychophysical results appear related to low-back pain.

Snook also criticized the psychophysical methodology:

(1) It is a subjective method that relies upon self-report from subjects.
(2) Psychophysical results vary as frequency of tasks are higher than recommended metabolic demand.
(3) Psychophysics does not appear to be sensitive to asymmetrical and torsional motions associated with the onset of low-back pain.

Snook explains criticism point 3 that psychophysical study results are higher for a floor to knuckle height lift than for a knuckle height to shoulder lift. He stated that the former lift uses larger and stronger muscles of the back and leg, but the action of bending is associated with half of the compensable cases of low-back pain. This may be dependent upon the differences in workload and low-back pain and a low -back disability (defined as a lost time from work or restricted duty). He cited Hult (1954) in an investigation of low-back pain and low-back disability in heavy and light Swedish industry. Hult found that low-back pain was experienced by 53% and 64% of workers in light and heavy occupations, respectively. However, when low-back disability was investigated, heavy occupations had twice the incident rate as did light occupations. Snook (1985) stated that at permissible workloads industry may have little impact upon low-back pain, but have a large impact upon low-back disability and compensation. Further evidence from

Mital and Fard (1986) showed that subjects accepted 8.5% less weight during asymmetrical psychophysical lifts. Subjects reported that asymmetrical lifting tasks were physically more difficult to perform. Additionally, asymmetrical lifts resulted in lower MAWLs than did symmetrical lifts.

Mital (1986) found that physiological methods and psychophysical methods did not result in similar conclusions. When using the psychophysical approach, models of heart rate and oxygen consumption accounted for only 46-53% of the experimental variance. He stated that high multiple correlations were found between the physiological responses and task variable in earlier studies, but the psychophysical approach yielded poor correlations. He stated that this may be caused by the differences between the psychophysical and physiological methodologies. If true, Mital suggests that the physiological methodology may be a more accurate reflection of fatigue while lifting maximal loads.

2.4 Physiology

In the discussion of CTD's, a review of the anatomy of the hand and wrist is appropriate. Further, anatomical issues were important in the development of the experimental apparatus. the design of the handles must be comfortable for the subject and simulate the type of handles used in power tools. Because of the importance of the anatomical mechanisms of the hand and wrist, a review of the anatomy of the hand and wrist as well as the physiology of muscles and tendons is provided in Appendix A.

2.4.1 Physiological Hand Studies

Considerable attention has been placed upon cumulative trauma disorders such as CTS and tendonitis and hand research studies have reflected this interest. Early research was focused on the clinical aspects of the amount of force a hand can generate during MVC's. Current research has focused on the changes in MVC during wrist deviation (flexion or extension) when compared to a wrist neutral posture.

Kellor, Frost, Silverberg, Iversen and Cummings (1971) sought to establish strength norms on a population of non-handicapped individuals. This information was intended as a general aid for occupational therapists and clinicians. This study investigated 252 subjects using a power hand grasp and a pinch grasp. The power grasping task used a Jamar dynamometer with the highest of two maximal exertions recorded. Subject ages ranged from 18 to 60+ years, grouped into three age categories, 18-39, 40-59 and 60+ years. The authors found that right handed exertions of men were 126.0 lbs (57.2 kg) for the youngest age group and 83.0 lbs (37.6 kg) for the oldest age group. Values recorded for females using the right hand were 64.0 lbs (29.0 kg) and 48.0 lbs (21.8 kg) for the youngest and oldest age group, respectively. The authors used this information to develop linear regression equations and clinical norms for age and gender.

Mathiowetz, Kashmar, Volland, Weber, Bowe, and Rogers (1985) sought to enhance the Kellor et al. (1971) study. They criticized Kellor et al. for a lack of standardized positioning or instructions. They also criticized the authors for not reporting test-retest reliability and interrater reliability. Mathiowetz et al. (1985)

discussed these issues and suggested a standardized procedure to assess reliability and validity of grip and pinch strength. Their study investigated 628 volunteers, ages ranged from 20 to 94 years. Standardized procedures followed for the hand strength test included the subject seated with the shoulder adducted and neutrally rotated, elbow flexed at 90°, the forearm in a neutral position and the wrist between 0° and 30° dorsiflexion and between 0° and 15° ulnar deviation. The scores of three successive trials were recorded. The authors found that grip strength peaked within the 25-39 year age group for both men and women and gradually declined thereafter (Table 1). They found the highest correlations were achieved between the right and left scores for each hand strength test. For both sexes, the right hand was stronger than the left and men were stronger than women. The authors confirmed a relationship between hand strength and age. However, unlike the Kellor et al. (1971) study which developed a linear inverse relationship, this study suggests a curvilinear relationship with hand strength peaking between 25 and 50 years and decreasing thereafter.

Table 1: Clinical Norms of Right Hand Strength (from Mathiowetz et al., 1985).

Age Group	**Men's Mean**		**Women's Mean**	
	(lbs)	**(kg)**	**(lbs)**	**(kg)**
20-39	120	54.4	74	33.6
40-59	109	49.4	64	29.0
60-70	90	40.8	53	24.0
70+	70	31.8	46	20.9
Overall (std)	104 (28.4)	47.2 (12.9)	63 (17.1)	28.8 (7.8)

Ramakrishnan, Brnhema and Hallbeck (1994) found mean grip strength to be less in 45° flexion and/or extension when compared to a neutral wrist position. They found that the values recorded in a wrist flexion and extension position were statistically similar. They also found that palm thickness and hand breadth were significant correlates of grip strength for both the dominant and non-dominant hand in all wrist positions. The study found a significant gender effect, such that females had 91% of the strength of males.

McMullin and Hallbeck (1991) and Putz-Anderson (1994) found that power grasp forces decreased 75-82% of the wrist neutral force when the wrist was extended 45°. When the wrist was flexed 45°, the forces decreased to 60-72% of the wrist neutral forces. O'Driscoll, Horii, Ness, Cahalan, Richards, and An (1992) found that grip strengths decreased to 75-80% of wrist neutral values when the wrist was in a flexion/extension angle of 10° - 15°. Putz-Anderson (1994) stated a neutral wrist position is preferable to a flexed or extended wrist because higher forces can be exerted and this position is less likely to contribute to the development of CTS. Gender had a significant impact upon grip strength with female grip strength values 60-76% of male values (Hallbeck and McMullin, 1993; McMullen and Hallbeck, 1992; McMullen and Hallbeck, 1991; Putz-Anderson, 1994).

Perez-Balke and Buchholz (1994) compared the effect of a resting wrist splint upon peak power grip strength. Using a Jamar grip strength dynamometer, the authors measured peak power grip strength with and without a wrist resting splint. The wrist resting splint was preset for 30° extension. Measurements were taken such that three measurements were recorded that were within 10% of each other. They found that grip strength decreased with the use of the splint. Females (N=44) decreased 18.52% from

340.26 N to 278.52 N and males (N=52) decreased 9.97% from 524.00 N to 470.00 N. This research suggested that the use of the wrist splint may increase the use of muscles and tendons due to the attenuated strength caused by the use of the splint. The splint may actually cause greater force to be exerted while achieving peak power grip strength.

Individuals in a work environment often work in non-neutral positions and high grip forces. Fredericks, Kattel and Fernandez (1995) investigated this in a study of twelve male subjects. Using nine wrist postures, three elbow positions and two shoulder postures, peak grip strength was recorded at various wrist, elbow and shoulder combinations. The positions included wrist combinations of neutral, 1/3 maximum (max) flexion (F), 2/3 max flexion, neutral, 1/3 max ulnar deviation (U), 2/3 max ulnar deviation; elbow angles of 90°, 135° and 180°; and shoulder postures of 0° and 20° abducted. Two or more trials of the dominant hand were collected such that the variations were limited to 10%. The authors found that the peak grip strength of 33.67 kg (74.2 lbs) was at shoulder neutral, elbow flexed at 135° and a wrist neutral position. The study showed that grip strengths for wrist posture combinations of 0 U and 2/3 F, 1/3 U and 2/3 F, 2/3 U and 1/3 F and 2/3 U and 2/3 F were significantly lower than all other wrist combinations. The authors found that as the wrist deviated, by either ulnar deviation, flexion or a combination of the two, grip strength decreased. This study found that grip strength values for all wrist combinations at an elbow angle of 135° were greater than the same values for an elbow angle of 90°.

2.4.2 Fatigue

Muscular fatigue may be defined as a decrement in the tension a muscle can exert due to the demands of work. Once maximum tension has been developed by a muscle, a reduction in strength can be observed as that muscle continues to exercise at an intensity above which steady state can be maintained (Clarke and Stull, 1969). Edwards (1978) defined fatigue as a failure to generate the required or expected force during sustained or repeated contraction. Physiologists debate whether fatigue of muscle is central (neuromuscular junction (NMJ) fatigue or excitation-contraction fatigue) or peripheral (muscle metabolite fatigue). Caldwell and Lyddan (1971) state that central fatigue was commonly viewed as a safety device to protect muscles from injury, however, Merton (1954) showed that there was no recovery of contractile strength of the muscles as long as the blood supply was occluded. He considered that fatigue was due to the alteration of the biochemistry of the muscle and would only be overcome when the muscles were supplied with fresh blood. However, Simonson (1971) stated that NMJ fatigue can be excluded.

Stephens and Taylor (1972) found evidence that during MVC, NMJ fatigue is most important during the first minute of contraction where force falls to 50% MVC, but that later, contractile element fatigue increases. They found that arterial occlusion does not affect the first phase of contraction, but in the second phase, causes force to fall to zero. Without the occlusion, they found that the force stabilizes at about 25% MVC. The authors state that NMJ fatigue is believed to be most marked in high threshold motor units, while contractile element fatigue most affects low threshold units.

Bigland-Ritchie, Jones, Hosking and Edwards (1978) showed that changes occurring proximal to the NMJ can account for up to 30% of the total force loss in well-motivated subjects during sustained contractions of the quadriceps. They state that these results demonstrate that fatigue cannot be all attributed to factors at or distal to the NMJ without ascertaining that central components are not also present. Edwards, Hill, Jones and Merton (1977) found that when the adductor pollicis muscle was fatigued after severe muscular contraction, recovery of force was largely complete after a few minutes, but not completely recovered for many hours. The long-lasting part of fatigue was not due to depletion of high-energy phosphate, but more probably the result of the impairment of the excitation-contraction coupling, according to the authors. As stated previously, they suggest that this may be the cause of the subjective feelings of weakness after exercise.

Clarke and Stull (1969) fatigued forearm flexors isotonically and isometrically at a rate of 30 contractions over 3 minutes. They found that recovery during the first minute was considerably faster following isotonic exercise. However, after that, recovery was 35% faster following isometric exercise than isotonic exercise. This would imply peripheral fatigue since restoration of blood flow would remove metabolites and replenish the fatigued muscle cells.

2.4.3 Blood Flow Occlusion

During an MVC, blood flow through the active muscle is partially or completely blocked. Simonson (1971) found that at contractions of 5%-10% MVC, blood flow to the active muscles raised to a steady state and dropped off quickly after exercise, an indication that the subjects were using aerobic processes. At 20%-30% MVC, blood flow increased steadily during exercise and further increased after the activity ceased. This showed that the muscle had a *blood flow debt* (oxygen debt) and required extra blood to replenish the muscle fibers and remove the anaerobic process metabolites. Blood flow began to be occluded at 30% MVC and was completely blocked at 70% MVC.

Humphreys and Lind (1962) found that blood flow through the forearm increased during hand-grip contractions that reached 70% MVC. They found that blood flow increased steadily through the contractions and that intramuscular pressure during contraction occluded the blood supply at 70% MVC. They also found that up to 50% MVC, the active muscle tissue temperature increased to that of the incoming arterial temperature of the blood. This could be altered by artificially occluding the blood flow to the muscles. They also found that there was little or no change in the temperature of the inactive muscles, whether or not blood flow was occluded. This suggests that the blood flow is shunted to the active muscle during muscular contractions of the hand and forearm, suggesting vasoconstriction of the inactive muscles. According to Cain (1973), occlusion of the blood supply to the arm had no noticeable effect for the first 45 sec during maximal isometric contractions of the hand. He stated that the occlusion was responsible for accelerated declines in MVC during 150 sec contractions and suggested that metabolites most likely created the feelings of fatigue and effort.

Dynamic contractions also periodically hinder the passage of blood, either partly or totally. Åstrand and Rodahl (1977) found that the workload in relation to the duration of the contraction period as well as the intervals between contractions determined the length of time that work can be endured. For frequent, dynamic, concentric contraction exercise, the energy output for a given tension is high and could be sustained for long periods of time as long as the contractions did not exceed 10% to 20% MVC. At 30% MVC, workload was reduced. They stated that the optimum ratio of work to rest was 1:2.

2.5 Psychophysical Hand Studies

As described previously, psychophysical methodologies have been used primarily in manual material handling studies. To date, few studies have applied the psychophysical paradigm to the upper limb (Marley, 1990; Kim, 1991; Abu-Ali, 1993; Wiker and Fuerlinger, 1994; Deivanayagam, 1994; Bishu, Hallbeck, King and Kennedy, 1995; Wood, Andres and Fisher, 1995; Hallbeck, Bishu and Adams, 1995; Marley and Ramalingam, 1995).

Two of the first psychophysical frequency wrist posture studies were conducted at Wichita State University (Marley, 1990 and Kim, 1991). Both studies simulated sheet metal drilling tasks using different forces and wrist postures (wrist flexion and ulnar deviation). Marley (1990) found that the maximum acceptable frequency (MAF) of grasping was significantly reduced during wrist flexion when compared to a wrist neutral posture. He found that the MAF at 1/3 of maximum flexion was 88% and the MAF for 2/3 of maximum flexion was 73% of the neutral posture MAF. He also found that the physiological measures of heart rate, systolic blood posture and EMG activity increased significantly with increased wrist flexion. Grip strength decreased significantly with wrist flexion, but there was no significant corresponding reduction in grip strength with ulnar deviation. However, a decreasing trend was noted. Kim (1991) also found that force and angle of wrist flexion had significant effects on MAF for the drilling task and that the physiological measures of heart rate, systolic blood posture and EMG activity increased significantly with wrist flexion. In addition, the Rating of Perceived Exertion (RPE) increased with wrist flexion. Kim found that wrist flexion angle had a significant effect on deltoid muscle activity, but found no significant flexor muscle activity. Both authors suggested that the psychophysical approach was valid and reliable for determining workload guidelines for hand and wrist work. However, neither study reported any reliability score.

Abu-Ali (1993) used the psychophysical method of adjustment to investigate the effect of wrist posture, force, and exertion period on acceptable levels of work cycle parameters of rest period, rest-to-work ratio, and duty cycle for females. He found a significant effect based on the level of force and the wrist angle. There was also a direction of change effect resulting from experimenter-induced rest time changes. Force, wrist angle and exertion period had significant effects on the rest period, duty cycle and rest-to-work ratio (RWR). The RWR he found increased at 50% MVC compared to 25% MVC and decreased at the 5-second exertion period compared to the 1-second exertion period. This indicated that subjects were resting for longer periods of time at the higher force level, but the ratio of rest period to the exertion period was smaller for the longer exertion period. This indicated that the rest period was not linearly proportional to the exertion time. Recovery time was the time which the subject reported feeling able to return to the task. Abu-Ali found that recovery time was 85 minutes in the worst case (50% MVC and 5-second exertion time).

Wiker and Fuerlinger (1994) and Jeng et al. (1994) studied the psychophysical aspects of pinch grasps. Wiker and Fuerlinger found that the discomfort associated with cyclic palmar pinch grasping increased with elevations in the intensity of the grasp force and its duration. Introducing more frequent breaks in cyclic exertions improved muscle endurance and reduced discomfort. The changes in the psychophysical functions suggested to the authors that the effects may be more central than peripheral. They conclude that activities using a palmar pinch grasp should not exceed 5% of the MVC. Jeng et al. (1994) studied a rapid pinch and release task. In a study using CTS patients and control subjects, they found that dominant hands performed 4% to 8% better than non-dominant hands with a greater pinch rate, a smaller overshoot force, and less time above the upper force level and below the lower force level targets. Control subjects performed 25% to 82% better than CTS subjects. The authors reported high test-retest reliability in this study.

Deivanayagam (1994) studied hand torque capabilities of people while tightening and loosening small fasteners. These fasteners included keys, wing-nuts and long and short Allen wrenches. Fourteen men and fourteen women were tested in two positions: facing the experimental setup and a transverse orientation with the subject facing 90° to the setup. The highest torque strength values occurred while using Allen wrenches and clockwise turning (men 70.96 inch-pounds, women 51.42 inch-pounds).

The weakest exertions occurred with a small key in the facing orientation and a clockwise direction. This orientation required a grip with the thumb and the lateral side of the index finger, similar to a lateral pinch grip. The pain experienced along the sides of the first and second phalanges of the index finger limited any attempt to make use of stronger muscles of the arm. There was a strong gender effect. The transverse position allowed the subjects to make use of stronger muscles and joint action and thus produced higher torque strengths than did the facing orientation.

Bishu et al. (1995) investigated the reliability of MVC as a measure and the recovery time required from producing a 100% MVC effort. Fifteen males provided eight MVC efforts over eight days, excluding weekends. Using a proportion deviation computed as $((MAX_{absolute} - MAX_{daily})/MAX_{absolute})$, they found an overall average deviation of 0.10, and considerable variation in deviation among subjects. The average coefficient of variation was around 8% with the variation ranging from 4.5% to 12.5%. The study also recorded discomfort frequency and discomfort severity up to 240 minutes after the MVC efforts. The recovery curve of both indices became asymptotic after 120 minutes.

Hallbeck et al. (1995) reported the effect of wrist posture upon fatigue during percent MVC efforts. The effect of gender, wrist position and percent MVC upon the dependent measure of time to fatigue was studied. This study investigated 30 subjects (15 male and 15 female), five wrist postures (maximal and half-maximal postures for flexion and extension plus neutral) and three MVC percentages (40%, 60% and 80%). The authors found that gender was not a significant main effect. However, wrist position and percent MVC were significant factors. The posture with the shortest endurance time was the wrist neutral position. This position was significantly lower than all other wrist positions. The authors speculated that blood occlusion at this position caused a lowering of the endurance times. The neutral position generated significantly higher forces than any other position.

Wood et al. (1995) examined the effect of fatigue of twenty college age women during one-hour isometric gripping sessions that simulated a work-rest pattern. The authors used three work-rest patterns (high, medium and low) where the duty cycle was adjusted to provide for three equivalent patterns. The subjects repeated submaximal efforts for nine minutes and performed a maximal effort for six seconds. Thus, seven maximal efforts were recorded in an hour. Using Borg's 10-point RPE scale force condition and trial were significant. As the trial number increased, the peak grip force decreased and the reported RPE value increased. The RPE values at high, medium and low force values were significantly different, with medium force yielding the lowest RPE values and low force yielding the highest RPE values. An attempt was made to isolate the location of the pain in the hand and forearm. Subjects reported more fatigue or pain in the hand than in the forearm. The authors did not ask the subjects what they thought caused the pain, but postulated that the pressure of the handles on the palms may have caused the pain.

The psychophysical method of adjustment was used by Marley and Ramalingam (1995) to examine acceptable hand forces under dynamic grasping conditions. Twelve males were used to investigate a grasping task for a 25-minute psychophysical adjustment session. The study examined four combinations of grasp frequency and velocity of tool activation. These included grasp frequencies of 1 and 6 grasps per minute and linear handle velocities of 7.6 cm/sec and 15.2 cm/sec (3 and 6 in/sec, respectively). Initial resistance for each session was set at magnitudes of "relatively low" and "relatively high," with each subject adjusting the resistance force so as to apply the maximum force level that could be performed in an 8-hour day without experiencing discomfort or fatigue. The data showed that both grasp frequency and tool handle velocity were significant factors. When subjects were required to perform frequent grasps, the subjects selected less resistance than the value selected at the lower frequency. Less resistance was also selected at the lower handle velocity than at the higher handle velocity. The authors claimed that this study was the first time that the psychophysical method of adjustment was applied to a dynamic hand grasping task and that the method appeared to provide valid results based upon general agreement with some published guidelines (Bystrom and Fransson-Hall, 1994; Kroemer, Kroemer, and Kroemer-Elbert, 1994).

2.6 Biomechanical Studies

The psychophysical method and biomechanical modeling are two competing methodologies attempting to describe the nature of CTD's and the limits of task parameters that may cause CTD development. Biomechanical models attempt to describe the underlying behavior of the hand and wrist and predict the response to stressors applied to the hand when performing typical work tasks. However, a review of the biomechanical models showed that to date they are not sufficient to define appropriate workplace limits. Biomechanical models require too many assumptions, they do not model the wrist and hand adequately, and the data do not indicate appropriate safety limits. The psychophysical methodology is the most attractive research method to date to study workplace limits. The biomechanical models reviewed for this study are presented in Appendix B.

The extrinsic finger flexor muscles, including the flexor digitorum profundus and superficialis and the flexor policus longus are the major force-producing muscles during exertion of the hand (Armstrong and Chaffin, 1979; Thompson, 1985; Tyldesley and Grieve, 1989). These muscles have an insertion in the forearm and are connected to the fingers with tendons that pass through the carpal tunnel. Deviation of the wrist from a neutral position (e.g., wrist flexion or a pinching grasp) causes the flexor tendons and the median nerve to bend around the flexor retinaculum (Armstrong and Chaffin, 1979; Smith et al., 1977). LeVeau (1974) and Armstrong and Chaffin (1979) describe the movement of the tendon as that of a belt around a pulley. This movement can be described by the equation:;

$$F_N = \frac{F_T}{R} \qquad \textbf{(2-1)}$$

where $\boldsymbol{F_N}$ is the normal supporting force per unit arc length (N/mm),
$\boldsymbol{F_T}$ is the average tendon force in tension (N), and
$\boldsymbol{R}$ is the radius of tendon curvature around the supporting tissues.

Phalen (1966) suggested that the force between the extrinsic finger flexor tendons and the trochlea in a flexed wrist is a contributing factor to carpal tunnel syndrome.

Additionally, according to Phalen, the synovial membranes of the radial and ulnar bursas that surround the extrinsic finger flexor tendons are compressed in flexed and extended wrists. Repeated compression causes synovial inflammation and swelling, which can lead to compression of the median nerve.

Smith et al. (1977), using cadaver forearms and replacing the median nerve with transducers, found that pressures during tendon loading were greater with a flexed wrist than when neutral or in extension. They also found that the pressures increase with increasing flexion. The study found that pressures caused by the flexor digitorum profundus tendon in digits 2 or 3 during wrist flexion were significantly greater than those caused by other tendon loadings. They concluded that the median nerve was vulnerable to compression in the carpal tunnel during contractions of the flexor tendons of the flexor digitorum profundus 2 and 3 and the flexor retinaculum.

Rydevik, Lundborg, and Bagge (1991) showed that carpal tunnel pressures of 20-30 mm Hg reduced venus blood flow within the carpal tunnel. Carpal tunnel pressures were greater using a standard computer keyboard than a split keyboard (Sommerich, 1994). Sommerich found mean pressures of 36.9, 0.0, 3.7 and 2.1 mm Hg in four female subjects using a typical keyboard while typing. The same subjects recorded mean pressures of 7.4, 0.0, 0.1 and 4.5 mm Hg while using a split keyboard (neutral wrist posture). Internal pressures within the carpal tunnel were found to be higher in patients with CTD than in patients with unaffected wrists (Luchetti, Schoenhuber, DeCicco, Alfarno, Deluca, and Landi, 1989). This suggests that inflammation does place mechanical pressure upon the median nerve and tendons passing through the carpal tunnel as suggested by Phalen (1966), Armstrong and Chaffin (1979), and Smith et al. (1977).

2.7 Occupational and Personal Factors

Research has found that there are several occupational and personal factors that may increase the risk of CTD. Personal factors include age, female gender, use of birth controls pills, pregnancy, menopause, obesity, smoking, alcoholism and prior trauma to the wrist. In addition, chronic diseases such as rheumatoid arthritis and diabetes mellitus may cause an increase in the susceptibility of CTD (Gordon et al. 1992; Stevens et al. 1992; Crumpton and Congleton, 1994). Occupational factors include forceful exertion of the hand and repetitive use of the hand, work while the wrist is flexed or in ulnar deviation, static muscle load, and vibration (Browne et al., 1984; Chatterjee, 1987; Hymovich and Lindholm, 1966).

2.8 Cross Modality Matching

Relying upon human subjects to rate acceptable levels of work has drawbacks such that experience, gender, subjective assessment and length of time the work is performed can affect the results generated by this methodology. The use of the psychophysical methodology requires that several modes of data collection be used in order to better evaluate the data obtained using this method. There are several alternatives that may prove useful in setting physical performance limits on their own or in conjunction with the psychophysical method. Of these alternatives, cross modality matching (CMM) has been widely used.

Cross modality matching (CMM) has been used with the psychophysical method since its development by Snook and Irvine (1967). The importance of CMM is that it can be an evaluation of environmental and work variables. Popular forms of CMM have been magnitude estimation (where the subject gives a numerical sense judgement upon a sense modality) and the Rating of Perceived Exertion (RPE). Kvålseth (1980) used magnitude estimation in a study of Norwegian ergonomics acceptance. He noted that the system, where people were given a booklet of factors and asked to rate each factor, was very simple. He cautioned that the subjects should have no limit of numbers to use in the rating.

Borg used the RPE form of category rating to judge perceived exertions (Pepermans and Corlett, 1983). Borg used a modified Likert type scale with verbal anchors to record subjective data. Borg's scale, a type of numerical rating scale is generally a 5-point or 7-point scale with verbal anchors to help focus the subjects. In the rating scale, no assumption is made regarding the distance between different categories. They are considered on an ordinal level (Gambercale, 1985). The RPE has proven popular because it is a linear function of workload. Gambercale (1985) states the RPE could be used as a complement to circulatory responses.

Continuous line scales have been used successfully as a subjective measure indicator. Scales have been constructed that are from 10 to 12.7 cm in length. Price and Hennigan (1975) used this type of scale with four anchor points to obtain a rating of degree of comfort in heat stress experiments. Subjects were asked to place an "X" at the point along the line corresponding to perceived warmth. Swensen (1987, 1992) used a similar scale to obtain subjective measures of slipperiness. A continuous scale with three anchor points was used. The subjects were asked to strike through the line at the point that represented the perceived slipperiness level. He found that experienced subjects could estimate slipperiness with a high degree of correlation to objective measurements.

Subjects in control of the stimulus present problems in the control of the experiment. Problems can arise from differences between subjects and their level of motivation. Problems also arise when comparing the responses of different subjects, because each subject uses his own reference system. It is important to keep the frames of reference the same for all subjects. Finally, range effects can bias the subjective data. To avoid range effects, one might have the subjects rate only one stimulus for the experiment, provide a response scale with bounds as well as with middle categories, or use an unlimited range (Pepermans and Corlett, 1983).

CHAPTER 3

EXPERIMENTAL METHODOLOGY

The research reported in this dissertation was concerned with: (1) investigating the test-retest reliability of psychophysical evaluations of subjects using the psychophysical method of adjustment on a repetitive power hand grasping task, (2) verifying a methodology for studying and quantifying the exposure limits to CTD occupational risk factors for hand-wrist repetitive tasks (Abu-Ali, 1993), and (3) evaluating the effect of exertion time on psychophysically determined flexion grasping frequency and rest time. This chapter describes the task, subjects, experimental variables, experimental design, and equipment required to complete this study.

3.1 Reliability

When performing scientific research, the *reliability* and *validity* of the collected data are important issues. Toothaker (1986) defined reliability as the ability to obtain the same value when measurements are made repeatedly. The values obtained from repeated measurements of the same subject using the same measure should be tightly clustered. Validity as described by Toothaker (1986) describes the accuracy of the measurement process. One asks: Are the obtained scores an accurate reflection of the variable measured? High reliability would indicate that the data were stable or that the measurements were dependable over a period of time. In this context, reliability is synonymous with dependability, consistency, and stability; validity is synonymous with relevance, predictive value and discrimination value (Guilford, 1954). In general, reliability refers to the ability to obtain similar values of data over multiple times that a task is performed.

3.1.1 The Reliability Concept

The concept of reliability is concerned with the consistency of scores obtained by the same individual when re-examined under the same conditions. It is known that scores are fallible, hence the obtained test score may be expressed as follows:

$$X_t = X_\infty + X_e \qquad \textbf{(3-1)}$$

where X_t = obtained test score,
X_∞ = true component, and
X_e = error component (Guilford, 1954).

Guilford (1954) stated that equation (3-1) relies on the following assumptions:

- Assumption I: $M_e = 0$. The mean of the errors equals zero. The errors are just as likely to be positive or negative with comparable magnitude.
- Assumption II: $r_{\infty e} = 0$. There is zero correlation between the true score and the error score. There is no tendency for individuals with high true scores to have greater positive or negative error scores.
- Assumption III: $r_{e_1 e_2} = 0$. The error scores of test 1 and test 2 have zero correlation.

Given the three assumptions, reliability can be defined as the ratio of the true variance to the total variance of the obtained test scores. If one assumes that the sum of the unweighted measures is equal to the sum of the variances, then by definition, the variances are:

$$\sigma_t^2 = \sigma_\infty^2 + \sigma_e^2 \tag{3-2}$$

where σ_t^2 = variance of the obtained test score,
σ_∞^2 = variance of the true component, and
σ_e^2 = variance of the error component.

But to obtain the definition of reliability from equation (3-2), one must form a ratio such that:

$$\frac{\sigma_\infty^2}{\sigma_t^2} + \frac{\sigma_e^2}{\sigma_t^2} = \frac{\sigma_t^2}{\sigma_t^2} \Rightarrow \frac{\sigma_\infty^2}{\sigma_t^2} + \frac{\sigma_e^2}{\sigma_t^2} = 1.0\,. \tag{3-3}$$

From the previous equation, we can define the general form of the coefficient of reliability as r_{tt}. This is defined as:

$$r_{tt} = \frac{\sigma_\infty^2}{\sigma_t^2} \Rightarrow r_{tt} = 1 - \frac{\sigma_e^2}{\sigma_t^2} \tag{3-4}$$

where r_{tt} = coefficient of reliability. Reliability is measured by the ratio of true variance to total variance, or by 1 minus the ratio of error variance to the total variance. It is assumed that the mean of the errors = 0.0 and that $\sigma_t > \sigma_\infty$ is always true (Guilford and Fruchter, 1973).

Lord and Novick (1968) described r_{tt} as the *coefficient of precision*. They stated that the only source contributing to the error variance is the unreliability of the measurement procedure. This is the variance ratio that would apply given no practice, fatigue, memory or any other factor affecting the repeated measurements. The authors stated that this coefficient represents the extent that the test unreliability is due solely to the inadequacies of the test form and testing procedure, not the extent to which changes are due to people over time. In other words, by controlling the experimental conditions (e.g., the instructions given, the environment of the laboratory, or time of day), the experimenter is reducing the error variance and making the test scores more reliable.

There are many correlation coefficients that may by computed. The most common of these is the Pearson Product-Moment Correlation Coefficient. This correlation coefficient takes into account the individual's position in the group and the amount of deviation above and below the group mean. The Pearson Product-Moment correlation is of the form:

$$r_{xy} = \frac{\sum xy}{N\sigma_x \sigma_y} \tag{3-5}$$

where x is the deviation of the score of X from the mean of X,
y is the deviation of the score of Y from the mean of Y,
xy is the cross product of the deviations of x and y,
N is the number of cases or subjects, and
σ_x and σ_y are the standard deviations of x and y, respectively.

3.1.2 Approaches to Estimate Reliability

Reliability of a test instrument refers to the consistency of scores obtained by the same individuals when re-examined with the same test on different occasions. Test reliability indicates the extent to which individual test scores may be attributable to *true* differences in the characteristics under consideration and the extent to which they are attributable to chance errors. Thus, reliability for any set of measurements is defined as the proportion of their variance (σ_t^2) attributable to the true variance (σ_∞^2).

There are at least three types of approaches to estimate reliability. Those are:

1. *Split-half* or internal consistency reliability (coefficient of consistency),
2. *Alternate-forms* or parallel-forms reliability (coefficient of equivalence) and,
3. *Test-retest* reliability (coefficient of stability).

The correlation coefficient (r) describes the degree of correspondence or relationship between two sets of data. A zero correlation ($r = 0.0$) indicates a complete absence of relationship, while a correlation of 1.0 indicates a perfect positive relationship and a correlation of -1.0 indicates a perfect negative correlation (Guilford and Fruchter, 1973, Guilford, 1954). A perfectly reliable measurement is one that is completely free from error. The test instrument given or applied to the same individual should yield the same value over time, provided the item measured has not changed.

3.1.3 Test - Retest Reliability

The most obvious method to compute reliability of test scores is to repeat the identical test on a second occasion (Anastasi, 1968; Cronbach, 1960). The reliability coefficient in this case is the correlation between the scores obtained by the same persons on the two administrations of the same test. The key aspect to this approach is stability of the measure over time. The error variance corresponds to the random fluctuations of performance from one test to another. The variations may also reflect conditions of the subjects, such as illness, fatigue or worry. Test-retest reliability shows the extent to which the measure can be generalized over different occasions, the higher the reliability, the less susceptible the measure is to random daily changes in the condition of the subject or of the testing environment (Anastasi, 1968). A high reliability under this procedure indicates that subjects remained stable in their performance. A low reliability coefficient indicates that subject performance was transient and fluctuated over time, or that the test was influenced by other things that fluctuate and was not controlled by the experimenter (Guilford, 1954). Anastasi (1968) and Guilford and Fruchter (1973) state that the interval between tests should be specified because the test-retest correlation decreases as the interval length increases. Anastasi (1968) stated that motor skill tests are not appreciably affected by repetition and lend themselves to the test-retest technique.

3.2 Application to Psychophysical Methodology

Psychophysics is the study of the relationship between stimulus and sensation. This relationship is used when a person's interpretation of the physical senses is required. Psychophysical methodologies have been used extensively in human factors engineering research to study manual material handling tasks. This methodology has also been used to study hand grasping activities (Abu-Ali, 1993; Kim, 1991; Marley, 1990). Because of the subjective nature of the data, reliability is a critical issue.

In order to address the problem of reliability of a test measure, the experimenter must develop a data collection procedure that incorporates a measure of stability. This can be accomplished by using a test-retest procedure. A test-retest correlation is obtained by administering the same test on separate occasions. This coefficient indicates the stability of a performance measure over a period of time. Hence, it is called the coefficient of stability. However, variation among trials for the same person is not addressed (Cronbach, 1960). The error variance corresponds to random fluctuations of performance from one test session to another. By controlling for most distractors (e.g., room environment, noise, lighting levels, instructions, etc.), most of the variations may result from changes due to the subject (i.e., emotions, fatigue, etc.) (Anastasi, 1968). This type of correlation would show that a particular test measure (e.g., a psychophysical measure of hand grasping strength, or the maximum acceptable weight of lift for whole body lifting) actually measures the same concept across different trials and does not measure items that are not of interest. A high test-retest reliability demonstrates the extent to which the scores may be generalized across different test administrations. Thus, the higher the reliability, the less likely the test scores from the test measure are affected by random daily changes in the subjects or the test environment (Anastasi, 1968).

3.3 Carpal Tunnel Syndrome Identification

Phalen (1966) described a test that could be used to diagnose CTS. The procedure involves a wrist flexion test that requires the patient to hold the arms vertically, allowing the hands to drop into complete flexion with the fingers extended loosely. This position is held for one minute. In this position, the median nerve is squeezed between the proximal edge of the transverse carpal ligament and the adjacent flexor tendons and radius (Phalen, 1966). This procedure increases the hydrostatic pressure and the mechanical pressure on the median nerve. Phalen stated that when the median nerve is already somewhat compressed, further compression with this technique causes an almost immediate aggravation to the median nerve. Phalen described this technique as being 74% sensitive. Sensitivity is described as the capability of a test to detect CTS in those patients who have CTS. Another measure found in the literature is called specificity. Specificity is the capability of a test to exclude those people who do not have CTS (ability to exclude false positive diagnosis).

Another type of nerve compression test that has been used to screen subjects was described by Durkan (1991), Williams, McKinnon, Novak, McCabe, and Kelly (1992), and Dr. Richard Ruffin [personal communication, May 3, 1995]. This method is a simple nerve compression test where the clinician mechanically compresses the carpal canal with the thumbs. Both thumbs are placed directly over the palmar side of the carpal canal and pressure is applied for up to 30 seconds. Ruffin stated that this quickly shows if the patient tests positive for CTS. As with Phalen's test, this test causes increased aggravation to the median nerve in the carpal canal. Williams et al. (1992) compared the nerve compression technique to the traditional Phalen's test and Tinel's test. They studied 30 CTS patients and 30 unaffected control patients using two values of compression, low (100 mm Hg) and high (150 mm Hg). A bulb attached to a sphygmomanometer was used measure the compressive pressures. Table 2 summarizes the sensitivity and specificity scores of the three tests.

Table 2: Summary Scores (from Williams et al., 1992).

Test	Sensitivity	Specificity	Positive Predictive Value
Compression	100	97	100
Phalen's	88	100	87
Tinel's	67	100	50

The authors described positive predictive value as the probability that a patient has CTS given a positive provocative test. They stated that the values found for Phalen's and Tinel's test were typical of those found by other studies. They found that the nerve compression test is a sensitive indication of median nerve compression with a mean time to symptoms of 9 seconds (high) and 19 seconds (low) as compared to 30 seconds for Phalen's test. Because of the high predictive value of the nerve compression test and Phalen's test, both were used in this study to medically screen subjects for carpal tunnel syndrome.

3.4 Pilot Study

Two pilot studies were conducted to address three questions. The major pilot study addressed two questions. The first question was to determine if time between test sessions had any effect on the psychophysically determined rest time during power hand grasp test sessions. The second question of interest was to determine if there was any difference in subject-derived rest times recorded at 10 and 20 minutes during the experimental session. A second pilot study was conducted to determine if there was any difference between the subject-derived rest times recorded at 20 minutes and 40 minutes into the test session. The evaluation of these questions was accomplished by using analysis of variance to determine the statistical significance of the parameters of interest. Covariate analysis was conducted involving anthropometric measures to test their effect upon the overall statistical model.

3.4.1 Subjects

Nine female subjects were recruited to participate in the first pilot study. Females have been identified as more susceptible to CTS than males (Armstrong and Chaffin, 1979; Crumpton and Congleton, 1994). The mean age for this group was 26.7 years. All subjects were right-handed and were pre-screened for previous repetitive motion injury and tested on site using carpal compression and a modified Phalen's test. All subjects tested negative and were cleared to participate in the pilot study. Upon clearing the pre-screening process, anthropometric measures and a baseline maximal voluntary contraction (MVC) of the right hand were recorded. Anthropometric measurements included hand grasp size, hand length, hand breadth, wrist circumference, and wrist thickness. These were measured as described in the NASA anthropometric tables (NASA, 1978). The MVC values served as the baseline from which the individual load of 30% MVC was determined. Subjects spent about 45 minutes per test session performing the required tasks and collecting pre- and post-session MVC data.

3.4.2 Task

The subjects were required to perform a simulated industrial hand grasping task. A dynamic hand dynamometer was fabricated for this purpose. The device allowed the simulation of movements required to operate a typical pneumatic or electric power tool. The subject was seated in a subject restraint chair. `A cast was used to position the upper arm and forearm at 135° at the elbow. The cast was anchored to the chair armrest with velcro so that the hand comfortably grasped the hand dynamometer handles. The dynamic hand dynamometer allowed one handle to move, simulating the motion required to activate a tool trigger lever or trigger.

3.4.3 Experimental Design

3.4.3.1 Independent Variables

The independent variables in the pilot study were Session, Elapsed Time, and the Starting Rest Interval. The levels of Session were the intervals between each subsequent experimental session. The time intervals between subsequent sessions were designed to test whether breaks between test sessions had any effect upon the mean rest time of the subjects. Table 3 depicts the time intervals between experimental sessions. Test sessions were conducted on Days 1, 2, 9, and 23, yielding intervals of 1, 7, and 14 days between sessions. The second question of interest was whether subjects could achieve a stable rest time in a 10-minute period or whether a 20-minute period was needed. Rest times were recorded at the end of 10 minutes and 20 minutes elapsed session time.

Table 3: Time Lapse between Test Sessions.

Session	Time lapse from last test session (days)
1	0
2	1
3	7
4	14

The starting rest interval was also an independent variable in the pilot study. Two starting rest period times were selected, two and nine seconds. These values were selected based upon the subject-determined rest times from Abu-Ali (1993). These were counterbalanced across subjects for the four sessions.

3.4.3.2 Dependent Variables

The dependent variables recorded were the pre- and post-session MVC values and the subject-determined rest times. MVC values were recorded during the training session to determine the stability of the values over time. To determine the initial MVC value, subjects performed five maximal force grasps. Two minutes elapsed between each exertion. The first two measurements were discarded and the last three were averaged to determine an average MVC value from which the initial load value for each session was set [from M. Bemben, personal communication, March 1996]. Immediately before and after each experimental session, three MVC measurements were recorded. The three pre-session measurements were averaged as were the three post-session measurements to provide single pre- and post-session MVC values for each subject.

Subject-determined rest times between successive hand grip exertions were continuously recorded during the experiment. The subject had an opportunity every two minutes to make adjustments to the rest time. The subject was able to add or subtract rest time by pressing the appropriate button on the rest time control box. The subject had five seconds to make any adjustment during the adjustment period. After each session, the data were reduced and the rest times at 10 minutes and 20 minutes elapsed session time were recovered.

3.4.3.3 Control Variables

The subject extertion time was fixed at five seconds and the force was held constant at 30% MVC. Additional control variables included vibration (none), handedness (right), pregnancy (none), torque (none), and previous CTD injury (no). Temperature, humidity and illumination were maintained at a relatively constant level using a climate-controlled laboratory space of the University of Oklahoma, School of Industrial Engineering.

3.4.3.4 Covariates

The recorded anthropometric measurements were analyzed as covariates. Those measurements were hand length, hand breadth, hand thickness, wrist circumference, wrist thickness and wrist breadth.

3.4.3.5 Statistical Model

Two statistical models were used to analyze the data recorded during the pilot study. The first model was for the MVC analysis:

$$Y_{ijkl} = \mu + T_i + O_j + B_k + S(B)_{l(k)} + TO_{ij} + TB_{ik} + TS(B)_{il(k)} + OB_{jk}$$
$$+ OS(B)_{jl(k)} + TOB_{ijk} + TOS(B)_{ijl(k)} + \varepsilon_{ijkl}$$

where Y_{ijkl} = MVC value for the ith session, the jth observation, the kth level of oral contraception use and the lth subject,

μ = overall main effect,
T_i = effect due to session, $i = 1, 2, 3, 4$,
O_j = effect due to pre- and post-session observation, $j = 1, 2$,
B_k = effect due to oral contraception use, $k = 1, 2$,
S_l = subjects, $j = 1, ..., 9$, and
ε_{ijkl} = random error.

The statistical model for the major measure of rest time was:

$$Y_{ijkl} = \mu + T_i + E_j + B_k + S(B)_{l(k)} + TE_{ij} + TB_{ik} + TS(B)_{il(k)} + EB_{jk}$$
$$+ ES(B)_{jl(k)} + TEB_{ijk} + TES(B)_{ijl(k)} + \varepsilon_{ijkl}$$

where Y_{ijkl} = rest interval for the ith session, the jth elapsed time, the kth oral contraception use and the lth subject,

μ = overall main effect,
T_i = effect due to session, $i = 1, 2, 3, 4$,
E_j = effect due to elapsed time, $j = 1, 2$,
B_k = effect due to oral contraception use, $k = 1, 2$,
S_l = subjects, $j = 1, ..., 9$, and
ε_{ijkl} = random error.

A secondary analysis of the main pilot study data used the following model:

$$Y_{ijkl} = \mu + E_i + C_j + B_k + S(B)_{l(k)} + EC_{ij} + EB_{ik} + ES(B)_{il(k)} + CB_{jk}$$
$$+ CS(B)_{jl(k)} + ECB_{ijk} + ECS(B)_{ijl(k)} + \varepsilon_{ijkl}$$

where; Y_{ijkl} = rest interval for the ith elapsed time, the jth initial rest interval, the kth oral contraception use and the lth subject,

μ = overall main effect,
E_i = effect due to elapsed time, $i = 1, 2, 3, 4$,
C_j = effect due to the initial rest interval, $j = 1, 2$,
B_k = effect due to oral contraception use, $k = 1, 2$,
S_l = subjects, $j = 1, ..., 9$, and
ε_{ijkl} = random error.

3.4.4 Experimental Procedure

3.4.4.1 Equipment

Equipment used in the pilot study included the following:

Zenith 486, 25 MHz computer with keyboard,
VGA monitor,
Dash 8 analog-to-digital converter board,
Load Cell (200 lbs),
Thompson Industries linear bearing and shaft,
Metrabyte STA-08PGA screw terminal accessory box,
Metrabyte PC6042 mechanical switch,
Experimenter built light switch box (Radio Shack large experimental box),

Experimenter built rest time adjustment box (Radio Shack small experimental box),
Experimenter built dynamic hand dynamometer,
restraint chair with adjustable arm rest, and
BASIC software.

The dynamic hand dynamometer was fabricated to record MVC values and simulate industrial tasks. The unit is designed around a rigid box structure that houses the grasping handles, linear bearings and rods that allow dynamic grasps. The unit has one fixed handle (proximal to the wrist) and one movable handle (distal). The movable handle is a small box structure with linear bearings attached. The linear bearings allow for smooth movement of the handle. This simulated the movement of a trigger lever on a power tool typically found in industry. The movable handle had a load cell attached which allowed for a quick change from MVC measurements to the experimental task. The unit had a hole drilled into the outer box structure through which could pass a threaded rod or cable. The threaded rod was used when MVC was measured. When the rod was tightened with a wing nut, it created a rigid structure with which MVC measurements could be taken. When the experimental task was configured, the threaded rod was removed, a screw eye was screwed into the load cell and a cable attached to the screw eye. The cable passed through the hole and around a pulley attached to the box structure. The other end of the cable was attached to a plate. This plate allowed slotted weights to be attached to make up the correct amount of weight to match the subject's 30% MVC value. The weight system was suspended above the laboratory floor. The weights pulled the handle against a stop attached to the frame of the unit.

Attached to the movable handle was a flange that was offset to rest just above the stop plate. The stop plate was configured with contact switches that recorded the position of the handle. Three switches were set on the stop plate to record the "resting state", the "tool activation" state and an "out-of-bounds" state. The distance between the resting and tool activation positions was 0.64 cm (0.25 inch). The out-of-bounds switch was provided to prevent the subjects from squeezing too hard and exerting more force than required to move the handles the required distance (see Figure 1). The stop plate was attached to the unit through slots that allowed adjustment of the plate. A scale was affixed to the bottom frame of the unit and pointers were attached to each handle. This allowed the handle spacing to be accurately and repeatedly set for each individual subject.

The stop plate was moved the appropriate direction to position the handle pointer at the proper hand grasp dimension. Since the contact switches were positioned accurately on the stop plate, the only adjustment required for each subject was to move the stop plate to the proper location. After adjustment, the stop plate was tightened to the unit and securely held the handle in the resting position. The unit was equipped with outriggers to provide additional support. The outriggers had casters to allow for movement of the entire dynamometer.

The unit was attached to the subject restraint chair by drawer glides. These glides allowed the entire unit to move back and forth freely to accommodate each subject. The free movement of the unit prevented the subject from generating more force than what was required to move the handles. The right arm of the subject was placed into a fiberglass cast molded to hold the upper and lower arm at a 135° angle at the elbow. The subject's arm was secured in the cast by velcro strips and the entire cast was then placed on the armrest. The velcro strip on the cast prevented the subject from moving the arm during the experiment (see Figure 2).

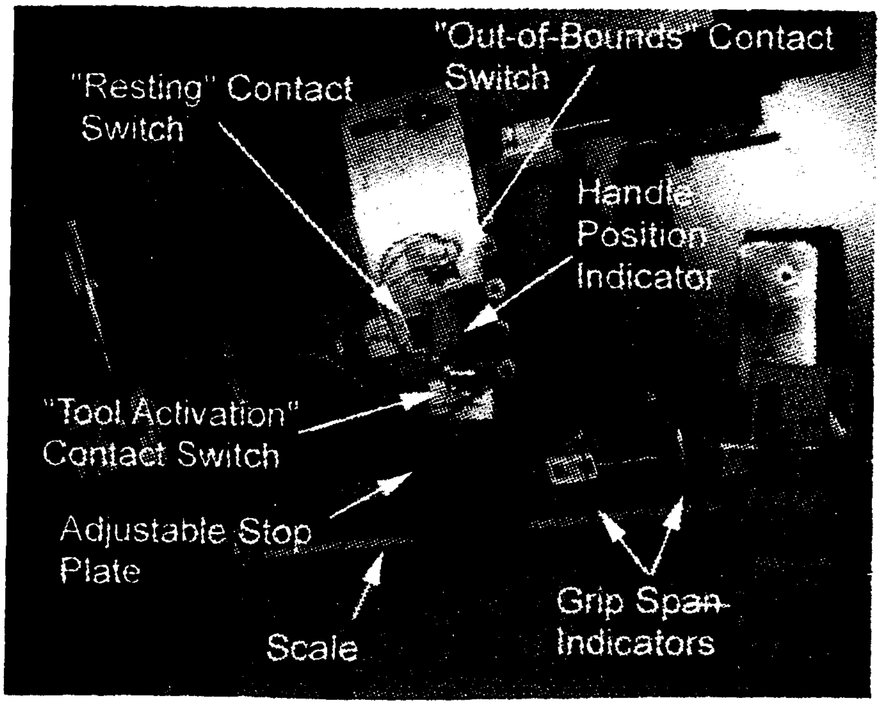


Figure 1: Handle Position Instrumentation.

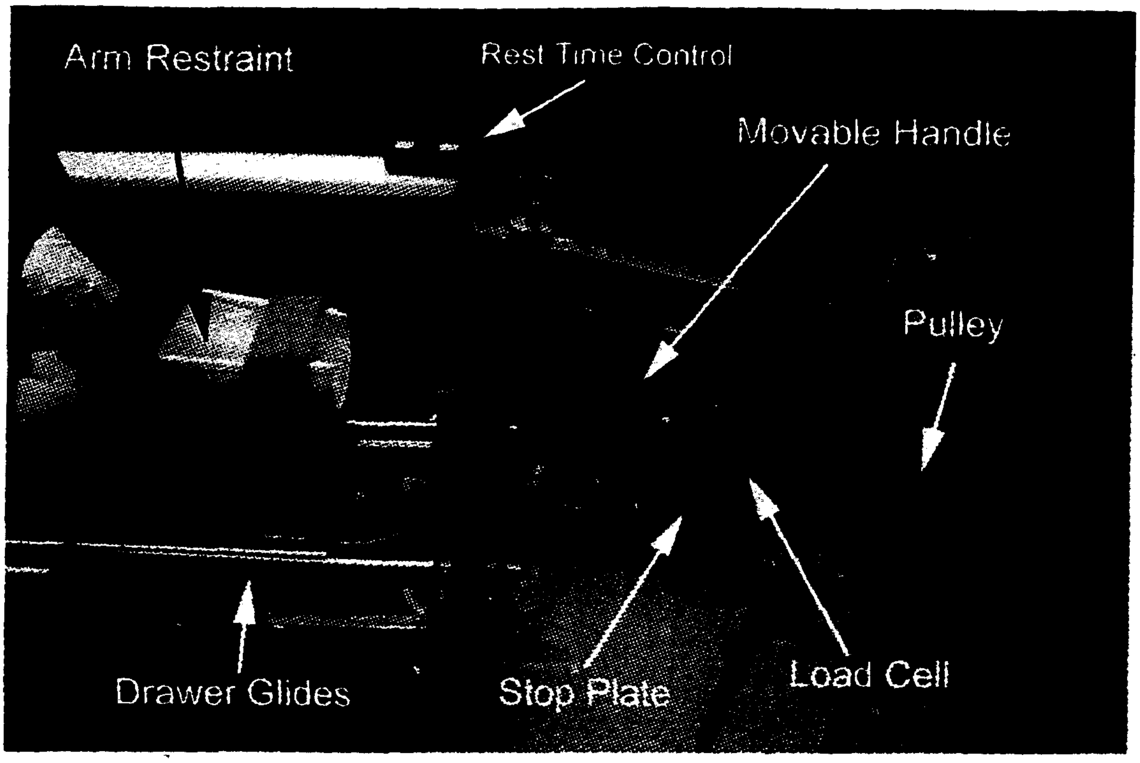


Figure 2: Experimental Apparatus.

All electrical components were connected through screw terminals to the Dash-8 analog-to-digital converter board installed in a Zenith 486, 25 MHz computer. A program was written in BASIC to acquire data and control the experiment. Based upon the position of the contact switches and the signal sent to the computer, lights were illuminated on a subject cue box that was used to prompt the subject during the experimental session. A subject response box was fabricated with two pushbuttons and wired directly to the computer keyboard to provide input to the program to record subject changes in the rest interval. The response box was attached by velcro to the left arm rest of the subject's chair.

3.4.4.2 Pilot Study Routine

The first session or training session began with the subject completing a medical screening questionnaire (Appendix C) and an informed consent form (Appendix D). Anthropometric data of the hand and wrist were then recorded. Hand grip diameter was recorded using the Functional Hand Anthropomometer (Lafayette Instruments). Other hand dimensions were collected by measuring with calipers and measuring tape. The subject was then fitted with the arm restraint cast and seated in the subject chair. The hand dynamometer was adjusted to the subject's hand grip measurement. The load cell was calibrated and data collected using LABTECH Notebook software. Five MVC measurements were taken with a two-minute rest between exertions. After completion of the MVC measurements, the subject was allowed to rest for five minutes. During this time the dynamometer was converted for the dynamic hand grasping task.

The training session was exactly the same as an experimental session, except for a session length of 10 minutes instead of 20 minutes which was used in the experimental pilot study session. The subject was instructed to maximize the number of hand grasp cycles, while minimizing any discomfort (Appendix E). Subjects were instructed to imagine they were on an assembly line being paid a piece-rate. They were instructed to adjust the rest interval such that they moved an assembly line as fast as possible without incurring any discomfort. The use of the rest time control box was described to the subjects. The subject was familiarized with the lighted cue box. The cue box presented the subject with the action cues required during the session. The cue box was designed to illuminate a specific cue word and colored panel to coincide with the action required of the subject. A series of contact switches was mounted on the apparatus to monitor the handle position and to control illumination of the cue box. The initial position was the condition where all contact switches were in contact with the handle. The control cue box actions and color cues are as found in Table 4. The cue box was designed such that a light illuminated a cue word copied onto a clear transparency covered with the appropriately colored gel. Velum was placed over this to prevent the subject from reading the cue words before illumination. This system allowed the proper cue word to be seen during the session and prevented miscues due to cue word confusion. The cover of the cue box held the gel and velum in place.

Table 4: Subject Cue Box.

Action Cue	Panel Color
SQUEEZE	Green
GOOD	Green
TOO MUCH	Red
ADJUST	Blue

At the beginning of the work cycle, a tone sounded and the SQUEEZE panel was illuminated. This cued the subject to squeeze the handle. When the subject moved the handle 0.64 cm (0.25 inches), the GOOD light illuminated. This informed the subject to hold the position for the five-second work period (see Figures 3 and 4). The travel distance for the handle was determined from typical distances that a trigger or trigger lever must move to activate a tool. If the subject moved the handle 0.64 cm (0.25 inches) past the required distance, the cue TOO MUCH illuminated and a warning tone sounded. The tone and cue continued until the subject released the grip slightly.

This caused the handle to recontact the out-of-bounds contact switch and extinguished the TOO MUCH light and tone. When the five-second exertion period ended, the SQUEEZE light extinguished, leaving the GOOD light illuminated until the subject released the grasp and the handle returned to the resting position. All lights were then extinguished and the rest period began, after which the cycle repeated. Every two minutes (and following the completion of the current exertion period), the ADJUST light would illuminate and the subject would be free to make adjustments as desired. The rest interval control box was a small box with two pushbuttons. This box was wired to a computer keyboard. When either key was depressed a tone sounded to indicate to the subject that input was recorded. The rest interval was increased or decreased 0.33 seconds with each key depression. The subject had five seconds to make adjustments during the ADJUST period. After this period, the cycle returned to a work cycle and the entire work/rest period began again.

Each experimental session began with collection of pre-session MVC data. The subject recorded three maximal contractions with a two-minute rest between exertions. After completion of the MVC data collection, the apparatus was converted to the experimental condition. The subject rested five minutes and then began the 20-minute experimental session. The procedure followed exactly as described previously. Upon completion of the experimental session, the subject recorded pain data on a map of the hand. The pain map was used to collect pain sensations from the subjects to evaluate the handle design and to determine whether adequate padding had been added to the handles. These data were collected only during the pilot study. At this time, the apparatus was converted for MVC data collection. The subject then performed three maximal hand contractions to record post-session MVC data. Upon completion of the MVC data collection, the subject concluded the experimental session and was released.

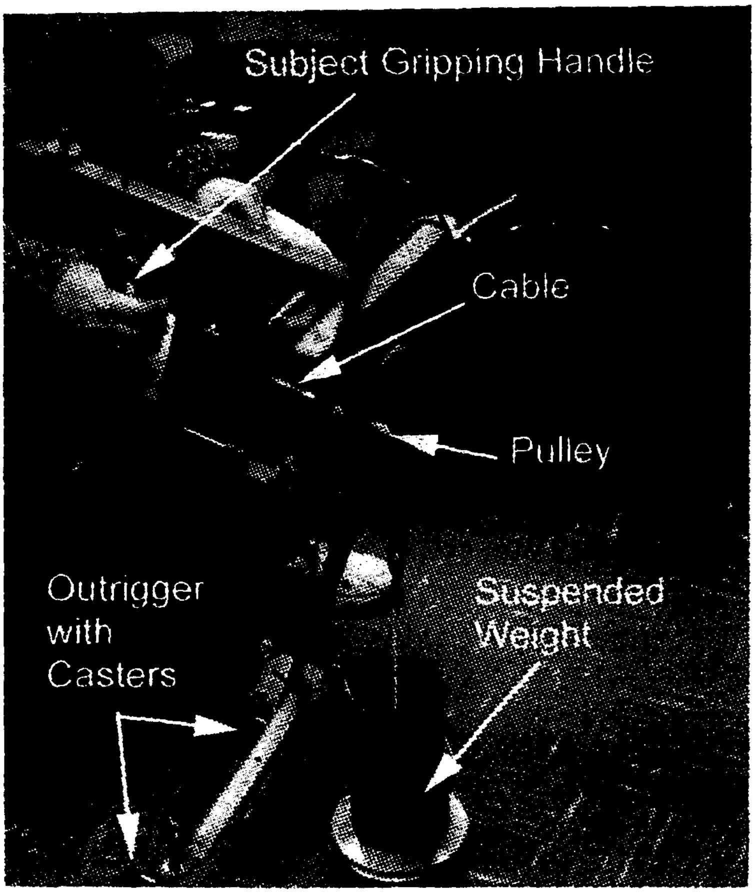


Figure 3: Subject Performing Task.

Figure 4: Subject Performing Task.

3.5 Data Analysis

3.5.1 MVC Values

Figure 5 presents the average pre-session MVC values recorded for each subject during the experimental sessions. Mean MVC values ranged from 15.9 to 33.1 kg (35 to 73 lbs). Generally, for each subject the pre-session MVC values were greater than the post-session MVC values. This was expected since the post-session MVC values were recorded following a 20-minute work session. The subjects were allowed to rest for approximately eight minutes as they recorded pain sensations on a hand diagram and as the experimenter changed the apparatus to measure MVC. Mean pre-session MVC values were 27.6 kg (60.9 lbs) while mean post-session MVC values were 25.7 kg (56.7 lbs).

Statistical analysis of MVC by Session, Observation (pre- and post-session), Oral Contraception Use and Subject revealed that Session, Observation, and Subjects were significant ($F(3,21) = 4.09$, $p < 0.0197$, $F(1,7) = 6.97$, $p < 0.033$, and $F(7,21) = 138.90$, $p < 0.0001$, respectively (see Table 5)). The data indicate that the mean pre-session MVC increased across the four test sessions. The mean pre-session MVC for Session 1 was significantly different from the MVC for Sessions 3 and 4 (see Figure 6). The figure shows a tendency for the MVC values to increase across the four test sessions. Table 6 shows the Tukey Studentized Range Test for MVC vs. Session. It is evident that the subjects continued to develop their grip strength as the study continued over the four-week period. The subjects had normal musculature and did not have any hobbies or job tasks that would have strengthened the hand muscles. The increase in mean MVC over the four week period was expected.

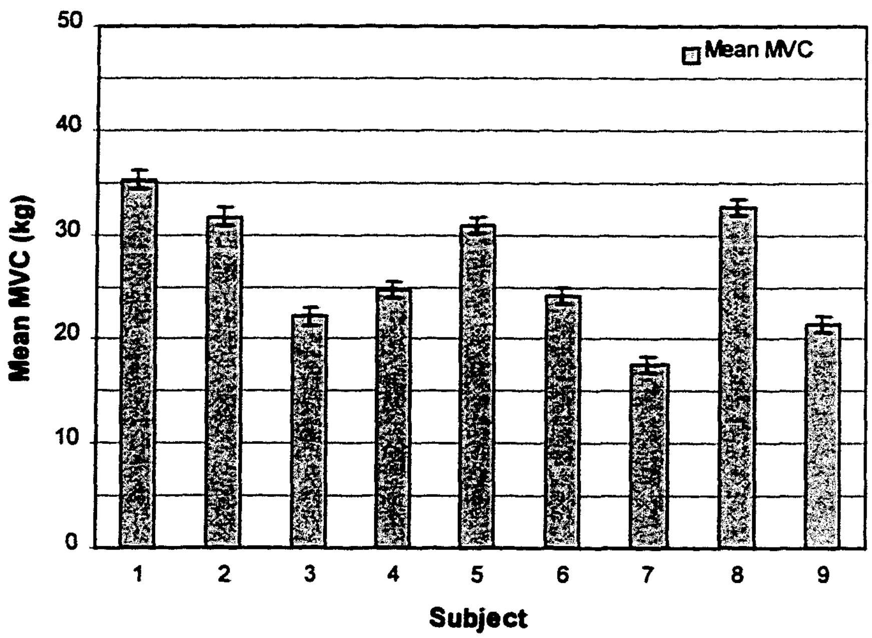


Figure 5: Subject Mean Pre-Session MVC Values.

Table 5: Analysis of Variance for MVC Observations.

Source	DF	Type III SS	Mean Square	F value	P > F
Session [T]	3	466.80	155.60	4.09	0.0197*
Observation [O]	1	342.657	342.66	6.97	0.0335
Oral Contraception Use [C]	1	879.84	879.84	0.58	0.4694
S(C)	7	10530.26	1504.32	138.90	0.0001*
T x O	3	16.04	5.34	0.49	0.6905
T x C	3	65.37	21.79	0.57	0.6396
T x S(C)	21	799.76	38.08	3.52	0.0029*
O x C	1	75.26	75.26	1.53	0.2560
O x S(C)	7	344.37	49.20	4.54	0.0032*
T x O x C	3	50.41	16.81	1.55	0.2307

* - Denotes significance at the $\alpha = 0.05$ level.

Table 6: Tukey Studentized Range Test for MVC vs. Session.

Session	Mean MVC (kg)	Grouping
1	25.00	A
2	26.39	A B
3	27.69	B
4	27.73	B

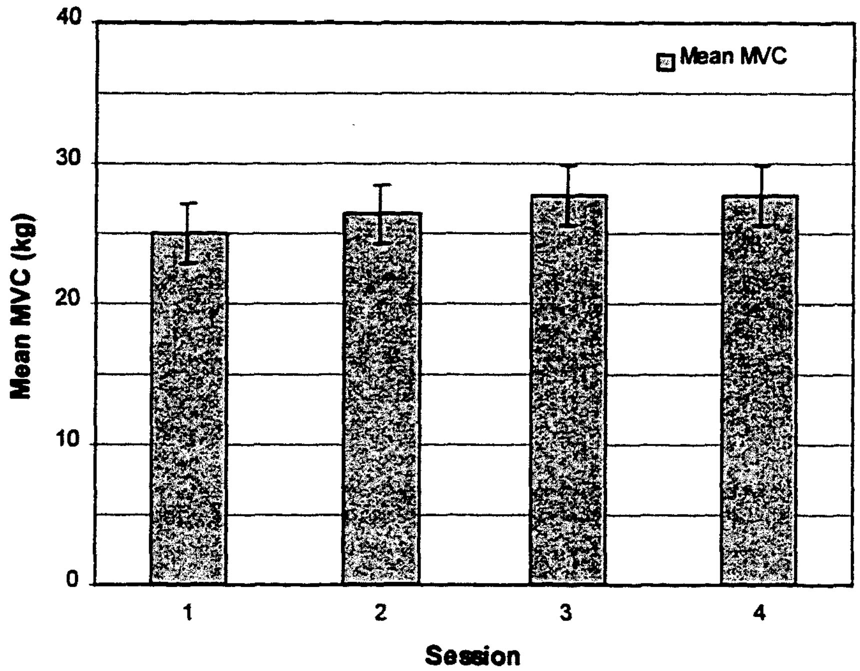


Figure 6: Mean Pre-Session MVC by Session.

Figure 7 shows the difference in the pre- and post-session MVC values during test sessions. It is evident that the pre-session MVC was greater than the post-session observation. Bishu et al. (1995) found that the recovery time from maximal MVC hand grasps was 120 minutes. Recovery time was defined as the point where Borg

Discomfort Scale values became assymptotic. Abu-Ali (1993) found that at 50% MVC the recovery times ranged from 40 to 80 minutes. Abu-Ali defined recovery times as the time it took for the subject to feel they could return to the task. As stated earlier, the subjects had approximately 8 to 10 minutes of rest before the post-Session MVC values were recorded. Neural muscular junction (NMJ) fatigue of the neural receptors and metabolic fatigue (due to a build-up of lactic acid) are the likely physical causes of the decrease in MVC.

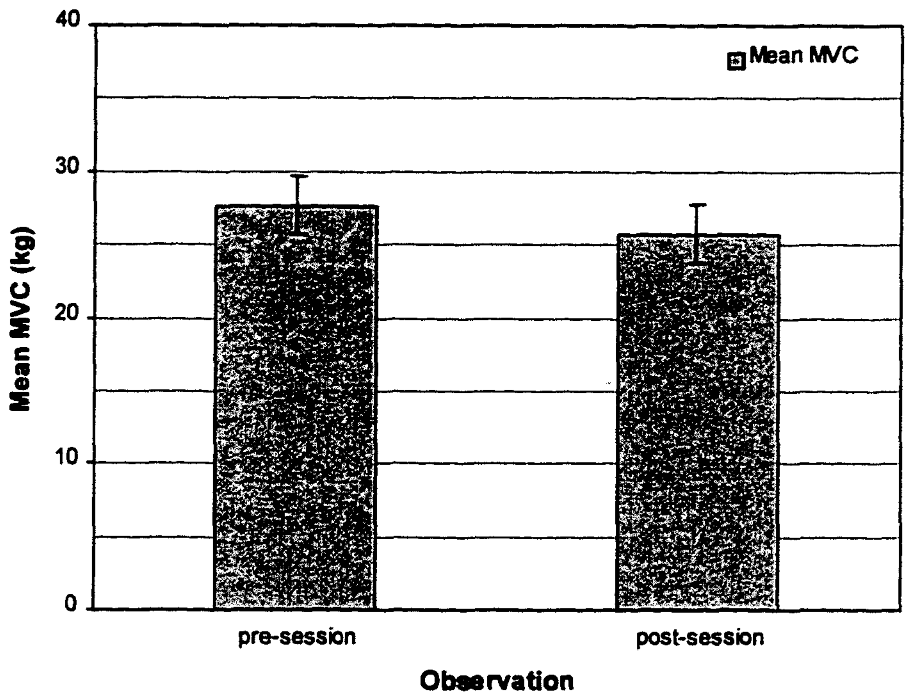


Figure 7: Mean MVC by Observation.

3.5.2 Rest Time Values

Mean rest intervals ranged from 3.0 to 6.0 seconds. The mean rest intervals over the four sessions showed a decreasing trend (Figure 8). The first session recorded the highest mean rest interval and the last session recorded the lowest mean rest interval. However, the second session mean rest interval was lower than the third session. The higher mean rest interval at the first session may have come from a lack of experience of the task required. Analysis of the data showed that no main effect was significant with the exception of Subject. Table 7 summarizes the results of the analysis of variance. Session was not a significant factor ($F(3,21) = 1.17$, $p < 0.3457$), nor was elapsed time ($F(1,7) = 4.36$, $p < 0.0752$) (see Figure 9). The lack of significance of Session upon the mean rest interval indicated that there was no difference whether the subject had a one-day break or fourteen-day break between experimental sessions.

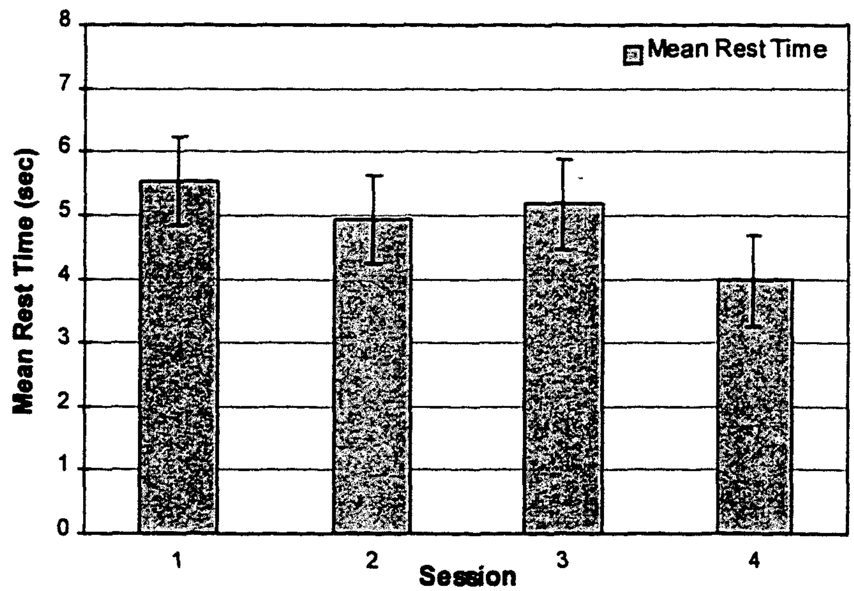


Figure 8: Mean Rest Time by Session.

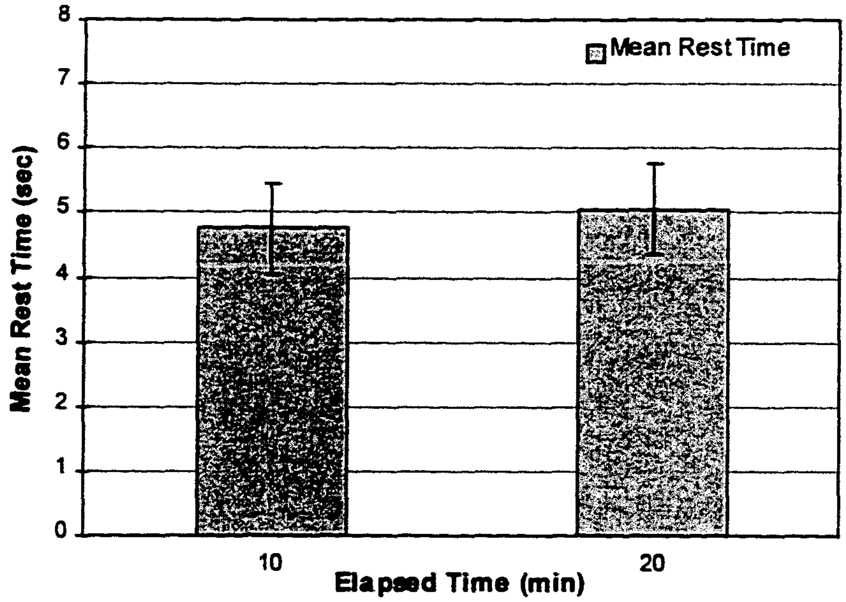


Figure 9: Mean Rest Time by Elapsed Time.

Table 7. Analysis of Variance for Rest Time Values.

Source	DF	Type III SS	Mean Square	F value	P > F
Session [T]	3	26.49	8.83	1.17	0.3457
Elapsed Time [E]	1	2.02	2.02	4.36	0.0752
Oral Contraception Use [C]	1	26.88	26.88	2.00	0.2000
Subject(C) [S(C)]	7	93.98	13.43	28.47	0.0001*
T x C	3	15.99	5.33	0.70	0.5599
T x S(C)	21	158.83	7.56	11.30	0.0001*
E x C	1	1.93	1.93	4.17	0.0806
E x S(C)	7	3.24	0.46	0.98	0.4690
T x E x C	3	5.55	0.93	1.96	0.1174

* - Denotes significance at the $\alpha = 0.05$ level.

Mean rest times did not vary among the sessions across the four-week period, indicating a reasonable level of stability in the psychophysical measure. There was no significant difference in the rest times selected at ten minutes vs. twenty minutes into the work session. This would indicate that subjects had adequately defined their work-rest schedule by ten minutes. However, the initial set-point of the rest time prior to subject adjustment did affect the final rest time value. Review of the data indicated that the starting rest interval had an effect on the final subject-determined rest interval (see Figures 10 and 11).

Comparison of the two initial set points showed a significant effect upon the ending rest time values ($F(1,35) = 9.74$, $p < 0.0168$). It was found that the initial rest time of two seconds resulted in a significant difference in rest time obtained at ten minutes vs. twenty minutes ($F(1,35) = 10.91$, $p < 0.0131$). The initial rest time of nine seconds did not produce a similar effect. When subjects were started at two seconds, they made adjustments after the ten-minute mark such that the concluding twenty-minute mark rest time was significantly greater than the ten-minute rest time value. This was not the case when subjects were started at nine seconds.

This effect confirms what Abu-Ali (1993) found when changes were made to subject-established rest times. He found that the force applied (% MVC) and the direction of change influenced the establishment of a new subject-determined rest time. In general, he found that when time was added to the rest time, subjects detected the change and reduced their rest time. However, they did not return to the previously set value. Similar reactions were found when rest time was subtracted. In like fashion, the current study found that when started at two seconds, subjects approached the study's overall mean rest time of 4.90 seconds, but they did not reach this value. When started at nine seconds, subjects adjusted the rest time downward, but again did not reach the mean rest time.

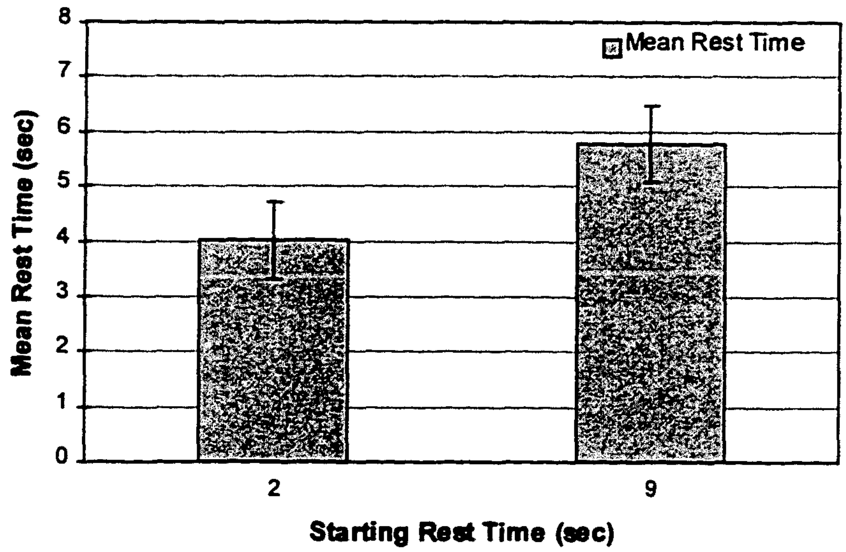


Figure 10: Mean Rest Interval by Starting Rest Interval.

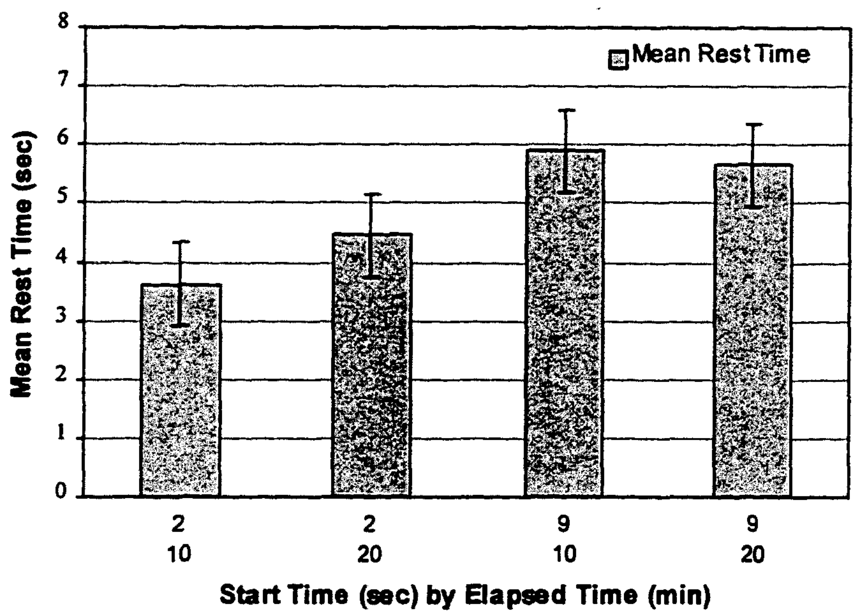


Figure 11: Mean Rest Interval by Start Interval and Elapsed Time.

3.5.3 Covariate Analysis

Analysis of the anthropometric measures was performed to determine if any of the measures explained a significant proportion of the variance. Previous research noted that size of the carpal canal, use of oral contraceptives, and previous hand and wrist injuries or illness may be of concern in hand/wrist motion injuries (Grant, 1994). Crumpton and Congleton (1994) found that use of oral contraception, hand length, wrist thickness and wrist circumference were factors associated with CTS symptoms. Abu-Ali (1993) found that grip span, hand length, hand breadth, hand thickness, wrist length, wrist thickness and wrist circumference correlated positively with maximum voluntary contraction (MVC) at 2/3 of maximum ulnar deviation and with MVC at zero degrees wrist angle. This pilot study identified only wrist circumference and wrist thickness as significant covariates ($p = 0.0281$ and $p = 0.0105$, respectively). These two measures have a direct relationship to the size of the carpal tunnel. The larger the wrist, the larger carpal tunnel area, which may reduce the onset of carpal tunnel symptoms. The larger carpal tunnel area would allow inflamed tendons to increase in size without impinging upon the median nerve.

3.5.4 Second Pilot Study

In order to investigate whether a twenty-minute task was sufficient, a second pilot study was conducted. Three subjects from the initial pilot study were recruited to participate in this study. Each subject performed the experimental task for forty minutes, that is, twenty minutes longer than the task performed in the first pilot study. As before, data were recorded continuously and rest intervals were recorded at the ten-minute, twenty-minute, thirty-minute, and forty-minute marks. Average rest intervals were 4.56 sec, 4.89 sec, 5.00 sec and 5.35 sec at 10, 20, 30 and 40 minutes, respectively. Analysis of variance identified no significant difference between any of the elapsed times ($F(3,6) = 0.9534$, $p < 0.2223$). This would indicate that there was no difference between a longer test session (forty minutes) and a test session of twenty minutes.

3.5.5. Conclusions

The objectives of the pilot study were to determine (1) the stability of psychophysically-determined rest times across sessions separated by 1 to 14 days, (2) the difference in subject-determined rest times for a ten-minute vs. a twenty-minute test session, and (3) the extent of variation across sessions in the maximum voluntary contraction (MVC) hand grip. Mean rest times did not vary among the sessions over the four-week period. There was no significant difference in subject-determined rest times for a 10-minute vs. a 20-minute task. Mean MVC coefficient of variation values averaged 0.06. This is similar to values determined by Bishu et al. (1995). However, the initial set-point of the rest time prior to subject adjustment did affect the final rest time value. Experimenter-selected rest time starting points had a significant effect upon the ultimate rest time set by the subject. It is evident from the data the starting rest time is very important when using the psychophysical method of adjustment. This study showed that subjects could determine a comfortable work/rest cycle within a twenty-minute session.

3.6 Principal Study Task Description

This experiment employed a psychophysical approach to study repetitive hand grasping in a wrist neutral and a 45 degree wrist flexion condition. The pilot study consisted of a major pilot study and a second pilot study. The major pilot study investigated the effect of time lapses upon the mean rest time and the effect of the work duration on mean rest time. Nine subjects were used in the major pilot study. The second pilot study used three subjects and furthered the investigation of the effect of work duration on mean rest time. Analysis of the data from the two studies determined that a twenty-minute task was appropriate. It was found that the start time should be close to the mean rest time so as to minimally affect the subject-determined rest times. This study employed a twenty-minute task as described previously and a starting rest time appropriate to the wrist position (five seconds and seven seconds). As in the pilot study, subjects were required to perform a simulated industrial hand grasping task. The same apparatus was used to simulate the movements required to operate a typical pneumatic or electric power tool as was used in the pilot studies.

3.7 Subjects

Sixteen university students were selected for participation in this study. The subjects were recruited from the University of Oklahoma Psychology Subject Pool. These students received course credit for participating in the study. Mital (1986) showed that there is no significant difference between industrial and non-industrial workers in subject-determined maximum acceptable weights of lift, given proper familiarization and instruction. Subjects were screened for previous CTD injury or any other adverse health condition that may cause injury or prevent them from performing the task safely (e.g., arthritis, abnormal ECG, recurring pain in hands and wrist, pregnancy, blood pressure and birth control pills). These subjects were screened using a questionnaire to recover medical precursor information (Appendix C) and by mechanical compression of the carpal tunnel as described previously. After passing the screening tests, subjects were further screened for normal hearing (could the subjects hear a computer-generated tone) and corrected-to-normal vision. Several authors (Loslever and Raniavosoa, 1993; Leifer et al., 1992; Radecki, 1994) have shown that handedness is not a factor in the development of CTS. Thus, subjects were not selected based on handedness. Subjects signed an informed consent form (Appendix D), and approval for the use of human subjects was obtained from the University of Oklahoma Institutional Review Board, Norman Campus. Data were coded to prevent identification of the participants.

3.8 Independent Variables

The independent variable manipulated during the study was wrist posture. Wrist posture was set at two levels, neutral (0°) and wrist flexion (-45°). Previous studies have shown that only 60% to 72% of the force exerted in a neutral position can be generated at 45° wrist flexion (Putz-Anderson, 1994; Ramakrishnan et al, 1994; Perez-Balke and Buchholz, 1994; Fredericks et al., 1995). This position would be considered undesirable in the workplace. Additionally, Session, and Oral Contraception Use were independent variables in the study. Seven days elapsed between each experimental session.

3.9 Dependent Variables

Three dependent measures were recorded during this study as follows:

1. rest time between two successive exertions, recorded throughout the session.
2. MVC at wrist neutral posture,
3. rating of perceived difficulty of the session on a scale similar to Swensen (1987 and 1992).

The experimental design for this study was developed to gather information about the reliability of this psychophysical methodology. Sixteen subjects were tested at a force level of 30% of the wrist neutral MVC and at two wrist angles: wrist neutral (0°) and 45° wrist flexion. There were two sessions per condition, separated by seven days. The sequence of exposures to the two wrist angles was counterbalanced across subjects. Half of the subjects began at 0° flexion and the other half began at 45° wrist flexion. After the two experimental sessions, the subjects performed the tasks at the remaining wrist angle. Table 8 depicts the experimental conditions.

Table 8: Model of Experimental Conditions.

	Wrist Angle (0°)		Wrist Angle (-45°)	
Subject	Session 1	Session 2	Session 1	Session 2
S1				
S2				
⋮				
S16				

The statistical model can be represented as:

$$Y_{ijkl} = \mu + T_i + A_j + C_k + S(C)_{l(k)} + TA_{ij} + TC_{ik} + TS(C)_{il(k)} + AC_{jk} + AS(C)_{jl(k)} + TAC_{ijk} + \varepsilon_{ijkl}$$

where Y_{ijkl} = rest time for the ith session, the jth wrist angle, the kth level of oral contraception use and the lth subject,

μ = overall main effect,

T_i = effect due to sessions, $i = 1, 2$,

A_j = effect due to wrist angle, $j = 1, 2$,

C_k = effect due to oral contraception use, $k = 1, 2$,

S_l = subjects, $j = 1, ..., 16$, and

ε_{ijkl} = random error.

The expected mean squares for the experimental design are shown in Table 9.

Table 9: Sources of Variability, Degrees of Freedom (df) and F-ratios for the Principal Study.

Source	df	F-Ratio
Session [T]	i-1=1	$F_T = MS_T / MS_{TS(C)}$
Angle [A]	j-1=1	$F_A = MS_A / MS_{AS(C)}$
Oral Contraception Use [C]	k-1=1	$F_C = MS_B / MS_{S(C)}$
Subject(C) [S(C)]	l-2=14	
T x A	(i-1)(j-1)=1	$F_{TA} = MS_{TA} / MS_{TAS(C)}$
T x C	(i-1)(k-1)=1	$F_{TC} = MS_{TC} / MS_{TS(C)}$
T x S(C)	(i-1)(l-2)=14	
A x C	(j-1)(k-1)=1	$F_{AC} = MS_{AC} MS_{AS(C)}$
A x S(C)	(j-1)(l-2)=14	
T x A x C	(i-1)(j-1)(k-1)=1	
T x A x S(C)	(i-1)(j-1)(l-2)=14	

3.10 Control Variables

Exertion time was fixed at 5 seconds. Abu-Ali (1993) used both a one-second and a five-second exertion time. He found that the five-second exertion time was more difficult for subjects and resulted in increased rest times, decreased frequency (MAF), and higher task difficulty ratings.

Exertion force was held constant at 30% MVC. Previous research has studied MVC's of 25% and 50% (Abu-Ali, 1993) and 40%, 60% and 80% (Hallbeck et al., 1995). Several subjects in the Abu-Ali (1993) study found the 50% MVC condition to be very difficult. Hallbeck et al. (1995) found that during a static hand grasp, 40% MVC provided the longest endurance time compared with 60% and 80% MVC. Above 30% MVC, blood flow to and from the hand is occluded (Simonson, 1971).

At the beginning of each trial, the rest interval was initially set to a level appropriate for the task (five seconds for wrist neutral versus seven seconds for 45° wrist flexion). Additional control variables were lack of vibration, no pregnancy, and zero torque, no previous CTD injury, and a 20-minute session duration. Temperature, humidity and illumination were maintained at relatively constant levels using a climate-controlled laboratory space at the University of Oklahoma, School of Industrial Engineering.

CHAPTER 4

RESULTS AND ANALYSES

4.1 Anthropometric Data

Data for the anthropometric and initial MVC measures are presented in Table 10. The recorded measures included:

1. subject number,
2. age,
3. hand dimensions: grip span, length and breadth,
4. wrist dimensions: breadth, thickness and circumference, and
5. initial mean MVC measurement.

MVC measurements were taken in a wrist neutral posture, while subjects grasped the dynamometer and exerted a maximum force for five seconds. The subject was instructed to grasp the handle with a power grip, that is, with the thumb and index finger overlapping slightly. The handles were adjusted to the proper grip span for each subject. As described in the previous section, the subject performed five maximal voluntary contractions of the hand. The initial two MVC values were discarded and the last three values were averaged to determine the mean MVC value from which the exertion level of 30% MVC was determined. This method provides a good estimate of the true MVC [personal communication with Dr. M. Bemben, March 1996]. As noted in Table 10, the mean age of the subjects was 19.6 years (range 18 to 27 years). The subjects were recruited from the University of Oklahoma Psychology Subject Pool and received six hours of credit towards their undergraduate psychology course participation requirements. This accounts for the young average age of the subjects. The mean MVC of the study group was 30.5 kg, with a range of 22.5 kg to 40.9 kg (67.3 lbs, range 49.7 lbs to 90.2 lbs). Seven subjects reported use of oral contraceptives and nine subjects indicated they did not use oral contraceptives.

Table 10: Anthropometric Measures of Subjects.

		Hand (cm)			**Wrist (cm)**			Mean
Subject	Age	Grip Span	Length	Breadth	Breadth	Thickness	Circumference	MVC (kg)
1	18	4.5	15.9	6.9	4.9	3.3	13.3	22.6
3	18	5.3	17.0	7.9	5.8	3.8	15.2	32.1
4	18	4.8	17.0	7.5	5.5	3.9	16.2	32.6
5	21	5.3	18.1	8.2	6.5	4.4	15.2	39.9
6	20	5.5	18.5	8.0	5.8	4.1	15.6	26.0
8	18	4.7	16.5	7.2	5.1	3.2	14.6	22.5
9	19	4.6	17.2	7.4	5.2	3.6	13.2	25.7
10	18	4.6	16.6	7.4	5.4	3.7	14.9	27.0
11	18	4.6	17.6	7.0	5.4	3.8	15.2	23.2
12	22	6.0	18.1	8.2	5.7	4.0	15.9	34.3
13	18	5.5	17.5	7.8	5.6	3.8	17.5	29.3
14	19	5.3	18.4	8.0	5.8	4.3	17.5	34.1
15	18	5.7	18.2	8.5	5.7	4.4	16.2	32.1
16	23	5.3	18.4	8.6	6.0	3.1	16.4	40.9
17	18	4.5	16.0	7.4	5.0	3.8	17.2	29.3
18	27	5.3	17.8	8.6	6.5	3.8	16.5	37.0
$\bar{x}$	**19.6**	**5.1**	**17.4**	**7.8**	**5.6**	**3.8**	**15.8**	**30.5**
σ	**2.6**	**0.5**	**0.9**	**0.6**	**0.5**	**0.4**	**1.5**	**5.9**

4.2 MVC Data Analysis

Figure 12 presents the mean pre-session and post-session MVC values of the sixteen subjects averaged across the four sessions. MVC data were analyzed using a repeated-measures design with observation (pre-session and post-session) and session (1, 2, 3, 4) as within-subject factors. The experimental model can be stated as follows:

$$Y_{ijk} = \mu + O_i + T_j + S_k + OT_{ij} + OS_{ik} + TS_{jk} + \varepsilon_{ijk}$$

where Y_{ijk} = MVC values for the ith observation, the jth session, the kth subject,
μ = overall main effect,
O_i = effect due to observation (pre-session vs. post-session), $i = 1, 2$,
T_j = effect due to session, $j = 1, ..., 4$,
S_k = subjects, $k = 1, ..., 16$, and
ε_{ijk} = random error.

Mean MVC values of the subjects ranged from 29.1 kg to 32.3 kg (64.1 lbs to 71.3 lbs) over the study period. For each subject, the average pre-session and post-session MVC values were computed across all four sessions. With the exception of subject 6, mean pre-session MVC measurements were greater than mean post-session MVC values. Subjects were allowed to rest for five minutes following completion of the experimental session and prior to collection of post-session MVC measurements. Mean pre-session MVC values averaged 31.7 kg, σ = 5.9 kg (69.9 lbs, σ = 12.9 lbs) and mean post-session MVC values averaged 29.8 kg, σ = 5.5 kg (65.7 lbs, σ = 12.1 lbs) (Figure 13).

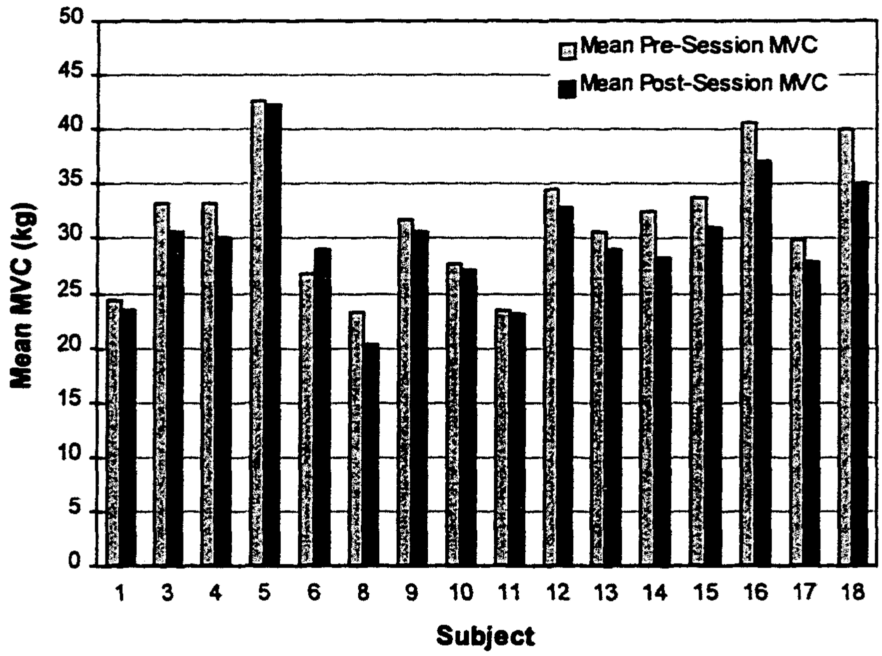


Figure 12: Mean Pre-Session and Post-Session MVC Values by Subject.

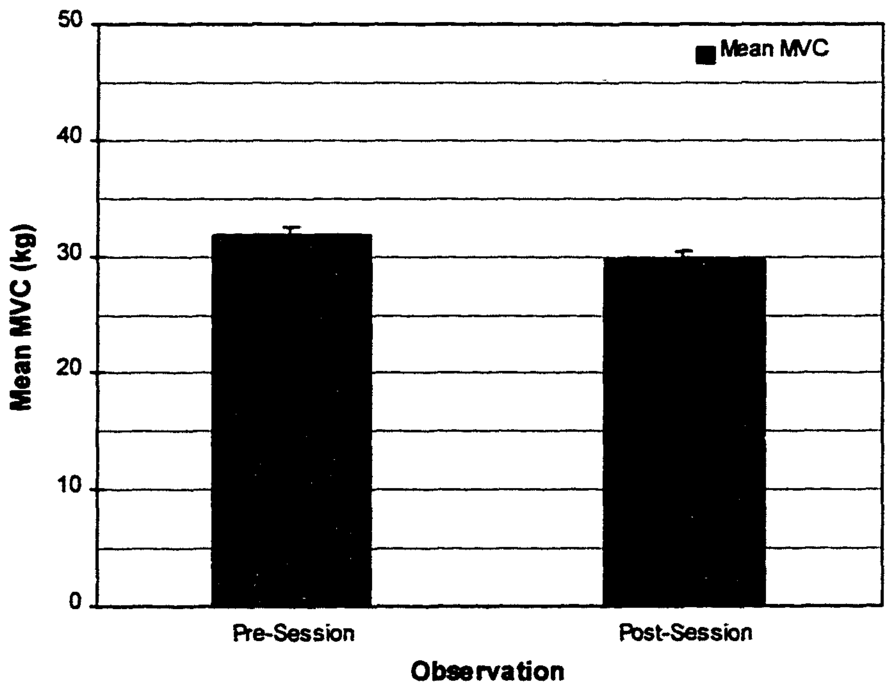


Figure 13: Mean MVC by Observation.

Statistical analysis of MVC revealed that both Session and Observation were significant ($F(3, 45) = 3.13$, $p < 0.0364$ and $F(1, 15) = 15.99$, $p < 0.0012$, respectively (see Table 11)). Overall mean MVC increased from Session 2 to Session 4 with no statistically significant difference among Sessions 1, 2 and 3 and Sessions 1, 3 and 4 (see Table 12). The difference between overall mean MVC values for Session 4 and Session 1 was 3.47% using Session 1 as the base (Figure 14). However, when pre-session and post-session values were analyzed separately, Session was no longer statistically significant (Figure 15). Pre-session MVC values ranged from 31.0 kg (68.4 lbs) on Session 2 to 32.3 kg (71.3 lbs) on Session 4 ($F(3,45) = 2.50$, $p < 0.0714$). The difference between Session 2 and Session 4 was 4.0%. Post-session MVC values ranged from 29.1 kg (64.1 lbs) on Session 1 to 30.7 kg (67.6 lbs) on Session 4 $F(3,45) = 2.54$, $p < 0.0684$) with a difference of 5.5% between Session 1 and Session 4. Pre-session MVC standard deviations calculated for each subject across the four sessions averaged 1.2 kg (2.7 lbs) with a range of 0.3 kg (0.7 lbs) to 3.5 kg (7.6 lbs). Post-session standard deviations ranged from 0.5 kg to 3.0 kg (1.2 lbs to 6.5 lbs) and averaged 1.5 kg (3.3 lbs). It is evident that grip strength was fairly stable across the four experimental sessions.

Table 11: Analysis of Variance Summary for MVC Observations.

Source	DF	Type III SS	Mean Square	F value	P > F
Observation [O]	1	533.42	533.42	15.99	0.0012*
Session [T]	3	142.29	47.43	3.13	0.0364*
Subject [S]	15	17665.43	1177.70	134.48	0.0001*
O x T	3	54.42	18.14	2.09	0.1153
O x S	15	500.45	33.36	3.84	0.0002*
T x S	45	681.00	15.13	1.74	0.0331*

* - Denotes significance at the $\alpha = 0.05$ level.

Table 12: Tukey Studentized Range Test for MVC by Session.

Session	Mean MVC (kg)	Grouping
2	30.23	A
1	30.43	A B
3	30.77	A B
4	31.52	B

Additionally, individual subject differences were significant ($F(15,45) = 134.48$, $p < 0.0001$), the Observation x Subject interaction was significant ($F(15,45) = 3.84$, $p < 0.0002$), and the Session x Subject interaction was significant ($F(45,45) = 1.74$, $p < 0.0331$). The Session x Subject interaction can be explained by a varying difference in the pre-session and post-session MVC values across subjects. As in the pilot study, pre-session MVC values were generally greater than post-session MVC values. Neural muscular junction fatigue and metabolic fatigue of the muscles are the likely physical causes of the decrease in MVC. Previous studies have shown that it takes 40 to 80 minutes to recover from a 50% MVC effort (Abu-Ali, 1993) and 120 minutes to recover from one maximal MVC effort (Bishu et al., 1995). Only one subject generated greater mean post-session MVC values than mean pre-session values. For this subject, post-session MVC values were greater than pre-session MVC values on three of the four sessions. As evidenced by the difference between pre-session and post-session MVC values, subjects appeared to develop muscular fatigue. The lack of an adequate recovery time after the experimental task before collection of the post-session MVC values contributed to the lower MVC's. Subjects rested five minutes following recording of the pre-session MVC values. After that time they were asked if they were ready to perform the experimental task. All subjects indicated readiness and the experimental session began.

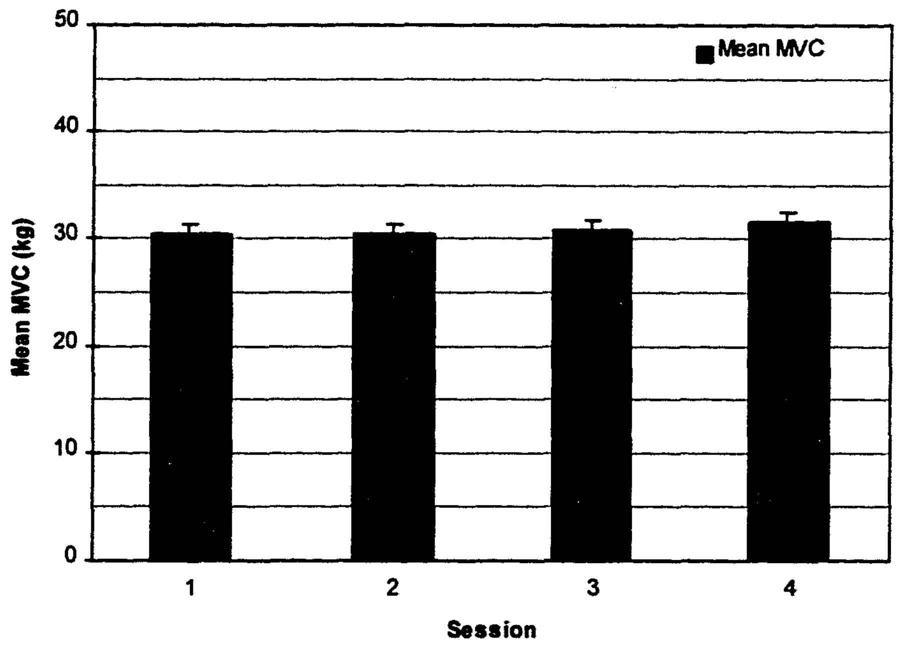


Figure 14: Overall Mean MVC by Session.

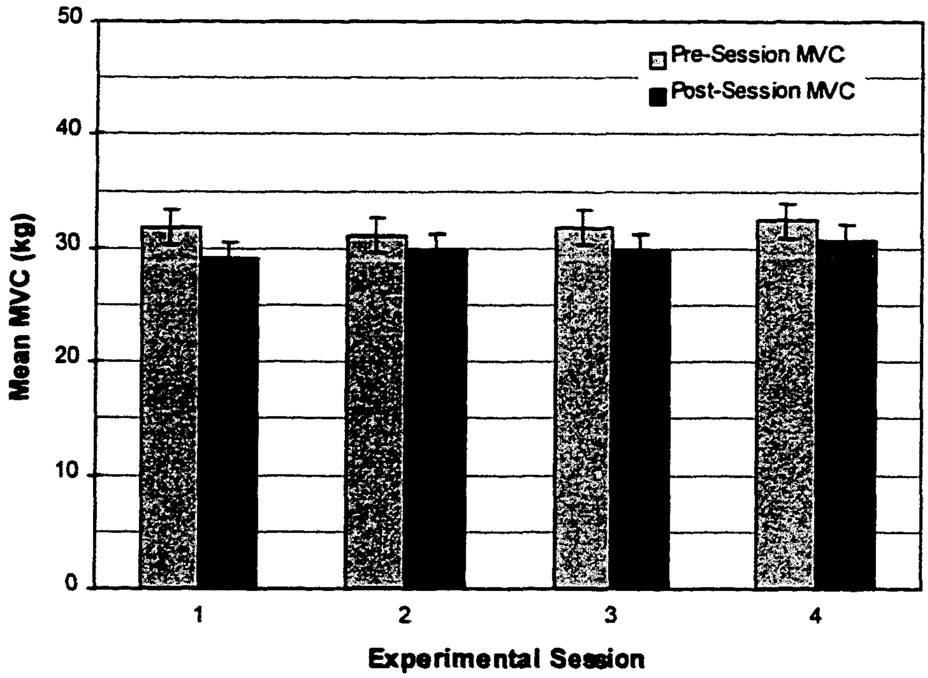


Figure 15: Mean MVC by Session and Observation.

4.3 Rest Time Data

Data acquisition was accomplished by continuously recording the position of the handles during the experiment. The raw data included the sequence number (an incremental number assigned to each recorded action), the position of the handles, and the time of the action in seconds into the session (Figure 16). The first line of the data file recorded the sequence number, the subject number, force in pounds, session number, wrist angle and date. The program to record this information was written in BASIC. A data reduction program, also in BASIC, was written to reduce the data into the three actions of grasping, resting and rest time adjustment. The program calculated when the action occurred from beginning of the experiment and recorded the elapsed time in seconds and in minutes, the action performed, and finally, the length of the action period in seconds (Figure 17). Finally, another BASIC program was used to capture the rest actions into a separate file. This file recorded the subject number, the session number, the time of the rest period in seconds from the beginning of the experiment, the rest action, and the length of the rest period. This file was used to determine the rest time values used in the analysis (Figure 18). Appendix F shows graphically the subject rest time values each minute for each subject and each experimental session.

The subjects were provided feedback about their performance by the subject cue box (previously described) and from tones generated by the computer during the experimental session. A tone sounded at the beginning of a grasping cycle. If the subject did not release the grasp immediately after completion of the five-second exertion period, a different tone sounded in addition to extinguishing the "SQUEEZE" light to remind the subject to release the grasp. Tones also sounded at the beginning of the adjustment cycle and to indicate a rest time adjustment had been made. The experimenter also supervised the subjects as they carried out their task and provided instructions when necessary to prompt the subject to hold the handle steady or to release the grasp if they squeezed too hard and illuminated the "TOO MUCH" light. The subjects had two twenty-minute practice sessions before actual data collection began and were very familiar with the task and the instructions. Any experimenter supervision was therefore kept to a minimum. To standardize the data collection effort, each subject was admonished to refrain from strenuous activity of the hand for twenty-four hours prior to the scheduled experimental session.

```
0,"s09",17,"e3",45,"12-03-1996"
1,"SQUEEZE ON          ",50986.84
2,"SQUEEZE AND GOOD ON ",50988.15
3,"SQUEEZE OFF         ",50993.15
4,"LIGHTS OFF          ",50993.65
5,"BEGIN REST PERIOD   ",50993.65
6,"END REST PERIOD     ",51000.68
7,"SQUEEZE ON          ",51000.68
8,"SQUEEZE AND GOOD ON ",51001.06
9,"SQUEEZE OFF         ",51006.06
10,"LIGHTS OFF          ",51006.55
11,"BEGIN REST PERIOD   ",51006.55
12,"END REST PERIOD     ",51013.58
13,"SQUEEZE ON          ",51013.58
14,"SQUEEZE AND GOOD ON ",51014.02
15,"SQUEEZE OFF         ",51019.02
16,"LIGHTS OFF          ",51019.52
17,"BEGIN REST PERIOD   ",51019.52
18,"END REST PERIOD     ",51026.55
19,"SQUEEZE ON          ",51026.55
20,"SQUEEZE AND GOOD ON ",51027.04
21,"SQUEEZE OFF         ",51032.04
22,"LIGHTS OFF          ",51032.53
23,"BEGIN REST PERIOD   ",51032.59
24,"END REST PERIOD     ",51039.62
25,"SQUEEZE ON          ",51039.62
26,"SQUEEZE AND GOOD ON ",51039.95
27,"SQUEEZE OFF         ",51044.95
28,"LIGHTS OFF          ",51046.21
29,"BEGIN REST PERIOD   ",51046.27
30,"END REST PERIOD     ",51053.3
```

Figure 16: Sample Raw Data Output.

```
"s09",17,"e3",45,"12-03-1996"
0,0,"WORK",5.5
5.5,.092,"REST",7.031
12.91,.215,"WORK",5.492
18.402,.307,"REST",7.027
25.871,.431,"WORK",5.5
31.371,.523,"REST",7.031
38.891,.648,"WORK",5.492
44.441,.741,"REST",7.031
51.801,.863,"WORK",6.262
58.121,.969,"REST",7.031
65.641,1.094,"WORK",5.492
71.191,1.187,"REST",7.031
78.551,1.309,"WORK",5.492
84.102,1.402,"REST",7.031
91.461,1.524,"WORK",5.602
97.113,1.619,"REST",6.977
104.473,1.741,"WORK",5.551
110.023,1.834,"REST",7.027
117.43,1.957,"WORK",5.551
123.203,2.053,"ADJUST",5
128.691,2.145,"WORK",5.551
134.242,2.237,"REST",7.031
142.043,2.367,"WORK",5.547
147.59,2.46,"REST",7.031
155.223,2.587,"WORK",5.5
160.773,2.68,"REST",7.027
168.633,2.811,"WORK",6.309
175,2.917,"REST",7.031
182.473,3.041,"WORK",6.309
188.781,3.146,"REST",7.031
196.203,3.27,"WORK",6.309
202.512,3.375,"REST",7.031
210.203,3.503,"WORK",5.547
215.75,3.596,"REST",7.031
223.113,3.719,"WORK",5.488
228.66,3.811,"REST",7.031
236.512,3.942,"WORK",5.5
242.063,4.034,"REST",7.027
249.09,4.151,"ADJUST",5.113
```

Figure 17: Sample Data Reduction Program Output.

```
"12-03-1996",17,45
9,"e3",.092,"REST",7.031
9,"e3",.307,"REST",7.027
9,"e3",.523,"REST",7.031
9,"e3",.741,"REST",7.031
9,"e3",.969,"REST",7.031
9,"e3",1.187,"REST",7.031
9,"e3",1.402,"REST",7.031
9,"e3",1.619,"REST",6.977
9,"e3",1.834,"REST",7.027
9,"e3",2.237,"REST",7.031
9,"e3",2.46,"REST",7.031
9,"e3",2.68,"REST",7.027
9,"e3",2.917,"REST",7.031
9,"e3",3.146,"REST",7.031
9,"e3",3.375,"REST",7.031
9,"e3",3.596,"REST",7.031
9,"e3",3.811,"REST",7.031
9,"e3",4.034,"REST",7.027
9,"e3",4.343,"REST",7.031
9,"e3",4.573,"REST",7.027
9,"e3",4.803,"REST",7.027
9,"e3",5.022,"REST",7.031
9,"e3",5.247,"REST",7.031
9,"e3",5.469,"REST",7.027
9,"e3",5.687,"REST",7.027
9,"e3",5.906,"REST",7.031
9,"e3",6.126,"REST",7.031
9,"e3",6.428,"REST",7.031
9,"e3",6.649,"REST",7.031
9,"e3",6.871,"REST",7.039
9,"e3",7.104,"REST",7.031
9,"e3",7.342,"REST",7.031
9,"e3",7.562,"REST",7.031
9,"e3",7.781,"REST",7.031
9,"e3",8.01,"REST",7.031
9,"e3",8.227,"REST",7.031
9,"e3",8.535,"REST",7.043
```

Figure 18: Sample Data Reduction Output for Rest Time Data.

To test the assumption that the error term followed a normal distribution, error residuals were calculated and tested with the SAS PROC UNIVARIATE procedure. The Shapiro-Wilk statistic (W) is provided by the Univariate procedure. It is the ratio of the best estimator of the variance to the corrected sum-of-squares estimator of the variance. W must be greater than zero and less than or equal to one. Small values of W lead to rejection of the assumption that the data has a normal distribution (SAS Institute, 1982). The Univariate procedure found that the Shapiro-Wilk statistic was $W = 0.9568$ with the $Pr(statistic < W) = 0.0601$. Additionally, the data had skewness equal to 0. The normal probability plot of the error residuals is presented in Figure 19. From this plot and the Shapiro-Wilk statistic, it appears that the normality assumption was met.

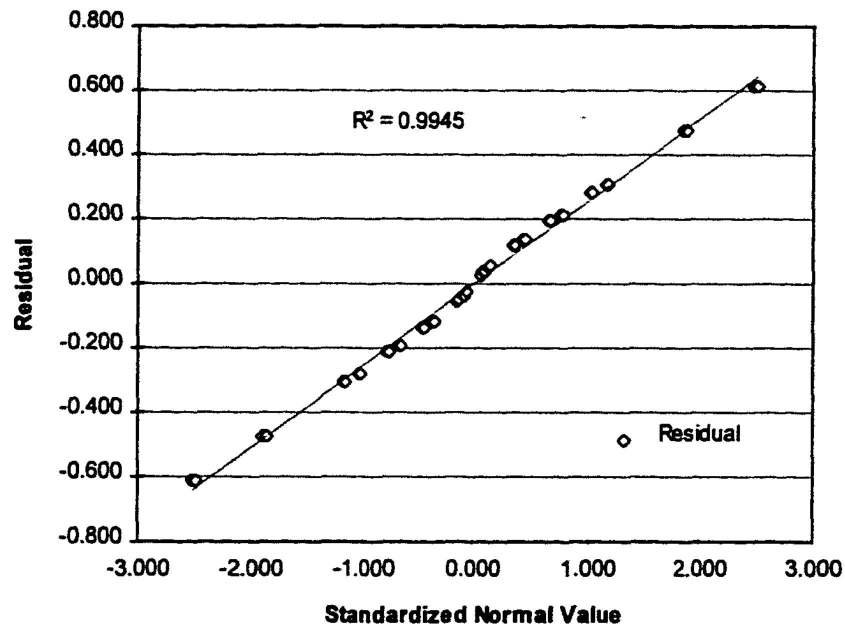


Figure 19: Normal Probability Plot of Residuals.

Rest time data were analyzed using a repeated-measures design with session (1, 2), and angle (0°, 45°) as within-subject factors. The experimental model can be stated as follows:

$$Y_{ijkl} = \mu + T_i + A_j + C_k + S(C)_{l(k)} + TA_{ij} + TC_{ik} + TS(C)_{il(k)} + AC_{jk} + AS(C)_{jl(k)} + TAC_{ijk} + \varepsilon_{ijkl}$$

where; Y_{ijkl} = rest time for the ith session, the jth angle, the kth oral contraception use and the lth subject,

μ = overall main effect,

T_i = effect due to session, $i = 1, 2$,

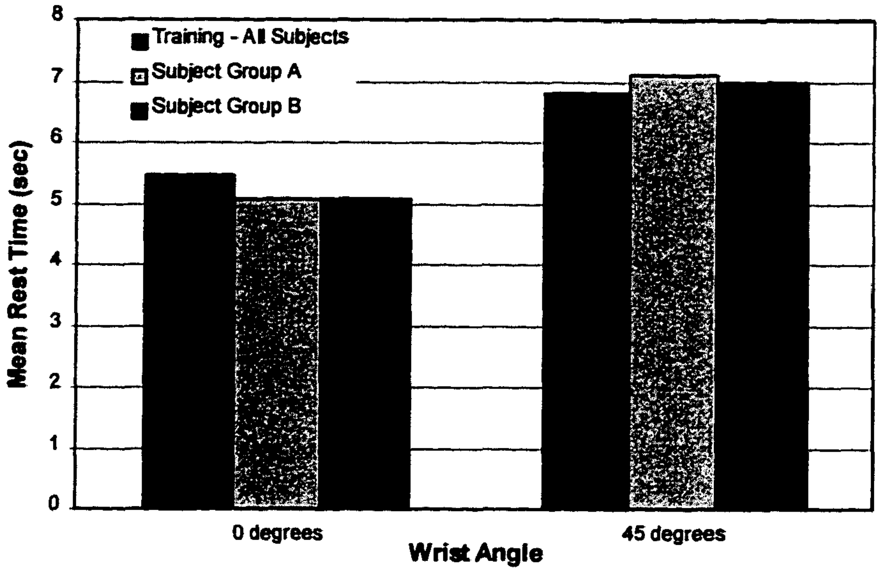
A_j = effect due to wrist angle, $j = 1, 2$,

C_k = effect due to oral contraception use, $k = 1, 2$,

$S(C)_{l(k)}$ = subjects nested within oral contraception use, $l(k) = 1, ..., 16$, $k = 1, 2$, and

ε_{ijk} = random error.

Mean rest times for the experiment were 5.1 seconds for the wrist neutral position and 7.2 seconds for 45° wrist flexion. The subjects were trained in two training sessions separated by seven days before experimental data were collected. The training sessions lasted twenty minutes and exposed the subjects to both the wrist neutral and the 45° wrist flexion conditions. Figure 20 shows the mean rest times for the training session, the first two experimental sessions, and the last two experimental sessions. Seven days elapsed following each session (both training and experimental sessions). As noted in the figures, there was little change between the two experimental sessions. The two training sessions were used to set the initial rest time for the experimental sessions. For all subjects, the first training session in a wrist neutral posture and the second training session in the 45° wrist flexion condition. Based upon the training sessions and the pilot study, the initial rest times selected were 5 seconds for the wrist neutral condition and 7 seconds for the 45° wrist flexion condition.



Group A tested first at 0°
Group B tested first at 45°

Figure 20: Mean Rest Time by Session.

Statistical analysis of rest times revealed that wrist angle was significant ($F(1, 14) = 72.78$, $p < 0.0001$). Subject differences and the Angle x Subject interaction were also significant (see Table 13). The mean rest time recorded at a wrist neutral position was 5.13 sec while the mean rest time for 45° wrist flexion was 7.05 sec (Figure 21). From Table 13, there was no significant difference between the first and second session rest time values. This would indicate that the subjects at either wrist angle were relatively consistent in determining their comfortable work/rest cycle and returning to that value in a subsequent experimental session. Figure 22 presents the mean Rest Time by Wrist Angle and Session.

Table 13: Analysis of Variance Summary for Rest Time Data.

Source	DF	Type III SS	Mean Square	F value	P > F
Session [T]	1	0.16	0.16	0.89	0.3623
Angle [A]	1	58.08	58.08	79.91	0.0001*
Oral Contraception Use [C]	1	1.57	1.57	0.22	0.6484
Subject(Oral) [S(C)]	14	100.90	7.21	27.51	0.0001*
T x A	1	0.48	0.48	1.82	0.1988
T x C	1	0.74	0.74	4.17	0.0603
T x S(C)	14	2.49	0.18	0.68	0.7609
A x C	1	0.002	0.002	0.00	0.9598
A x S(C)	14	10.17	0.73	2.77	0.0331*
T x A x C	1	0.17	0.17	0.64	0.4368

* - Denotes significance at the $\alpha = 0.05$ level.

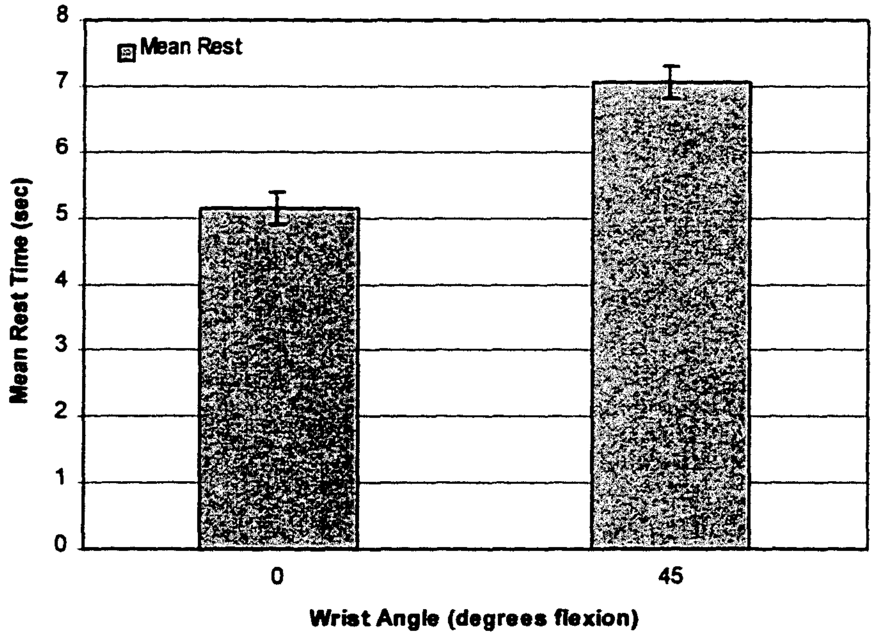


Figure 21: Mean Rest Time by Wrist Angle.

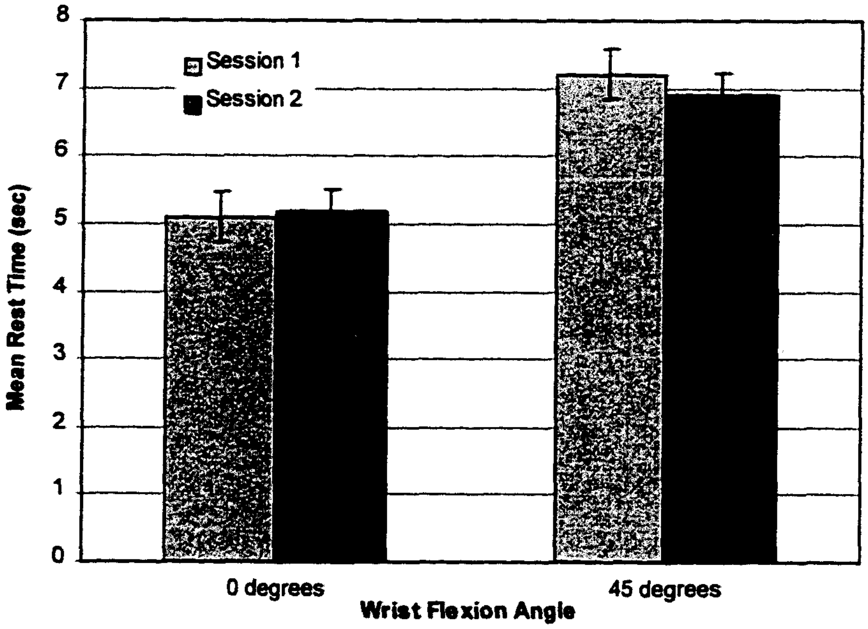


Figure 22: Mean Rest Time by Wrist Angle and Session.

Abu-Ali (1993) reported a mean rest time of 3.42 sec for a 25% MVC task with a 5-second exertion period. The values found in his study ranged from 1.67 to 3.42 seconds for the 25% MVC load and from 2.77 to 9.83 seconds for the 50% MVC load. The mean rest time Abu-Ali found at 25% MVC (3.42 sec) is a third of the value found in this study. The difference is likely due to the difference in MVC values. This study used an MVC percentage that was shown by Simonson (1971) and Åstrand and Rodahl (1977) to begin blood flow occlusion during muscular contraction. The 25% MVC level used by Abu-Ali may not have created this condition. Subjects in the current study exerted a greater % MVC than those in the Abu-Ali study and possibly needed more rest time to perform at a pace that was comfortable to them without experiencing pain.

4.4 Maximum Acceptable Frequency Analysis

Maximum acceptable frequency (MAF) was reported by Kim (1991), Marley (1990) and Abu-Ali (1993). This value was calculated by adding the exertion time (5 seconds) to the rest time, taking the inverse of the result, and multiplying this by 60 to produce MAF in repetitions per minute (rpm). Since MAF is calculated from the inverse of the rest time, the data are consistent and opposite the rest time data. Frequency data were analyzed using a repeated-measures design with session (1, 2), and angle (0°, 45) as within-subject factors. The experimental model can be stated as follows:

$$Y_{ijkl} = \mu + T_i + A_j + C_k + S(C)_{l(k)} + TA_{ij} + TC_{ik} + TS(C)_{il(k)} + AC_{jk} + AS(C)_{jl(k)} + TAC_{ijk} + \varepsilon_{ijkl}$$

where Y_{ijkl} = MAF for the ith session, the jth angle, the kth oral contraception use and the lth subject,

μ = overall main effect,

T_i = effect due to session, $i = 1, 2$,

A_j = effect due to wrist angle, $j = 1, 2$,

C_k = effect due to oral contraception use, $k = 1, 2$,

$S(C)_{l(k)}$ = subjects nested within oral contraception use, $l(k) = 1, ..., 16$, $k = 1, 2$, and

ε_{ijk} = random error.

Mean MAF values were 5.08 rpm for 45° wrist flexion and 5.99 rpm for the wrist neutral position. Figure 23 shows the mean MAF data for this study. Mean MAF values for Session 1 and Session 2 were almost identical (5.51 rpm and 5.56 rpm, respectively).

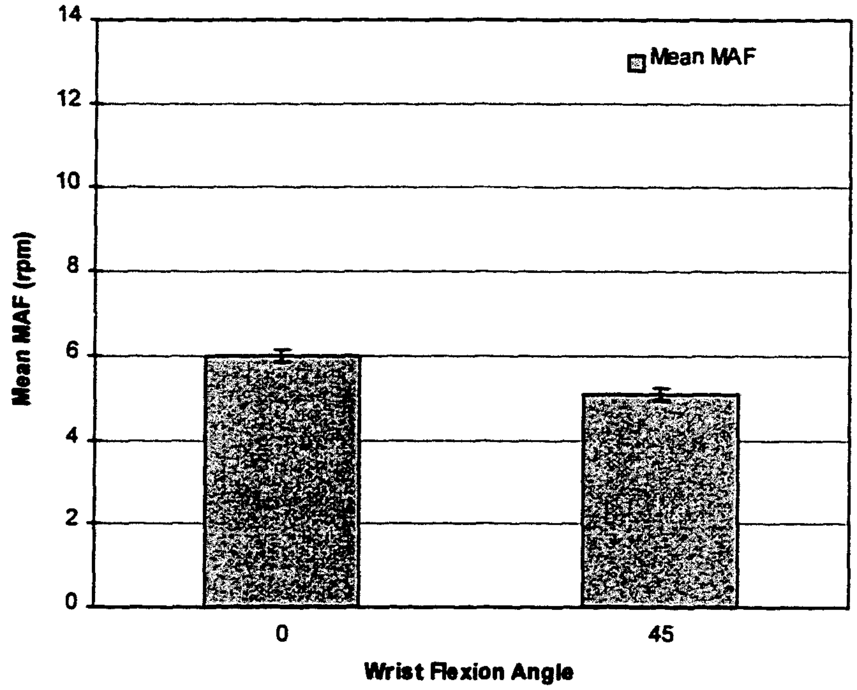


Figure 23: Mean MAF by Wrist Flexion Angle.

Statistical analysis of MAF revealed that Wrist Angle was significant ($F(1, 14) = 72.78$, $p < 0.0001$) as were subject, and the Session x Oral Contraception, and Angle x Subject interactions (Table 14). There was no significant difference between the first and second session MAF values. The statistical significance of the Session x Oral Contraception interaction term was noted with interest. Further analysis revealed a possible reason for the statistical significance of this interaction term for MAF. Figure 24 shows that the mean MAF values for subjects not using oral contraception increased from Session 1 to Session 2, while the opposite was true for subjects using oral contraception. Graphical analysis of the data for individual subjects revealed that subjects 9 and 11 had large changes in the mean rest time (and thus, MAF) from Session 1 to Session 2. Both subjects did not use oral contraception. When these subjects were removed from the analysis, the interaction term for MAF was no longer significant ($F(1,12) = 3.60, p < 0.0822$). It appears that these two subjects were responsible for the significant Session by Oral Contraception interaction found in Rest Time and MAF.

Table 14. Analysis of Variance Summary for MAF Data.

Source	DF	Type III SS	Mean Square	F value	P > F
Session [T]	1	0.17	0.17	0.47	0.5020
Angle [A]	1	13.51	13.51	72.78	0.0001*
Oral Contraception Use [C]	1	0.02	0.02	0.01	0.9171
Subject(Oral) [S(C)]	14	28.05	2.00	45.92	0.0001*
T x A	1	0.08	0.08	1.78	0.2034
T x C	1	0.20	0.20	5.61	0.0327*
T x S(C)	14	0.50	0.04	0.82	0.6388
A x C	1	0.08	0.08	0.43	0.5234
A x S(C)	14	2.60	0.19	4.26	0.0052*
T x A x C	1	0.002	0.002	0.04	0.8353

* - Denotes significance at the $\alpha = 0.05$ level.

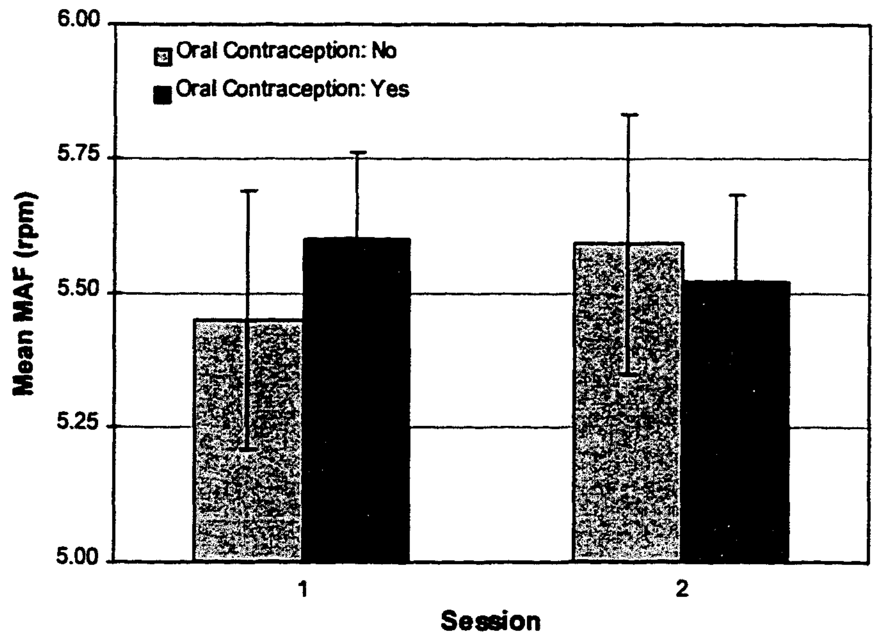


Figure 24: Session by Oral Contraception Interaction.

Maximum acceptable frequency has been reported in three previous studies. Marley (1990) and Kim (1991) investigated a simulated drilling task using female subjects. Both studies used a twenty-five minute task. Marley used a 1-second exertion period while Kim used a five-second period. The mean MAF values for these studies ranged from 10.67 rpm (Marley, 1990, 0° wrist flexion) to 3.79 rpm (Kim, 1991, 20° wrist flexion). The current study reported a MAF of 5.08 rpm at 45° wrist flexion. The two studies most closely related were Kim (1991) and the current study. Kim recorded MAF values at 0° and 20° wrist flexion with 8.2 kg (18 lbs) of force, compared to 0° and 45° wrist flexion with 30% MVC (mean of 9.2 kg, 20.2 lbs). Both studies used a five-second exertion period. Figure 25 shows a similar relationship between wrist neutral and wrist flexion for the two studies. MAF decreased as wrist flexion increased. Kim reported a difference of 28% between the two wrist angles compared to a 15% difference in this study. The direction of the percent differences was unexpected. Comparing the two studies, the current study would be expected to have the larger percentage difference. One explaination for this would come from the subjects used. Performance was relatively stable in the current study. Subjects in Kim's study could have been more variable, increasing the MAF range, and thus producing a large percentage difference.

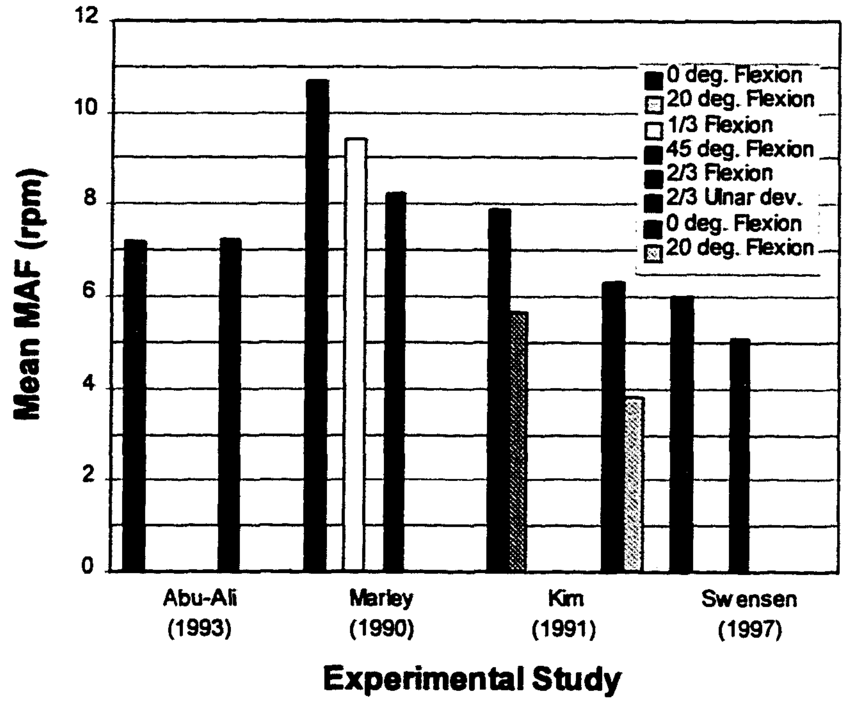


Figure 25: Mean MAF Values by Experimental Study.

Similarly, Marley (1990) showed decreases from a wrist neutral posture to a wrist flexion posture. He found a decrease of 12% from a wrist neutral posture to a 1/3 θ flexion angle (where θ = maximum wrist flexion angle for a particular subject), and a 23% decrease from wrist neutral to a 2/3 θ flexion angle. Abu-Ali (1993) is the only study that did not report a decrease from the wrist neutral posture to a deviated wrist posture. He studied a wrist neutral and 2/3 θ ulnar deviation wrist posture. However, he also used 25% and 50% MVC where the MVC was generated at each wrist position. Thus, two differenet MVC values were used, one at the wrist neutral position and one at the 2/3 θ ulnar deviation position. The fact tha the force level used for a particular wrist angle was based on the MVC for that wrist angle could account for the stable MAF values reported in Abu-Ali's study.

4.5 Test-Retest Reliability Analysis

The main aspect of this study was to determine the test-retest reliability of rest interval values determined for a hand grasping task using the psychophysical method of adjustment. In other words, this study investigated the ability of subjects to obtain similar rest time values when the measurements were repeated one week later under the same conditions. There were two test sessions for each wrist angle, separated by seven days. The most commonly used correlation coefficient for evaluating test-retest reliability, the Pearson Product-Moment Correlation coefficient (*r*) was used to describe the degree of correspondence between two sets of data. A high correlation using this measure along with the lack of a significant change in rest time would indicate that subject performance remained stable over the test sessions. A low coefficient or reliability would indicate that the performance measure was not reliable due to random fluctuation over time or the influence of uncontrolled factors.

Pearson Product-Moment Coefficients were computed for the study. Analysis of the entire data set was performed and a secondary analysis was conducted to test the sensitivity of the coefficients to individual subject contributions. The secondary analysis iteratively removed each subject from the data set and recomputed the correlation using the remaining fifteen subjects. Removing a subject from the data set tests the extent to which the correlation was driven by that particular subject. The data set was analyzed in its entirety and separately for each wrist angle. Table 15 shows the overall test-retest reliability coefficients and Table 16 shows the test-retest reliability coefficients with individual subjects deleted. Table 17 presents the research data in tabular form.

Table 15: Test-Retest Reliability Coefficients.

Data Set	Pearson Product-Moment Correlation Coefficients (n = 16 pairs)
Complete	0.9235
0° Wrist Flexion	0.9370
45° Wrist Flexion	0.8760

Table 16: Sensitivity Analysis of Test-Retest Reliability Coefficients.

	Data Set		
Subject Deleted	Complete	0° Wrist Flexion	45° Wrist Flexion
1	0.9281	0.9470	0.8803
3	0.9221	0.9370	0.8772
4	0.9248	0.9529	0.8768
5	0.9228	0.9296	0.8768
6	0.9223	0.9391	0.8772
8	0.9216	0.9333	0.8762
9	0.9256	0.9350	0.8796
10	0.9209	0.9341	0.8783
11	0.9306	0.9129	0.8760
12	0.9221	0.9370	0.8772
13	0.9254	0.9385	0.8834
14	0.9221	0.9475	0.8752
15	0.9211	0.9475	0.8752
16	0.9300	0.9456	0.8884
17	0.9271	0.9348	0.8899
18	0.9140	0.9227	0.8350

The test-retest reliability coefficient for the overall study was 0.9235. The reliability coefficients were slightly higher for the wrist neutral posture (0.94) and slightly lower for the wrist flexion posture (0.88). This indicates that the rest intervals determined by the psychophysical method of adjustment were highly repeatable across a one-week period. There was a 6.5% difference between the rest time correlations of wrist neutral and 45° wrist flexion. This would indicate that there was slightly more variability present for rest times at the 45° wrist flexion angle than in the wrist neutral posture.

Table 17: Research Data Summary.

Subject #	Training 1[1] MVC (kg)	Training 2[2] MVC (kg)	Order[3]	Wrist Angle (0°, wrist neutral) Session 1 MVC PRE (kg)	MVC POST (kg)	Rest Times (sec)	Subjective Rating	Session 2 MVC PRE (kg)	MVC POST (kg)	Rest Times (sec)	Subjective Rating	Wrist Angle (45° wrist flexion) Session 1 MVC PRE (kg)	MVC POST (kg)	Rest Times (sec)	Subjective Rating	Session 2 MVC PRE (kg)	MVC POST (kg)	Rest Times (sec)	Subjective Rating
1	22.7	20.9	0	23.0	22.5	5.00	7.50	23.2	24.2	4.33	7.25	25.5	24.8	5.66	9.00	25.7	22.1	6.33	9.00
3	32.1	31.6	0	33.6	29.1	7.00	7.25	33.6	31.9	7.00	6.75	32.0	29.6	5.00	6.25	33.7	31.8	5.00	5.50
4	32.6	34.4	0	33.1	29.7	6.33	4.75	31.8	29.8	5.66	4.00	33.7	29.6	7.66	7.00	34.1	30.8	7.00	5.50
5	40.6	39.4	0	41.7	39.0	6.66	6.00	41.0	43.4	6.66	6.00	43.4	42.9	7.66	8.50	44.4	45.8	7.00	9.00
6	26.0	26.0	0	35.9	37.8	4.66	5.25	26.6	29.0	5.00	4.75	28.2	27.5	7.00	5.25	26.0	31.7	7.00	4.75
8	22.6	23.1	0	23.9	20.3	6.00	2.75	25.3	20.2	6.33	3.00	23.2	21.1	4.00	1.00	20.9	19.7	3.66	1.25
9	25.7	27.9	0	32.5	31.8	6.00	4.25	31.6	31.2	6.00	3.75	30.6	30.2	9.67	6.75	32.2	29.2	8.00	5.50
10	27.1	27.5	45	27.6	27.6	6.00	3.75	28.1	28.4	6.33	6.50	26.9	24.4	9.00	8.50	28.1	27.8	9.33	4.75
11	23.2	24.8	45	21.8	22.7	7.33	4.75	24.2	22.3	8.00	4.75	23.9	23.8	11.33	5.50	23.9	23.2	9.00	6.25
12	34.3	32.8	45	34.7	34.1	5.00	3.00	35.5	34.1	5.00	2.00	33.4	31.2	7.00	4.00	34.5	32.0	7.00	3.00
13	29.3	29.7	0	31.6	29.6	4.33	5.50	30.3	29.8	4.66	7.00	30.8	29.3	6.00	4.50	29.6	27.1	6.67	4.00
14	34.1	33.3	45	31.5	27.6	5.00	0.75	32.9	28.9	5.00	0.75	33.3	30.7	7.00	0.75	32.2	25.9	7.00	0.50
15	32.1	30.1	45	34.5	33.1	3.66	4.50	33.8	33.0	4.33	6.25	37.6	28.0	6.66	5.25	29.2	29.7	6.33	5.50
16	40.3	40.6	45	40.0	36.2	5.00	7.50	41.6	37.0	5.66	8.25	40.8	36.7	5.66	8.25	40.8	36.7	6.66	7.00
17	29.3	30.1	45	30.2	26.8	4.33	8.00	30.1	27.7	4.33	7.00	30.0	27.6	7.66	5.50	29.5	29.1	6.33	5.50
18	37.0	42.2	45	38.3	33.1	3.33	4.50	42.7	39.3	3.00	4.75	40.0	32.9	3.33	6.50	39.0	34.8	2.66	5.50
$\bar{x}$	30.6	30.9		32.1	30.1	5.35	5.00	32.0	30.6	5.46	5.17	32.1	29.4	6.89	5.78	31.4	29.9	6.56	5.16
σ	5.84	6.12		5.80	5.45	1.17	1.96	6.0	5.99	1.25	2.08	6.01	5.22	2.04	2.42	6.16	6.32	1.69	2.28

[1] Training session 1 was at wrist neutral posture.
[2] Training session 2 was at 45° wrist flexion posture.
[3] Indicates wrist angle presentation order, 0 = wrist neutral posture presented first and 45 = 45° wrist flexion posture presented first.

4.6 Subjective Ratings Analysis

Subjects were asked to mark the difficulty of the session along a 10 cm horizontal line similar to Swensen (1987, 1992). This line had three anchors from which the subjects could gauge their response. The lower end of the scale was marked with the notation "moving the handles with no weight", the upper end had the notation "maximal force squeeze" and the middle was marked as "middle". Subjects were exposed to both boundary conditions during the first training session and asked to use these extremes in marking their difficulty scores. After concluding each experimental session, the subject was asked to place a vertical tick mark across the line at the appropriate difficulty level and was asked to score the difficulty of the session. The subjective ratings were scored on a 0 to 10 scale subdivided into quarter point increments. The mean ratings by session and by angle are shown in Figures 26 and 27, respectively. Analysis of variance identified no statistically significant main effects or interactions with the exception of the subject main effect ($F(14,14)=16.13$, $p < 0.0001$). Figure 28 shows the mean ratings by angle and session.

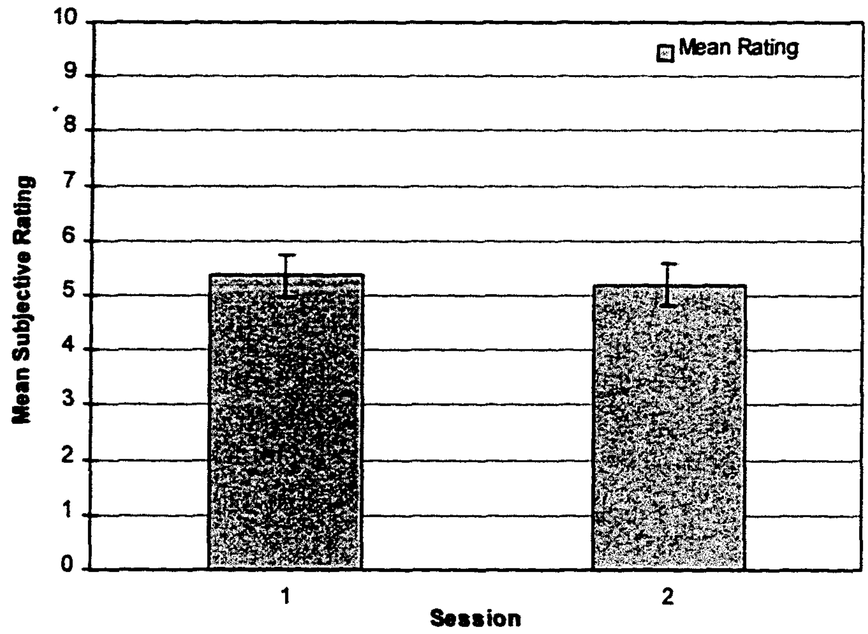


Figure 26: Mean Subjective Rating by Session.

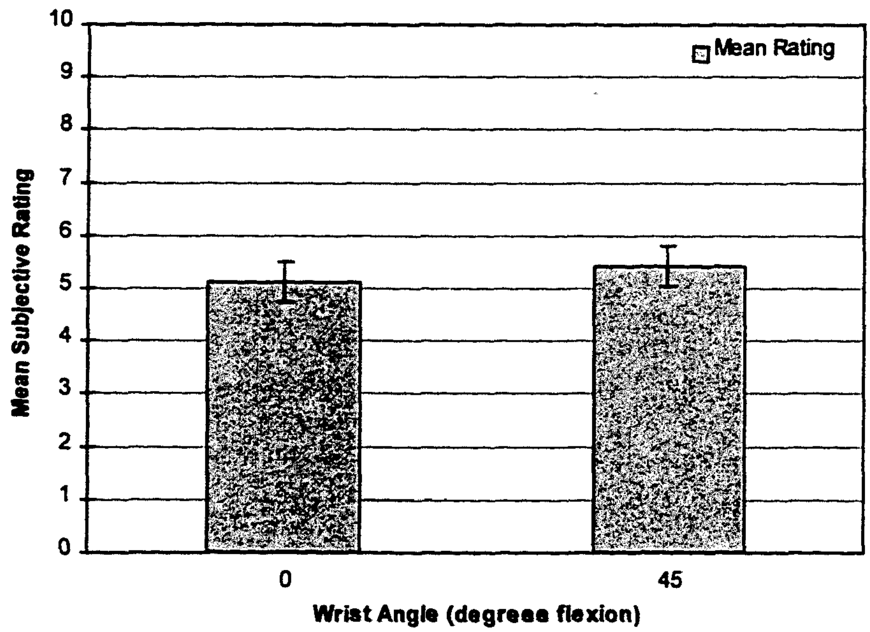


Figure 27: Mean Subjective Rating by Wrist Angle.

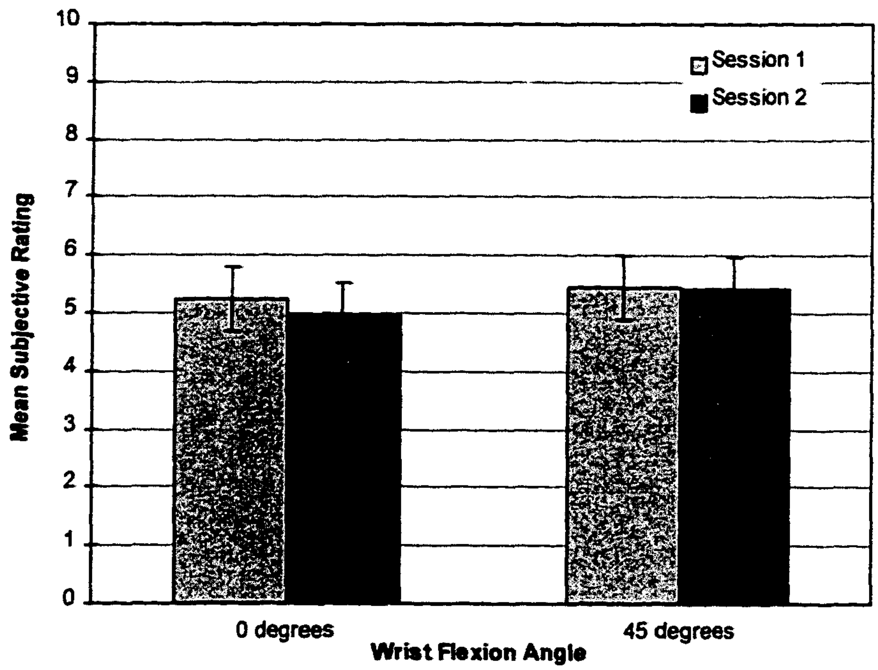


Figure 28: Mean Subjective Rating by Wrist Angle and Session.

It is interesting to note the lack of significance in the mean ratings by angle. One may suspect that the 45° wrist flexion angle would show higher subjective difficulty ratings. However, when one considers that the subjects were able to adjust the rest time to a pace they could comfortably work for eight hours, then this is not surprising. Mean ratings were 5.11 and 5.43 for 0° and 45°, respectively. This is in the middle of the subjective difficulty rating scale. These scores are very close to the ratings Abu-Ali (1993) obtained for a five-second exertion time at 25% MVC using a 0 to 100 scale (Figure 29). Abu-Ali (1993) obtained a mean subjective rating of 48 (out of 100) and 48.33 for 0° and 2/3 maximum ulnar deviation, respectively. The subjects were asked to report a subjective rating of difficulty of the task. This would include the exertion time, the load and the rest interval. The instructions presented to the subject stressed the need to work as fast as possible without experiencing pain. It is apparent from these studies that subjects rate a workload of five seconds and a rest interval of 3 to 7 seconds at a 25%-30% MVC level near the middle of a difficulty rating scale. From the perspective of scaling subjective data, the results indicate that subjects adequately understood the rating process and that the scale anchors were appropriately defined.

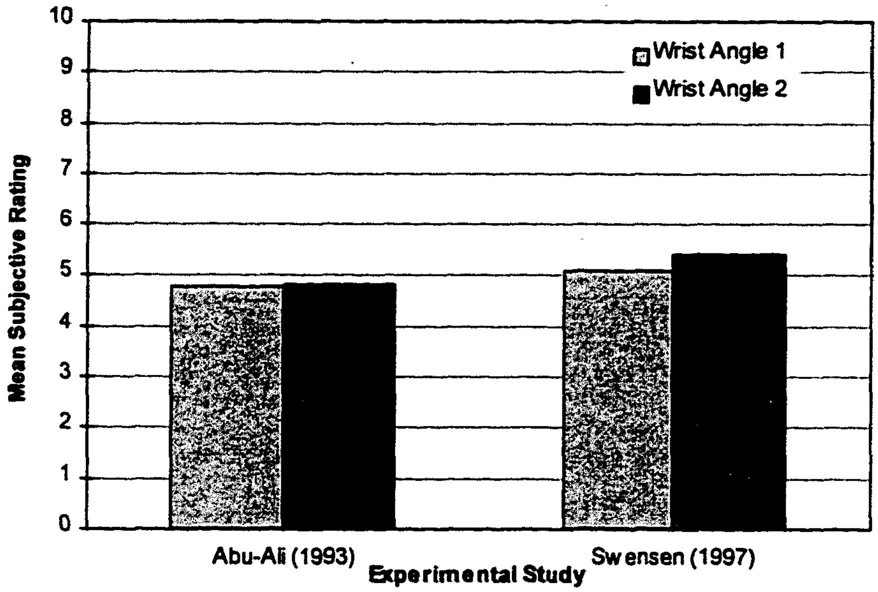


Figure 29: Comparison of Mean Subjective Ratings by Experimental Study.

4.7 Covariate Analysis

Analysis of the anthropometric measures was performed to investigate whether any of these measures had an effect upon the data. Previous studies indicated that smaller hand length, wrist thickness and wrist circumference were associated with an increased incidence of CTS symptoms (Crumpton and Congleton, 1994). Abu-Ali (1993) indicated that grip span, hand length, hand breadth, hand thickness, wrist length, wrist thickness and wrist circumference correlated positively with MVC. The results of this study indicated that grip span, hand length, hand breadth, wrist breadth and wrist circumference were significant covariates of pre-session MVC (Table 17). Not surprisingly, this study and that of Abu-Ali (1993) showed that the size of the hand and wrist are significant factors for MVC force generation. With evidence from previous studies that hand length, wrist thickness and wrist circumference are correlated with CTS symptoms, these anthropometric measures should be further studied to determine their relative significance in predicting the onset of CTS symptoms.

All anthropometric measures were significant covariates of rest time with the exception of wrist breadth and wrist circumference (Table 18). Similarly, when comparing the anthropometric data with the mean subjective ratings, all anthropometric measures were significant with the exception of wrist thickness and wrist circumference (Table 19).

Table 18. Analysis of Covariance Summary of Anthropometric Measures on Pre-Session MVC.

Source	DF	Type III SS	Mean Square	F value	P > F
Grip Span	1	2664.96	2664.96	220.82	0.0001*
Hand Length	1	350.24	350.24	29.02	0.0001*
Hand Breadth	1	4400.38	4400.38	364.62	0.0001*
Wrist Breadth	1	445.02	445.02	36.87	0.0001*
Wrist Thickness	1	7.99	7.99	0.66	0.4295
Wrist Circumference	1	79.51	79.51	6.59	0.0224*

* - Denotes significance at the $\alpha = 0.05$ level.

Table 19. Analysis of Covariance Summary of Anthropometric Measures on Subject-Determined Rest Time.

Source	DF	Type III SS	Mean Square	F value	P > F
Grip Span	1	12.45	12.45	47.52	0.0001*
Hand Length	1	18.48	18.48	70.52	0.0001*
Hand Breadth	1	21.23	21.23	81.03	0.0001*
Wrist Breadth	1	0.14	0.14	0.53	0.4775
Wrist Thickness	1	1.77	1.77	6.74	0.0211*
Wrist Circumference	1	0.78	0.78	2.97	0.1069

* - Denotes significance at the $\alpha = 0.05$ level.

Table 20. Analysis of Covariance Summary of Anthropometric Measures on Subjective Ratings.

Source	DF	Type III SS	Mean Square	F value	P > F
Grip Span	1	13.90	13.90	14.96	0.0017*
Hand Length	1	4.64	4.64	5.00	0.0422*
Hand Breadth	1	31.90	31.90	34.35	0.0001*
Wrist Breadth	1	8.19	8.19	8.82	0.0101*
Wrist Thickness	1	1.57	1.57	1.70	0.2134
Wrist Circumference	1	0.25	0.25	0.27	0.6116

*- Denotes significance at the $\alpha = 0.05$ level.

4.8 Correlation Analysis

Pearson correlation coefficients were calculated for the the anthropometric measures and dependent variables. The following coefficients were significant at $\alpha = 0.05$ (Table 20). The anthropometric measures all correlated positively with each other. The highest correlation values were found between grip span and hand length, grip span and hand breadth, hand length and hand breadth and hand breadth and wrist breadth. Rest time correlated negatively with grip span and hand breadth. Pre-session MVC correlated positively with all anthropometric measures. Post-session MVC correlated positively with all anthropometric measures and subjective rating. Subjective rating correlated negatively with hand length.

Table 21: Significant Pearson Correlation Coefficients.

	GRIP	HLEN	HBRE	WBRE	WTHI	WCIR	REST	MVC1	MVC2	RATE
Grip Span (GRIP)		0.7743	0.8191	0.6480	0.5051	0.4725	-0.2635	0.5094	0.5169	
Hand Length (HLEN)			0.7659	0.7414	0.5076	0.5314		0.5113	0.5514	-0.2498
Hand Breadth (HBRE)				0.8332	0.3874	0.6588	-0.3330	0.8056	0.7539	
Wrist Breadth (WBRE)					0.4554	0.5976		0.7804	0.7859	
Wrist Thickness (WTHI)						0.2692		0.2790	0.3577	
Wrist Circumference (WCIR)								0.6297	0.5743	
Rest										
Pre-session MVC (MVC1)										
Post-Session MVC (MVC2)										0.2678
Rating										

(All correlations are significant at $\alpha = 0.05$)

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study investigated the test-retest reliability of a psychophysical method to determine acceptable rest times for a repetitive power hand grasp. The study used the psychophysical method of adjustment and used a dynamic hand dynamometer built by the experimenter. A computer program automatically recorded data for deriving the response variable and featured a system to prompt the subject to squeeze a movable handle, thus simulating an assembly line environment, and audible tone feedback to allow the subject to evaluate performance.

The force level as a percent of MVC, the exertion time and the time between test sessions were fixed, while two different wrist postures were studied. Sixteen female subjects participated in the experiment. They were instructed to repetitively grasp the handles at a maximum acceptable frequency controlled by varying the rest time between grasps. Rest time, frequency, and task difficulty ratings were recorded and analyzed for each subject. The force used was normalized to 30% of each subject's MVC. Each subject was exposed to both wrist angle conditions. Each of the two wrist angles was tested twice, with one week separation between sessions. There were two training sessions to expose each subject to each wrist angle condition prior to collection of experimental data.

Analysis of variance procedures were conducted yielding the following results:

1. One-week test-retest reliability of subject-determined rest times was high (0.9235). When isolated by wrist angle, the test-retest correlation was 0.94 for the 0° wrist neutral condition and 0.88 for the 45° wrist flexion condition. Sensitivity analysis of the correlation values revealed that they were not unduly influenced by individual subjects.
2. Mean MVC values increased from Session 1 to Session 4, with no statistically significant difference among Sessions 1, 2 and 3, and Sessions 1, 3 and 4. The mean pre-session MVC value was higher than the mean post-session MVC value. The pre-post by session interaction term was also statistically significant.
3. Wrist angle and individual subject differences significantly affected rest time, with the 45° wrist flexion condition requiring a greater rest time. Additionally, the angle by subject and the session by oral contraception interaction term were significant.
4. MAF was significantly affected by angle, subject, the session by oral contraception interaction and the angle by subject interaction.
5. Subjective difficulty ratings were not affected by any main effect or interaction with the exception of the subject main effect. This was not unexpected since the subject was able to adjust the rest time to what could be comfortably maintained for an eight-hour work period.

Pearson correlation coefficients were calculated for the the anthropometric measures and dependent variables. The following coefficients were significant at α = 0.05 (Table 20). The anthropometric measures all correlated positively with each other. The highest correlation values were found between grip span and hand length, grip span and hand breadth, hand length and hand breadth and hand breadth and wrist breadth. Rest time correlated negatively with grip span and hand breadth. Pre-session MVC correlated positively with all anthropometric measures. Post-session MVC correlated positively with all anthropometric measures and subjective rating. Subjective rating correlated negatively with hand length.

5.2 Recommendations

This study showed that female subjects were able to produce subjectively-determined rest times with a high degree of reliability. This research study seems to confirm the validity of the methodology used by Abu-Ali (1993), Marley (1990) and Kim (1991). Future research using this methodology should address the following areas:

1. Conduct further studies to investigate the impact of starting point variation on reliability. As noted in the pilot study, the starting rest interval used by the experimenter had an impact upon the final rest interval selected by the subject. This finding is important as it impacts future psychophysical studies and should be fully understood.

2. Conduct a field study using female assembly line personnel to compare with the reliability values found in this study. If the methodology is to simulate an industrial environment, then researchers should know whether there is any difference in results obtained among an experienced work population versus an inexperienced one.
3. Investigate the effect of other wrist postures and percent of MVC load upon the reliability values, rest time, MAF and subjective ratings.
4. Broaden the available body of research using this methodology by investigating the effect of gender upon the reliability of this measure.
5. Investigate the use of this method to determine acceptable limits for exertion time, force and wrist posture requirements.

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Appendix A

Anatomy and Physiology of the Hand and Wrist

Anatomy of the Hand and Wrist

The hand is made up of three groups of bones, the wrist bones (carpals), the bones of the palm (metacarpals) and the fingers (phalanges). There are eight carpal bones which are arranged in two rows of four bones each. The bones of the wrist on the ulnar row are known as the scaphoid, lunate, triangular and pisiform. The bones of the distal row are the trapezium, trapezoideum, capicate and hamate. The metacarpal bones are numbered I through V, starting from the thumb or radial side. The digits of the hand or phalanges consist of fourteen bones, three for each finger and two for the thumb (Rasch and Burke, 1978).

The wrist joint or radiocarpal joint is a condylar articulation formed by the distal end of the radius and distal surface of the articular disk of the scaphoid, lunate and triangular bones (see Figure A-1). The three bones slide across the end of the radius, the direction of movement depending upon the nature of the movement. The intercarpal articulation is a gliding joint between two rows of the carpal bones. It has its own synovial sac which often includes portions of the carpometacarpal joint. The wrist permits all movement except rotation. Abduction (radial deviation or radial flexion) is a bending of the wrist to the thumb side. The movement of the hand to the little finger side is called adduction (ulnar deviation or ulnar flexion). Bending the wrist so that the palm approaches the anterior surface of the forearm is called flexion and the reverse movement is called extension. A combination of these movements produces circumduction, which allows the hand to travel through 270°. The seven carpal bones are spanned on the palmar side by the flexor retinaculum ligament and on the dorsal side by the extensor retinaculum. These ligaments band the wrist and contain in place most of the wrist, arteries, veins and the median nerve. The flexor retinaculum ligament and the carpal bones enclose the area known as the carpal tunnel. (Rasch and Burke, 1978).

The carpometacarpal joints are gliding joints except for the first (thumb) which is a saddle joint with a thick, loose capsule. Metacarpals II through V are united to nearby carpal bones and to each other by the dorsal, palmar and interosseous ligaments. The five metacarpophalangeal joints (MP joints) each have a capsule, one palmar and two collateral ligaments. Metacarpals II, III, IV, and V are joined to one another by the transverse carpal ligament on the palmar aspect (see Figure A-2). Each finger has two interphalangeal joints (IP joints) with the exception of the thumb, which has one IP joint. Each finger has a proximal and distal interphalangeal joint (PIP and DIP, respectively). All IP joints are hinged joints capable of only flexion and extension and each has a capsule, one palmar and two collateral ligaments (Rasch and Burke, 1978).

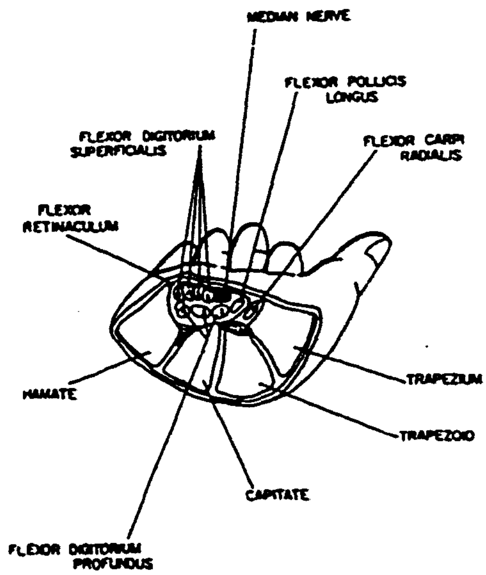

Figure A-1: Anatomy of the Wrist (from Armstrong and Chaffin, 1979).

There are six principal muscles acting on the wrist joint, they are the flexor carpi radialis, palmaris longus, flexor carpi ulnaris, extensor carpi radialis longus, extensor carpi radialis brevis and extensor carpi ulnaris. Of these, the palmaris longus does not act upon the wrist, but tightens the fascia of the palm. The flexor carpi radialis produces flexion and abduction of the wrist and the flexor carpi ulnaris produces flexion and adduction of the wrist. The extensor carpi radialis longus and brevis both produce extension and abduction of the wrist while the extensor carpi ulnaris produces extension and adduction of the wrist.

During extension of the wrist, there is reciprocal innervation between extensors and flexors. The extensor carpi radialis and extensor carpi ulnaris work synchronously. During forced extreme flexion, there is a reactive co-contraction of the extensor carpi ulnaris which stabilizes the wrist joint. This does not occur in the extensor carpi radialis. During flexion of the wrist, the flexor carpi radialis and ulnaris act synchronously while the radial extensors of the wrist are passive. In extreme flexion of the wrist, the extensor carpi ulnaris shows activity as an antagonist. In abduction and adduction, the appropriate flexors and extensors act reciprocally, with the antagonist muscles relaxing (MacConaill and Basmajian, 1969).

There are three muscles in the forearm that act on all four fingers at once, they are the flexor digitorum superficialis, flexor digitorum profundus and extensor digitorum. Action from the flexores digitorum superficialis and profundus aid in wrist flexion while the extensor digitorum aids in extending the wrist. During the act of grasping an object with a power grasp, the phalanges are flexed around the object by the flexores digitorum superficialis and profundus inserted on the palmar side of the middle and distal phalanges of the four fingers. These fingers are innervated by the median nerve that travels through the carpal tunnel to reach the phalanges. The long flexor tendons are kept in close contact with the phalanges by the flexor retinaculum which serves as a pulley. All the muscles of the fingers and thumb are active. The thenar and hypothenar muscles keep the hand in contact with the object grasped. The hypothenar muscles are important to stabilize the medial side of the palm against the handle and the muscles of the fingers and thumb grasp the handle. The wrist extensors are active to provide a stable base for the gripping action and they increase the tension in the long finger flexors and prevent them from acting on the wrist. As the hand grips harder, the wrist extensors increase their activity (Tyldesley and Grieve, 1989).

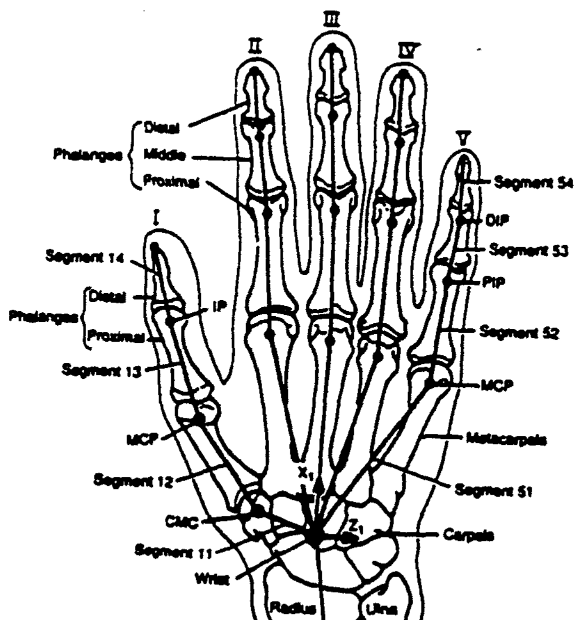

Figure A-2: Anatomy of the Hand (from Buchholz, Armstrong, and Goldstein, 1992).

Anatomy of the Fingers

The mechanism of the DIP, PIP and MCP joints in simultaneous participation results from the actions of the extensor digitorum, flexor superficialis and the flexor profundus in conjunction with the lumbrical and interosseous muscles. The DIP joint has two insertions, the flexor profundus on its volar aspect and the extensor on the dorsal aspect. The distal joint is formed by the junction of the base of the distal phalanx with the head of the middle phalanx. Volarly, the articulation permits flexion to almost 90°. The PIP differs from the DIP in the connections between the ligaments and the extensor and flexor systems. Except for slight variation in size, there are no differences in the PIP joints of the four fingers (Spinner, 1984). The PIP joints are important in the control of extension and flexion of the entire finger. In extension of the joint, the dorsal expansion must remain centered to avoid displacement in relation to the transverse axis of the joint and the longitudinal axis of the finger. In flexion, the dorsal expansion must maintain its central position without displacement volar to the transverse axis of the joint. The metacarpophalangeal (MCP) joint is not a hinged joint like the DIP and PIP joints, but a multiaxial condyloid joint permitting flexion, extension, abduction, adduction and to some degree, circumduction. The extensor digitorum ligament reinforces the joint, with the ligament taut in flexion and more relaxed in extension. Although the ligament aids to the stability of the of the joint, the actual stability of the fingers at the MCP joint is provided by the contraction of the intrinsic muscles and the tautness of the flexor tendons and the extensors (Spinner, 1984).

Finger Flexion

Flexion takes place only when the fingers are relaxed. Strong finger action requires a rigid wrist. It is not possible to achieve complete flexion of the fingers and the hand simultaneously, because the antagonistic muscle, the extensor communis digitorum, will not stretch sufficiently to permit it. When complete flexion of the fingers is desired, the wrist can be flexed to about half its usual range. This involuntary movement is due to the tendon or pulley action of multijoint tendons (Wells, 1955).

Finger Extension

Extension of the human finger is achieved by a complex mechanism. In the normal finger, extension of the DIP is performed entirely by the lateral bands. The oblique retinacular ligament acts as a retaining ligament maintaining tendon centralization on the dorsum of the finger. The extensor mechanism of the PIP may be thought of as a trifurcation of the extensor tendon into the central slip and the two lateral bands. The central slip of the extensor tendons inserts into the base of the middle phalanx while the two lateral bands pass on either side of the PIP and fuse distally into the distal phalanx. The entire joint is held centered over the joint by the transverse ligaments. This mechanism must be in balance. The lengths of the central clip and of the two lateral bands must be such that extension of the PIP and the DIP takes place together. When the middle phalanx is brought into alignment with the proximal phalanx, the distal phalanx is aligned at the same instant. Within the range of normal function of the finger about the MCP, the proximal slip of the extensor never becomes tight, but swings back and forth with the movements of the extensor. If the MCP joint is held in position and the fingers are flexed and extended, flexion is accomplished by the profundus tendon. Extension of the DIP and PIP is accomplished by the intrinsics (Harris and Rutledge, 1972).

Co-contraction

Co-contraction has been described as being inefficient since muscles are fighting each other without producing a net movement (Winter, 1990). During a power hand grasp, co-contraction occurs to stabilize the finger joints. DeLuca and Mambrito (1987) found that coactivation was used under two conditions: either during states of uncertainty about the required task or when a compensatory force correction is required. Marsden, Obeso, and Rothwell (1981) found that when movements were halted mechanically with the subject's prior knowledge there was little or no antagonist activity. They found that the action of the antagonist muscle assisted in halting fast movement. The amount and timing of the antagonistic activity was adjusted to the circumstances (braking activity) and did not occur where it was not needed. It was found that if a subject moved through a small distance quickly, the antagonist burst was large and started soon after the agonist fired. Winters, Stark, and Seif-Naraghi (1988) found that people tended to voluntarily change the co-activation level of the antagonistic muscles when a "stiffer" or "less stiff" limb was desired.

Tendon Physiology

Muscle fibers are wrapped and separated by connective tissue, or endomysium. These bundles are grouped into units of about 150 fibers into the fasciculus which is surrounded by the perimysium. This system is further grouped into larger bundles and surrounded by the fibrous connective tissue of the epimysium. The epimysium is a protective sheath that is tapered at its distal end and blends in and joins intramuscular tissue sheaths to form tendons. Tendons are made of collagen fibers arranged in parallel bundles. Tendons are found surrounded by fibrous tissue in which friction would create problems in movement. To counter this friction problem, the tendon has an inner lining, the synovium, which produces synovial fluid. Synovial fluid allows the tendon to glide easily within the tendon sheath. Transverse ligaments, such as the transverse carpal ligament, exist to provide the function of pulleys and tendon guides. This allows tendons to function around corners, such as those found in the hand.

The Golgi tendon organs are the tendon sensory receptors. The Golgi tendon organs are located in the ligaments of joints and are responsible for detecting differences in muscle tension. The Golgi tendon organs are connected in series to about 25 extrafusal muscle fibers. The function of the Golgi tendon organ is to respond to tension created in the muscle when it shortens or is passively stretched. They act as a protective sensory mechanism in that when the change in tension or stretch is too great, they discharge to depress the activity of the motoneurons and reduce the tension generated in the muscle fibers. They protect the muscle and its connective tissue from injury due to excessive loads (McArdle, Katch, and Katch, 1991; Chaffin and Andersson, 1991).

Muscle Physiology

Muscle tissue has the ability to actively contract. The connective tissues as well as the muscle cells can be passively stretched and actively shorten. The function of the skeletal muscle is to shorten to produce movement of the body at the joints and to resist active stretching by external forces (Tyldesley and Grieve, 1989). The muscle is composed of water (75%), protein (20%) and inorganic salts and other substances (5%). The most abundant muscle proteins are myosin, actin and tropomyosin. Each muscle fiber is composed of myofibrils which lie parallel to the long axis of the muscle fiber. The myofibril is composed of myofilaments that align along the long axis of the myofibril. These myofilaments are generally composed of actin and myosin with other proteins in small quantities. The sarcomere is defined between the ends or Z lines which bisect the I bands. Each I band consists of thin actin filaments. Actin and myosin filaments within the sarcomere are involved in muscle contraction. In between the I bands is the A band which contains the H zone. The A band consists of overlapping myosin and actin (see Figure A-3). The H zone is noted by a lack of actin filaments (McArdle et al., 1991; Chaffin and Andersson, 1991; Tyldesley and Grieve, 1989).

Muscle movement occurs due to the spatial orientation of the proteins in the sarcomere. Projections or *cross-bridges* spiral above the myosin filament in the A band area, where actin and myosin interact. The myosin head interacts with the actin providing a functional and structural link between the myofilaments. Tropomyosin is distributed along the length of the actin filament, and is believed to prevent a permanent bonding of the actin and myosin filaments. Troponin, which is embedded along the actin strands, has a high affinity for Ca^{++}. It is the action of Ca^{++} and troponin that allows the myofibrils to interact and slide past each other. This theory, the sliding filament theory, states that the muscle shortens or lengthens because the thick and thin myofilaments slide past each other with the filaments themselves changing length. This general action pulls the Z bands towards the center of the sarcomere (Chaffin and Andersson, 1991; McArdle et al., 1991).

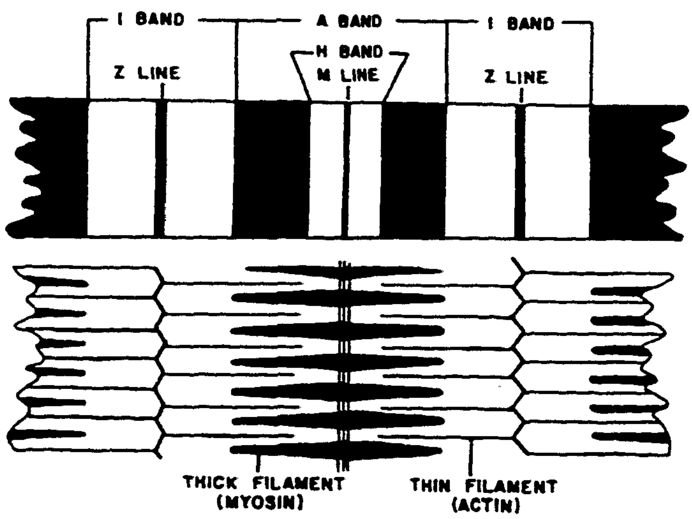

Figure A-3: Anatomy of a Muscle Fiber (from Chaffin and Andersson, 1991).

Each muscle is innervated by a motor nerve unit. The anterior motoneuron and the muscle fiber it innervates is called a motor unit. The motor units operate by the *all or none* principle. When an impulse or action potential reaches the motor unit, the muscle fibers in the unit contract simultaneously. The force of contraction varies by (1) increasing the number of motor units recruited for the activity and (2) by an increase in the frequency of discharge. In addition to receiving inputs, the muscle spindle can also send feedback to the brain. The muscle spindle provides information about muscle length and tension of the muscle fibers. Its function is to respond to the stretch of a muscle and, through reflex action, initiate a stronger contraction to reduce the stretch. The spindle is fusiform in shape and attached in parallel with the extrafusal fibers of the muscle, such that when the muscle is stretched, so is the spindle. There are three components to the stretch reflex: the muscle spindle, which is the muscle sensory receptor which responds to stretch; the afferent nerve fiber that carries impulses from the muscle spindle to the spinal cord; and the efferent motor neuron that innervates the muscle to contract. Excitatory impulses are conveyed to the muscles that support the desired movement (synergistic muscles) and inhibitory impulses are sent to the muscles that are antagonists to the movement. In this way, the stretch reflexes are self-regulating and allow the muscle to adjust automatically to a change in load without higher processing (McArdle et al., 1991; Chaffin and Andersson, 1991).

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Appendix B

Biomechanical Models of the Wrist

Biomechanical Models of the Wrist

Numerous biomechanical models of hand functions have been developed (Landsmeer, 1960; Solonen and Hoyer, 1967; Armstrong and Chaffin, 1978; Buchholz, Armstrong and Goldstein, 1992). Landsmeer (1960) developed the landmark work in which he described three tendon models from which to model finger movement. Research in this area has focused on extending Landsmeer's work and further refining the tendon model. These models end at the metacarpophalangeal joint (MCP) and do not attempt to extend the muscle forces and moments to the wrist. Kern, Jacod, and Sennwald (1994) proposed a model of force transmission through the carpals and Gielo-Perczak (1994) proposed a model of wrist movement. However, no one model extends an external force from the fingers to the wrist. The moment of the muscle at a joint is given by the equation: $\vec{M} = \vec{F} \times d$. If a tendon were pulling on the end of a lever (or bone) extending from the joint axis to the tendon insertion point at a right angle, the length of this imaginary lever is what determines the moment of the tendon at the joint (Brand, 1974). The most important measurement is the distance between the center of the joint and the tendon. The available amplitude of a muscle or tendon is the distance the tendon can move from its position when fully relaxed to the fully contracted position. Brand (1974) describes that the available amplitude of a muscle refers to its capability, while the required amplitude at a joint refers to the distance a tendon must move to put the joint through its full range of motion. This required amplitude is described as the excursion of the tendon. When a tendon crosses more than one joint, the available amplitude is usually of the same order as the sum of the required excursions for all the joints it crosses (Brand, 1974). The flexor digitorum profundus can flex all finger joints when the wrist is neutral, but when the wrist is fully flexed, the muscle may not have enough amplitude to fully flex all joints fully. The primary wrist movers approach the wrist from the periphery while the finger flexors pass through the carpal tunnel. When the wrist is flexed, the tendons which pass through the carpal tunnel are supported by the retinaculum and when the wrist is extended, the tendons are supported by the carpal bones.

Landsmeer (1960) described the first models of the length change of tendon in relation to the joint angle. He proposed three models to describe the tendon joint displacement relationships. Landsmeer's Model I describes the tendon as being held against the curved surface of the proximal bone of the joint. The relationship for the tendon and joint displacement may be described by $x = r\theta$ (Landsmeer, 1960; Armstrong and Chaffin, 1978). The center of curvature for the joint coincides with the center of the joint, thus r is equivalent to the tendon moment arm. If the tendon is not held securely against the joint, then the tendon may be displaced away from the joint as the joint is flexed. This is termed *bowstringing* by Landsmeer (1960) and is the basis for Models II and III.

The second model of Landsmeer (1960) assumes that the tendon is prevented from bowstringing by support at a point of constant distance from the joint center. The system that describes this relationship is given by:

$$x = 2r\sin\left(\frac{\theta}{2}\right) \qquad \textbf{(B-1)}$$

where:

x = tendon displacement past the joint
r = the distance from the joint center to the tendon constraint
θ = the angle of joint rotation from the neutral position (Landsmeer, 1960; Armstrong and Chaffin, 1978).

The third model of Landsmeer (1960) allows for bowstringing of the tendon, that is, the tendon is allowed to change its position as the joint is displaced. The equation that defines this model is given by:

$$x = \theta\, d + y\left(2 - \frac{\theta}{\tan\frac{\theta}{2}}\right) \tag{B-2}$$

where:

x = tendon displacement past the joint
θ = the angle of joint rotation from the neutral position
y = the distance along the axis of the bone from the point where the tendon begins to curve to the joint center. The distance equals 1/2 the tendon arc length when $\theta = 0$ (Landsmeer, 1960; Armstrong and Chaffin, 1978).

The moment arm of a tendon allowed to bowstring is given by:

$$h = y\left[\frac{1-\cos\left(\frac{\theta}{2}\right)}{\sin\left(\frac{\theta}{2}\right)}\right] + d. \tag{B-3}$$

Armstrong and Chaffin (1978) tested Landsmeer's models to evaluate the joint tendon mechanics. They found that Landsmeer's Model I was based on the most creditable assumption that the tendon is displaced over a trochlea, such as the curved articular surface of the proximal bone of the joint. They stated that Model I is the best description of the tendon joint mechanics. They also found that Model II, which is based upon the assumption of intersecting straight lines, was not validated. They stated that the human body seldom tends to be straight or symmetric.

A dynamic model of the finger in the sagittal plane was developed by Buchner, Hines and Hemami (1988). This model considered only inter-phalangeal movements. They found that the forces of the flexor digitorum superficialis, interosseus and lumbricalis remained constant at zero. Flexion of the middle and distal phalanges is brought about by the flexor digitorum profundus and the extensor digitorum. The other muscles were quiet during this movement. They agreed with Landsmeer that the extensor digitorum acts as a brake during finger flexion and the intrinsic muscles are passive during this movement. The braking phenomenon may explain why the force of the flexor digitorum profundus and the extensor digitorum approaches a constant value. They stated the flexing of the unloaded interphalangeal joints is possible when the extensor brake is released by reducing the antagonistic force which opposes flexing and lengthening of the extensor digitorum. Simultaneously, the flexor digitorum profundus contracts to its minimum length.

Solonen and Hoyer (1967) describe three alternative pulley mechanisms that may be used to investigate the amount of force transferred from the fingers to the wrist (see Figure B-1). They assumed that:

1. The force which the muscle exerts on the tendon is independent of the positions of the pulleys.
2. There is no friction in the pulleys.
3. The tendon is long enough to allow complete extension of the finger.
4. The proximal pulley is always situated close to and on the proximal side of the MCP joint.
5. The two distal pulleys and the distal insertion of the tendon can be chosen at will.

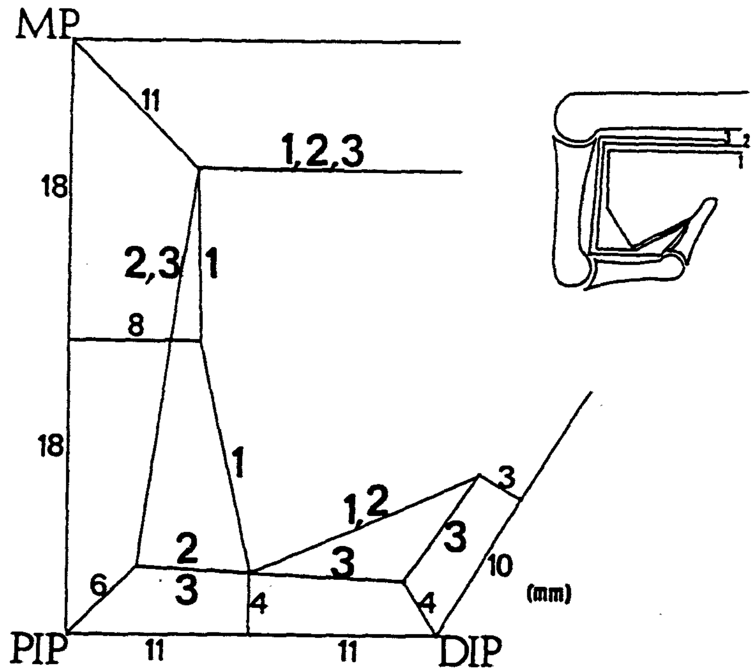

Figure B-1: Diagram of Model Comparison (from Solonen and Hoyer, 1967).

The authors' goal was to create a state where the full range of movement was achieved with the smallest possible excursion of the muscle and where the moments or torques about the joint were not too great or too small (Solonen and Hoyer, 1967). Analysis of the three models is shown in Table B-1. Solonen and Hoyer found that for all models, the moments in extension are approximately equal to those of the normal, non-injured finger. They state that Model 3 seemed to be the model most nearly resembling a normal situation. The excursion is the shortest and there are no excessive moments. The main difference in the three models is that the moment tends to grow very large about a joint which does not have a pulley. This explains why $\bar{M}_{PIP}$ and $\bar{M}_{DIP}$ in Models 1 and 2 are twice as large as in the normal finger (Model 3).

Table B-1: Model Comparison (from Solonen and Hoyer, 1967).

		Extension	Flexion	Excursion (mm)
Model 1	$\vec{M}_{MP}$	11 F	7.5 F	
	$\vec{M}_{PIP}$	6 F	11.5 F	
	$\vec{M}_{DIP}$	3.5 F	8 F	
	Δl			36.5
Model 2	$\vec{M}_{MP}$	11 F	8.8 F	
	$\vec{M}_{PIP}$	6 F	4.3 F	
	$\vec{M}_{DIP}$	3.5 F	8 F	
	Δl			30.0
Model 3	$\vec{M}_{MP}$	11 F	8.8 F	
	$\vec{M}_{PIP}$	6 F	4.3 F	
	$\vec{M}_{DIP}$	3 F	3.5 F	
	Δl			28.0

where, F is the moment of the flexor profundus force, and
Δl is the excursion or difference in length in extension and flexion states of the portion of the tendon which lies in the finger.

In order to develop this model for use, the length of the finger segments and the moment arm of the tendon must be known. Buchholz, Armstrong and Goldstein (1992) described an anthropometric model of the hand from which the finger segment lengths from each joint center can be determined from known hand lengths. Buchholz developed the segment length equations from cadaver data of six hands (4 male and 2 female). Figure A-1 describes the skeleton of the human hand with the segment and phalangeal numbering. Measurement of the segments begins from the first carpal row and moves distally. Buchholz found that the differences between the joint centers found using Reuleaux's method and an anatomically estimated center of rotation were smaller for the DIP than for the PIP. For the PIP, the x location varied from 0.40 mm for digit IV to 1.32 mm for digit V, and the average x position difference was 0.72 to 0.79 mm. The y location differences varied from 0.08 mm for digit II to 0.88 mm for digit IV, and the average y position difference was 0.36 to 0.80 mm. The DIP x location differences varied from 0.17 mm to 0.51 mm with an average difference of 0.36 to 0.47 mm for digits II through V. The y location differences varied from -0.32 mm to 0.08 mm with an average difference for digits II through V of -0.14 to 0.62 mm. The equations developed by Buchholz to define finger segment length from hand length are shown in Table B-2. Buchholz et al. (1992) stated that the collected data indicate that the bony skeleton of the hand is proportioned consistently. Ratios in this study had small standard deviations. Buchholz stated that the models for estimating the lengths of the hand segments using the hand length accounted for 49% to 99% of the variability in the segment length.

Table B-2: Segment Length Model (mm) (from Buchholz et al., 1992).

Thumb (digit I):	$SL_{11} = 0.118 * HL$
	$SL_{12} = 0.251 * HL$
	$SL_{13} = 0.196 * HL$
	$SL_{14} = 0.158 * HL$
Index (digit II):	$SL_{21} = 0.463 * HL$
	$SL_{22} = 0.245 * HL$
	$SL_{23} = 0.143 * HL$
	$SL_{24} = 0.097 * HL$
Middle (digit III):	$SL_{31} = 0.446 * HL$
	$SL_{32} = 0.266 * HL$
	$SL_{33} = 0.170 * HL$
	$SL_{34} = 0.108 * HL$
Ring (digit IV):	$SL_{41} = 0.421 * HL$
	$SL_{42} = 0.244 * HL$
	$SL_{43} = 0.165 * HL$
	$SL_{44} = 0.107 * HL$
Little (digit V):	$SL_{51} = 0.414 * HL$
	$SL_{52} = 0.204 * HL$
	$SL_{53} = 0.117 * HL$
	$SL_{54} = 0.093 * HL$

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APPENDIX C

Screening and Medical History Questionnaire

University of Oklahoma
School of Industrial Engineering
Screening and Medical History Questionnaire

Date: ____________________________

Subject Name: ______________________ Subject Number: ______________

Age: __________________

Nerve Compression Tests: Positive Negative

1. Check box if you have ever been diagnosed with:

- ❑ Carpal Tunnel Syndrome
- ❑ Tendonitis
- ❑ Tenosynovitis
- ❑ Trigger Finger
- ❑ DeQuervain's Syndrome
- ❑ Ganglionic Cysts
- ❑ White Fingers
- ❑ Epicondilitis
- ❑ Radial Tunnel Syndrome
- ❑ Pronator Teres Syndrome
- ❑ Extensor / Flexor Tenosynovitis
- ❑ Guyon Tunnel Syndrome
- ❑ Any other cumulative trauma disorder

2. Check box if you have ever been diagnosed with:

- ❑ rheumatoid arthritis
- ❑ high blood pressure
- ❑ pains in the chest or heart
- ❑ difficulty in breathing
- ❑ an abnormal ECG / EKG
- ❑ recurring pain in the hand, wrist, arm, elbow or shoulder
- ❑ recurring headache or migraine
- ❑ kidney problems
- ❑ vision (not correctable to 20/20)

- ❑ hearing problems
- ❑ glaucoma or pressure in the eyes
- ❑ severe menstrual pain
- ❑ diabetes mellitus
- ❑ vitamin B6 deficiency

3. Check box if :

- ❑ you are pregnant
- ❑ you are undergoing renal dialysis
- ❑ you get out of breathe when sitting still or sleeping
- ❑ your heart skips beats, ever

4. Check box if you are taking any medication for:

- ❑ diabetes, or abnormal blood sugar
- ❑ thyroid
- ❑ anti-inflammatory drugs
- ❑ glaucoma
- ❑ blood pressure
- ❑ birth control
- ❑ other, please specify: ______________________________

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APPENDIX D

Informed Consent Form

UNIVERSITY OF OKLAHOMA
INFORMED CONSENT FORM

Research Title: Reliability of Psychophysical Evaluations of Repetitive Grasping
Researcher: Eric E. Swensen, School of Industrial Engineering, (405) 325-3721.

This is to certify that I, ________________________________, hereby agree to participate as a volunteer in a scientific experiment as part of an authorized Ph.D. dissertation experiment at the University of Oklahoma under the supervision of Dr. Robert Schlegel and Dr. Jerry Purswell.

The purpose of this research is to establish the reliability of human subjects performing a hand grasping task. This research may ultimately contribute to reducing cumulative trauma disorders. My gender as a female is a primary reason for being selected to participate since, during the performance of similar jobs, females are more likely to develop Carpal Tunnel Syndrome than men.

I understand that I will be asked a series of questions to prescreen me for this study. The prescreening process will also include a simple test to check prior exposure to repetitive stress injuries. This test may present minimal discomfort to me. If I do not pass the prescreening process, I understand that I will be discharged from the study and will not be tested further.

I understand that the experiment will require 4 sessions of 40 minutes each and two training sessions that will gather medical information, maximal hand grasping force and a short testing session to acquaint me with the actual experiment. I will be required to perform a power grasping task.

I understand that I may expect minimal physical and/or mental discomfort during the course of this research. I understand that by participating in this research, I will be subjected to minimal physical, mental, and/or social risks.

I understand that my participation is completely voluntary. I can withdraw from participation, or refuse to answer any question at any time without prejudice to me. I understand that by agreeing to participate in this research and signing this form, I do not waive any of my legal rights.

I understand that this research will continue over six (6) weeks. It is important that I attend each session for credit. All information obtained during this study by which I could be identified will be held in strict confidence. If I have a question regarding this research, I may contact either Eric Swensen, or Dr. Robert Schlegel, School of Industrial Engineering, University of Oklahoma.

By signing this form, I indicate that I have read all the above information, and I am willing to participate.

Signature: ______________________

Date: ______________________

APPENDIX E

Subject Instructions

Experimental Instructions

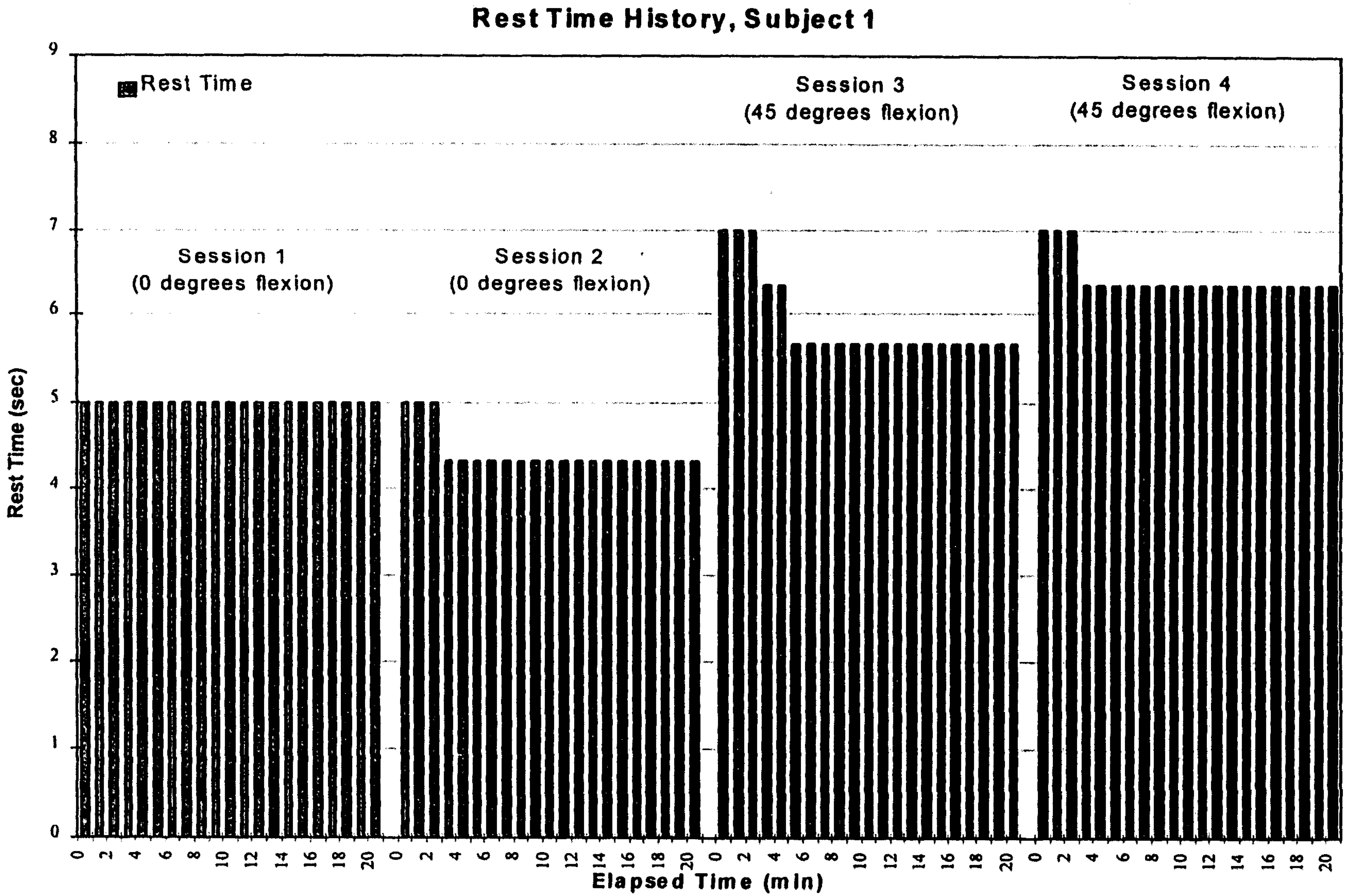
This is not a contest to determine the maximum frequency at which you can perform the hand grasping task. Rather, it is a study to find reasonable, safe, and acceptable frequencies under which an individual can perform a repetitive task. Imagine that you are working on an assembly line for an 8-hour period, and your are paid piece-rate. That is, the more you produce the more you earn. However, I want you to minimize any pain you may feel in your hand, wrist and forearm. You want to maximize your pay, but minimize any pain you may feel.

You will be performing this task for 20 minutes per session, as frequently as possible without straining yourself (i.e., without experiencing soreness, stiffness, or other similar symptoms of over-exertion). You will be able to adjust the rest time during the ADJUST rest period. If you feel you can work more, then you will be able to decrease the rest time between exertions. If, however, you feel you cannot maintain the current frequency, then you may increase the rest time as you wish. You may make as many adjustments as you wish during the ADJUST period.

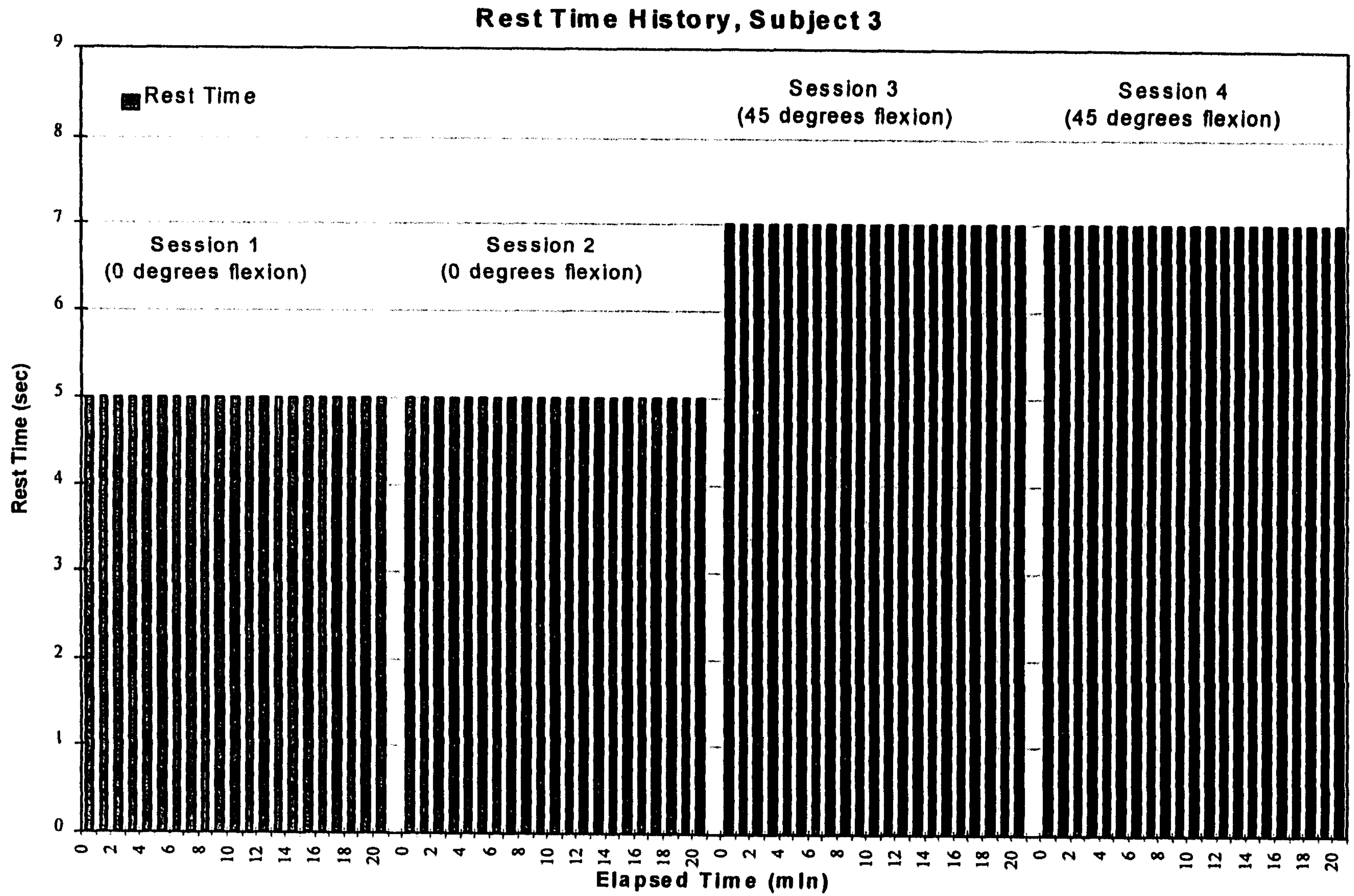
Remember, this is not a contest. I want you to work as hard as you comfortably can during the experimental session. Do you have any questions?

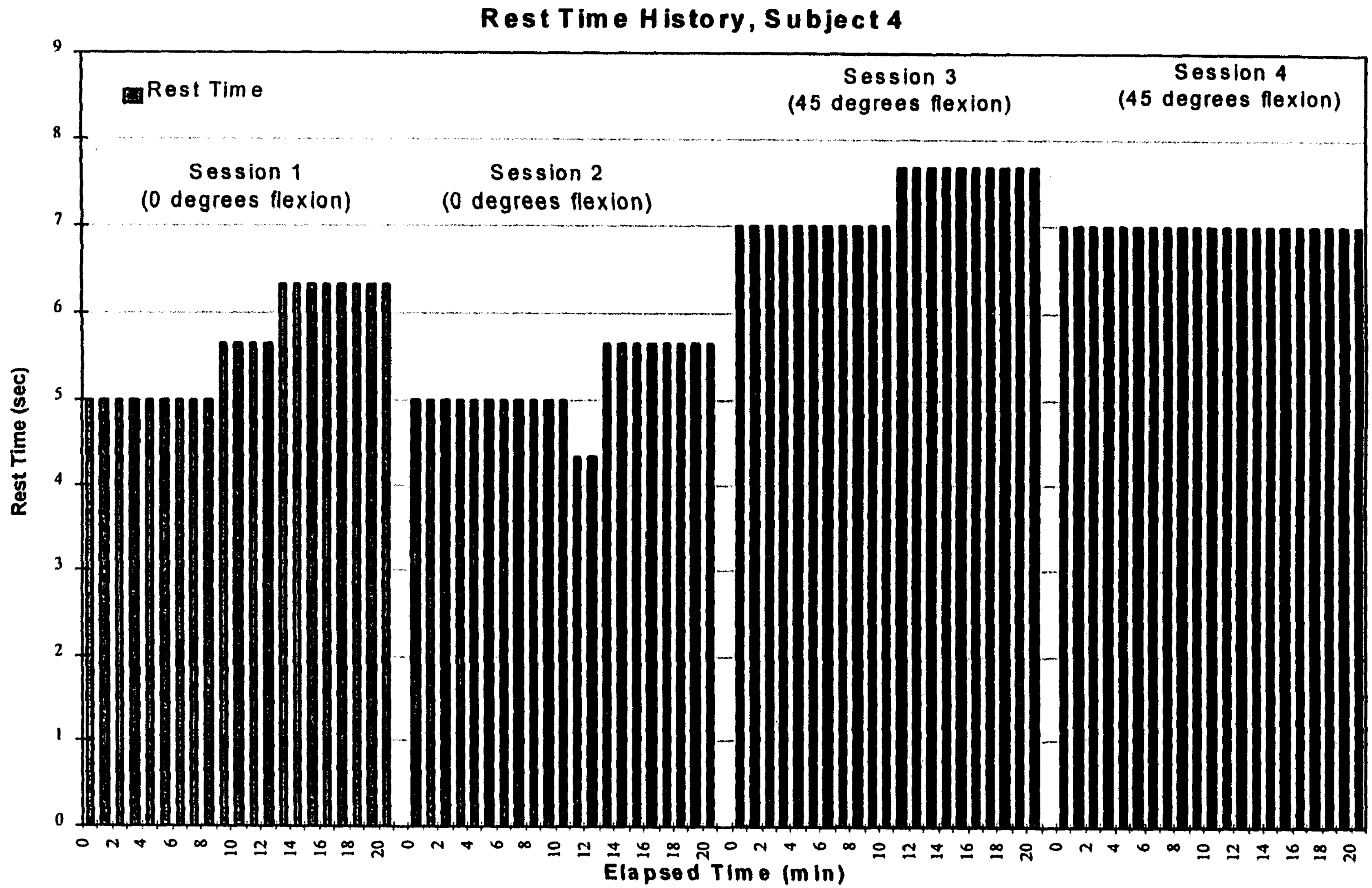
Appendix F

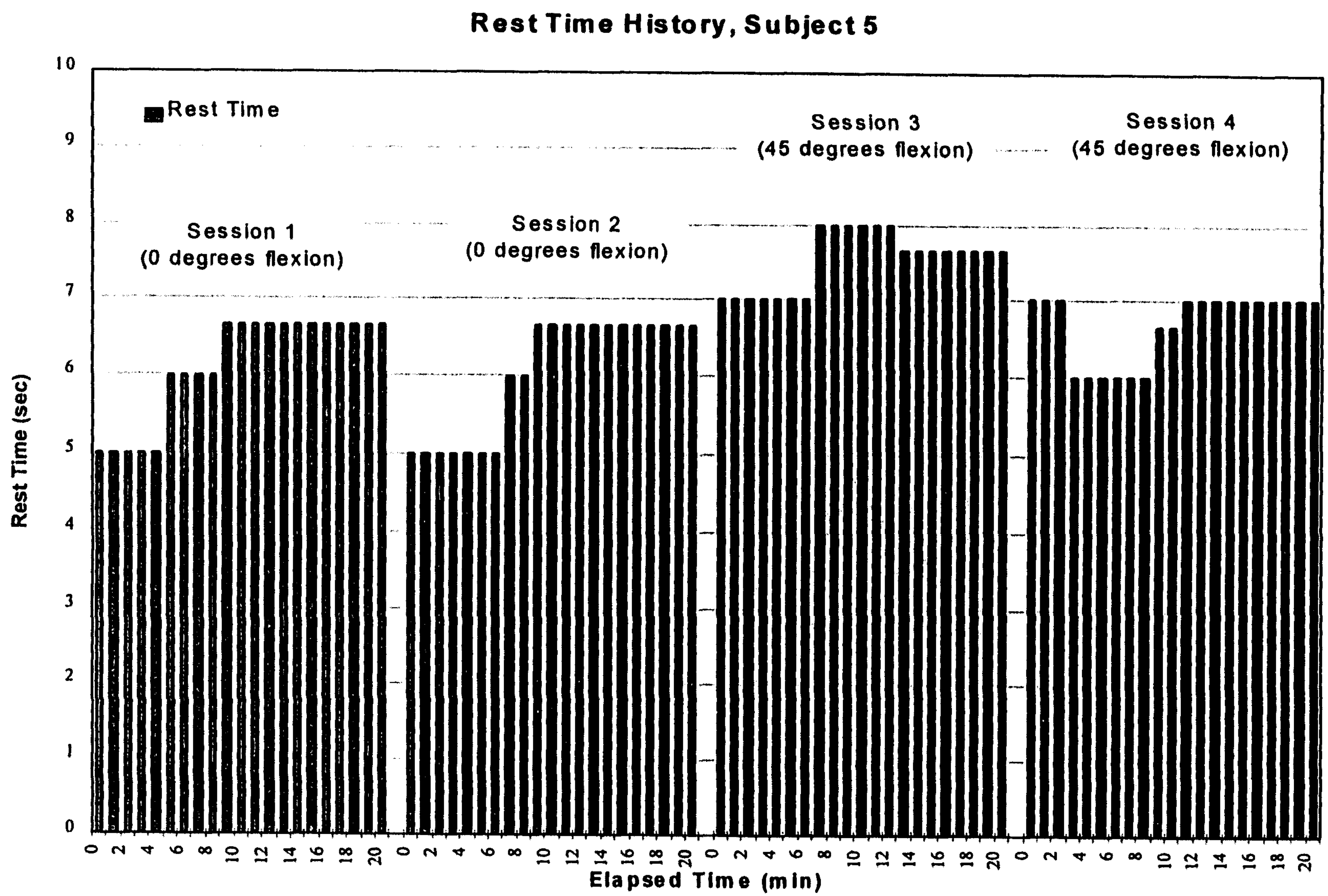
Subject Rest Time Graphs



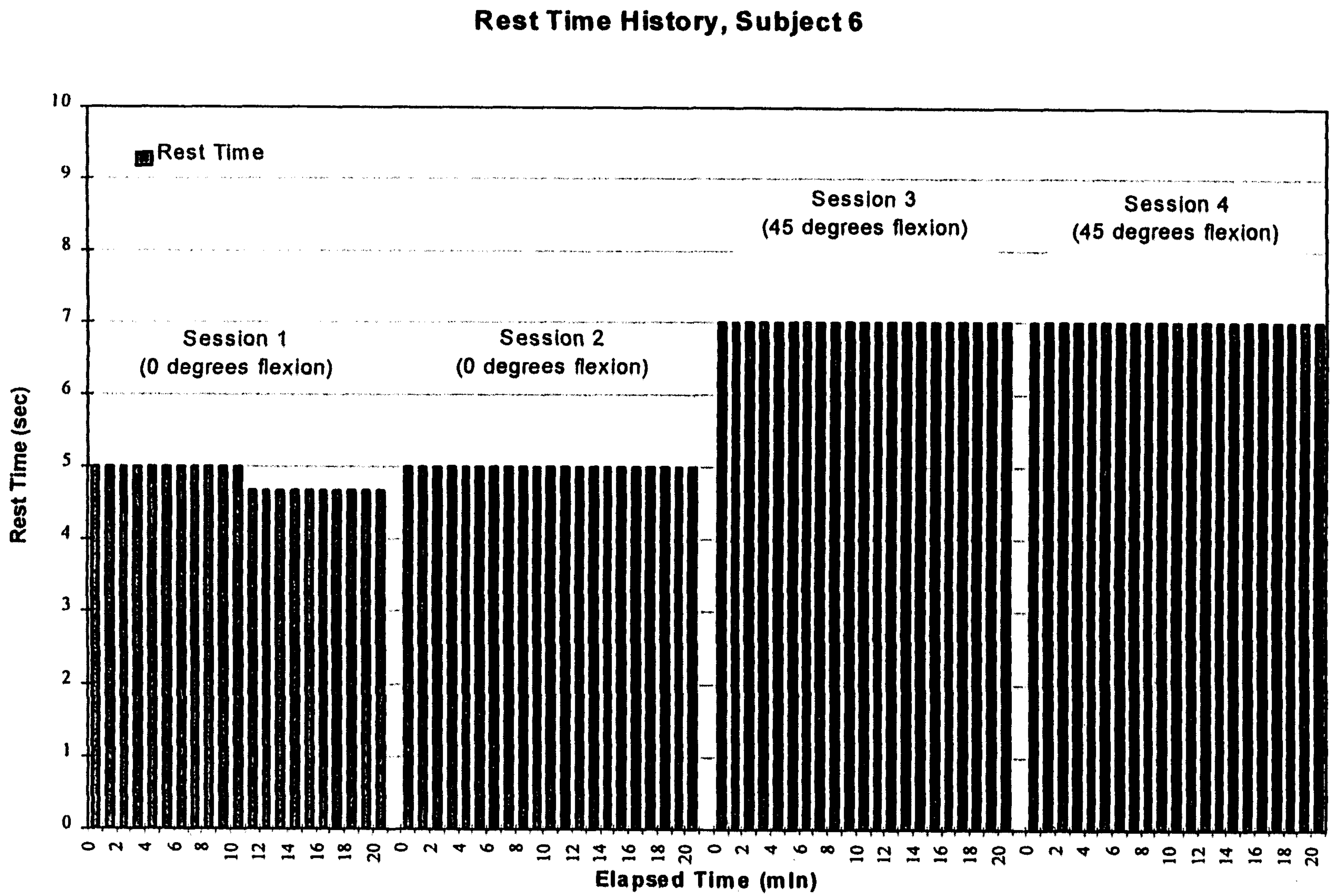
Rest Time History, Subject 1
Rest Time
Session 1
(0 degrees flexion)
Session 2
(0 degrees flexion)
Session 3
(45 degrees flexion)
Session 4
(45 degrees flexion)
Rest Time (sec)
0
1
2
3
4
5
6
7
8
9
0 2 4 6 8 10 12 14 16 18 20
Elapsed Time (min)


Rest Time History, Subject 3
Rest Time
Session 1
(0 degrees flexion)
Session 2
(0 degrees flexion)
Session 3
(45 degrees flexion)
Session 4
(45 degrees flexion)
Rest Time (sec)
0
1
2
3
4
5
6
7
8
9
0 2 4 6 8 10 12 14 16 18 20
Elapsed Time (min)

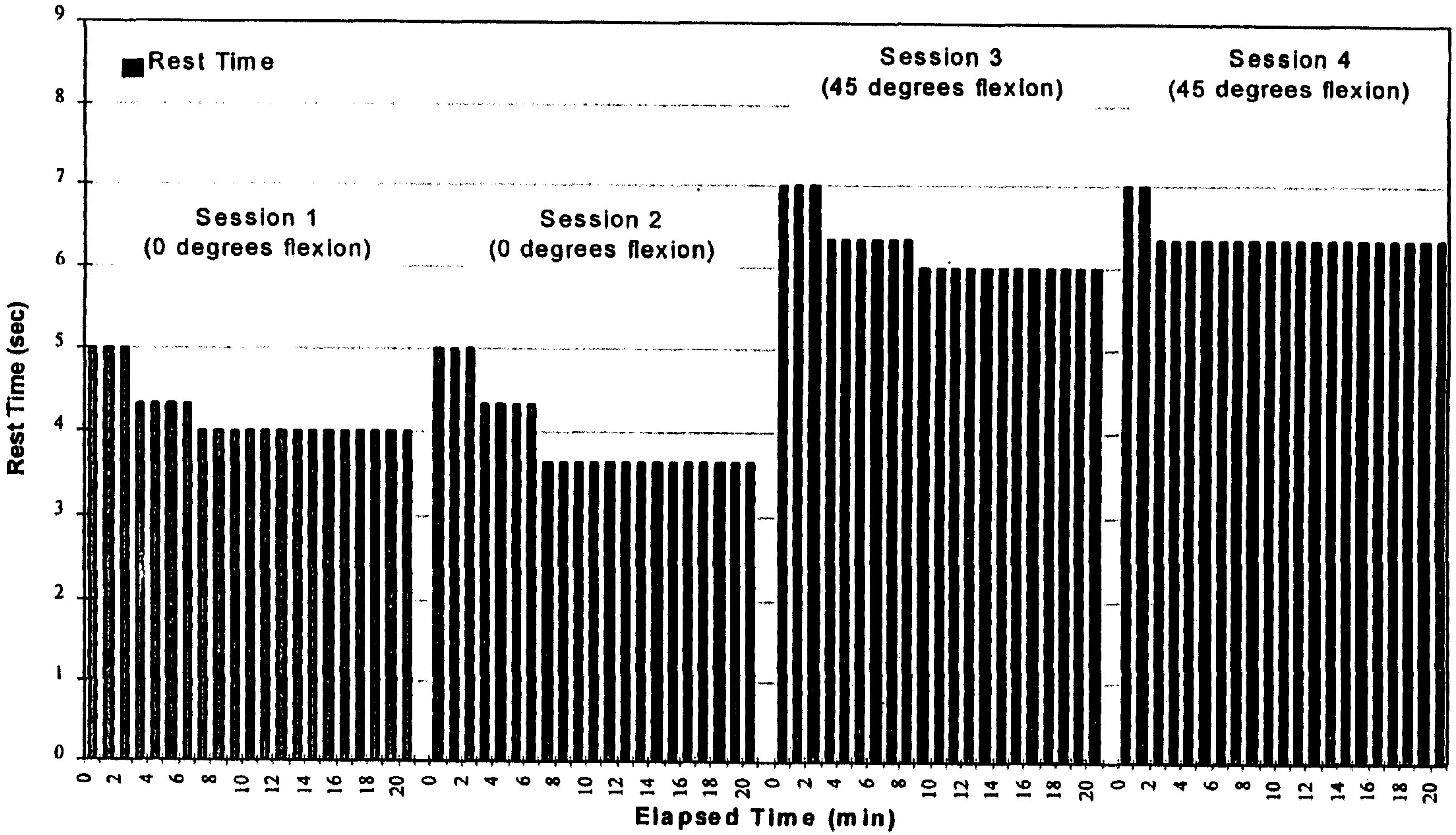

Rest Time History, Subject 4
Rest Time
Session 1
(0 degrees flexion)
Session 2
(0 degrees flexion)
Session 3
(45 degrees flexion)
Session 4
(45 degrees flexion)
Rest Time (sec)
0
1
2
3
4
5
6
7
8
9
0 2 4 6 8 10 12 14 16 18 20
Elapsed Time (min)



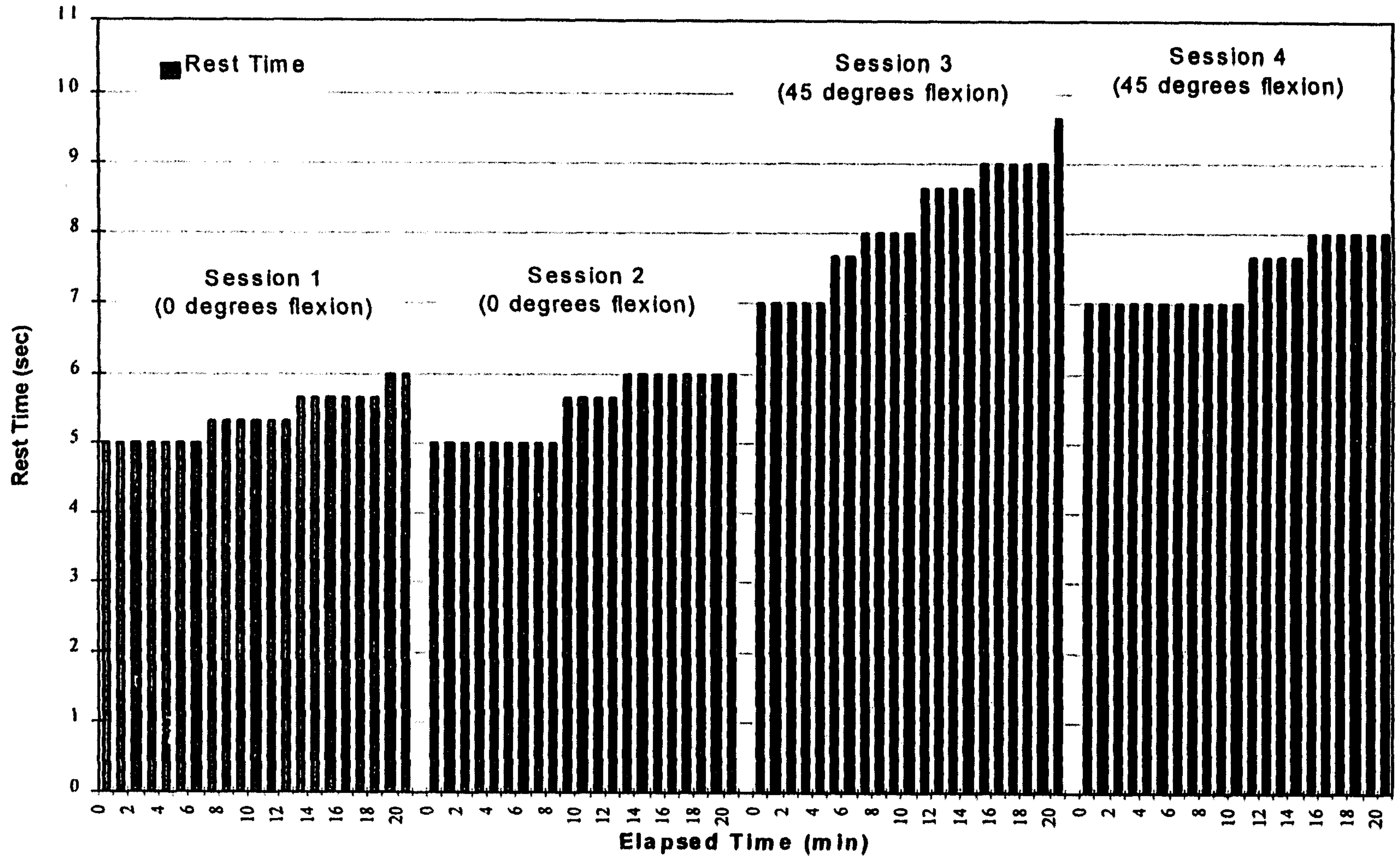
Rest Time History, Subject 5
Rest Time
Session 1
(0 degrees flexion)
Session 2
(0 degrees flexion)
Session 3
(45 degrees flexion)
Session 4
(45 degrees flexion)
Rest Time (sec)
Elapsed Time (min)
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16
18
20


Rest Time History, Subject 6
Rest Time
Session 1
(0 degrees flexion)
Session 2
(0 degrees flexion)
Session 3
(45 degrees flexion)
Session 4
(45 degrees flexion)
Rest Time (sec)
0
1
2
3
4
5
6
7
8
9
10
0 2 4 6 8 10 12 14 16 18 20 0 2 4 6 8 10 12 14 16 18 20 0 2 4 6 8 10 12 14 16 18 20 0 2 4 6 8 10 12 14 16 18 20
Elapsed Time (min)

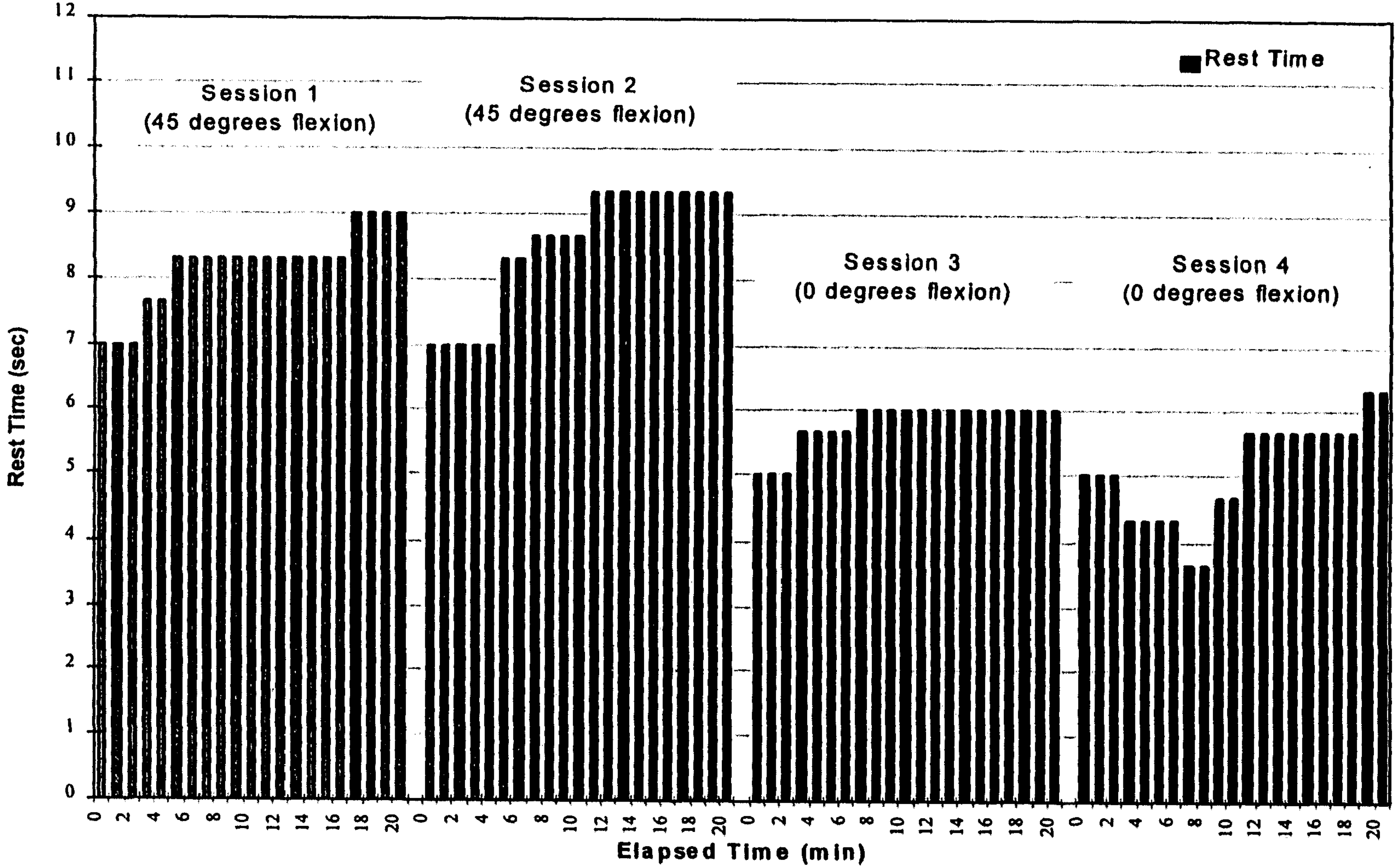
Rest Time History, Subject 8

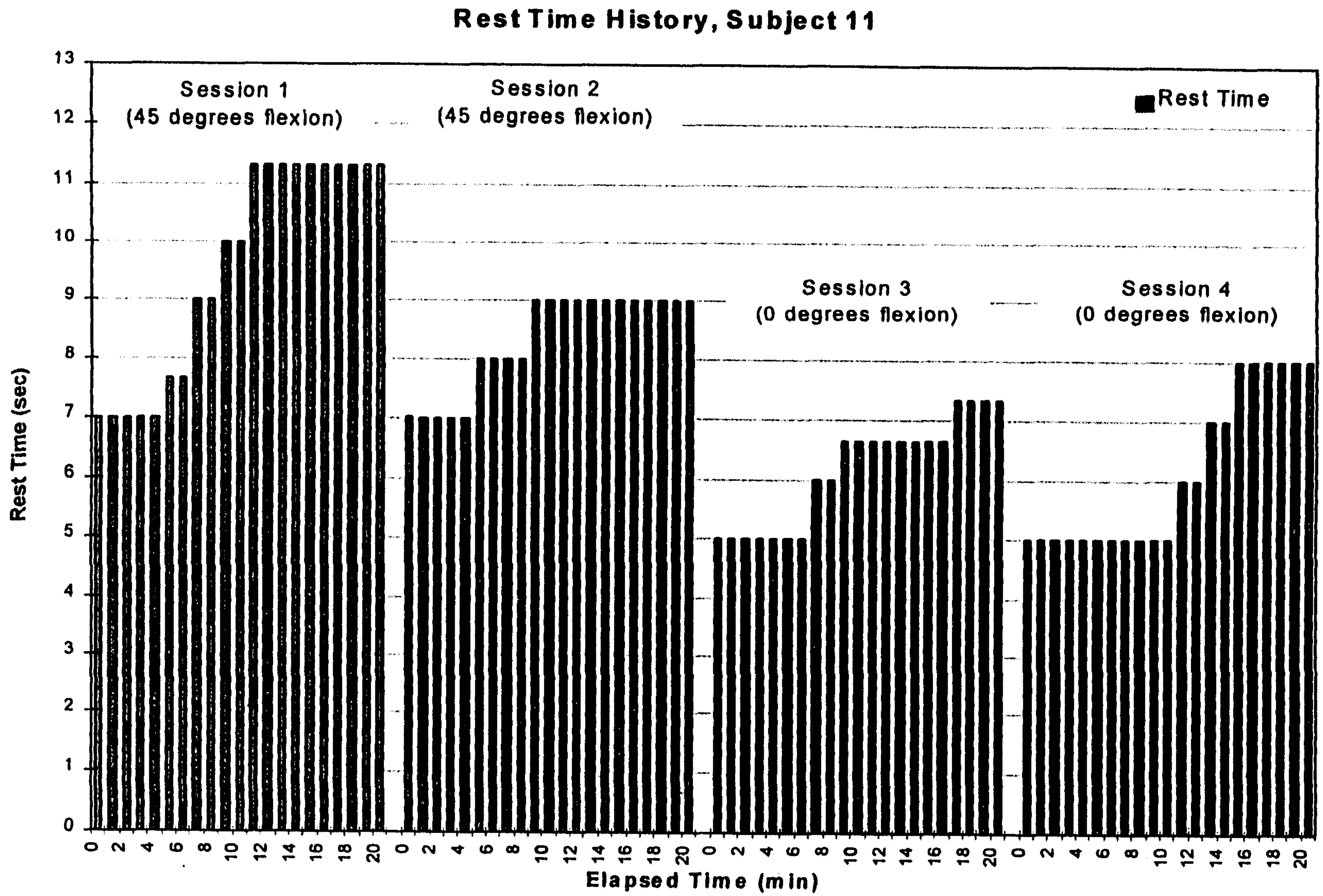


Rest Time History, Subject 9

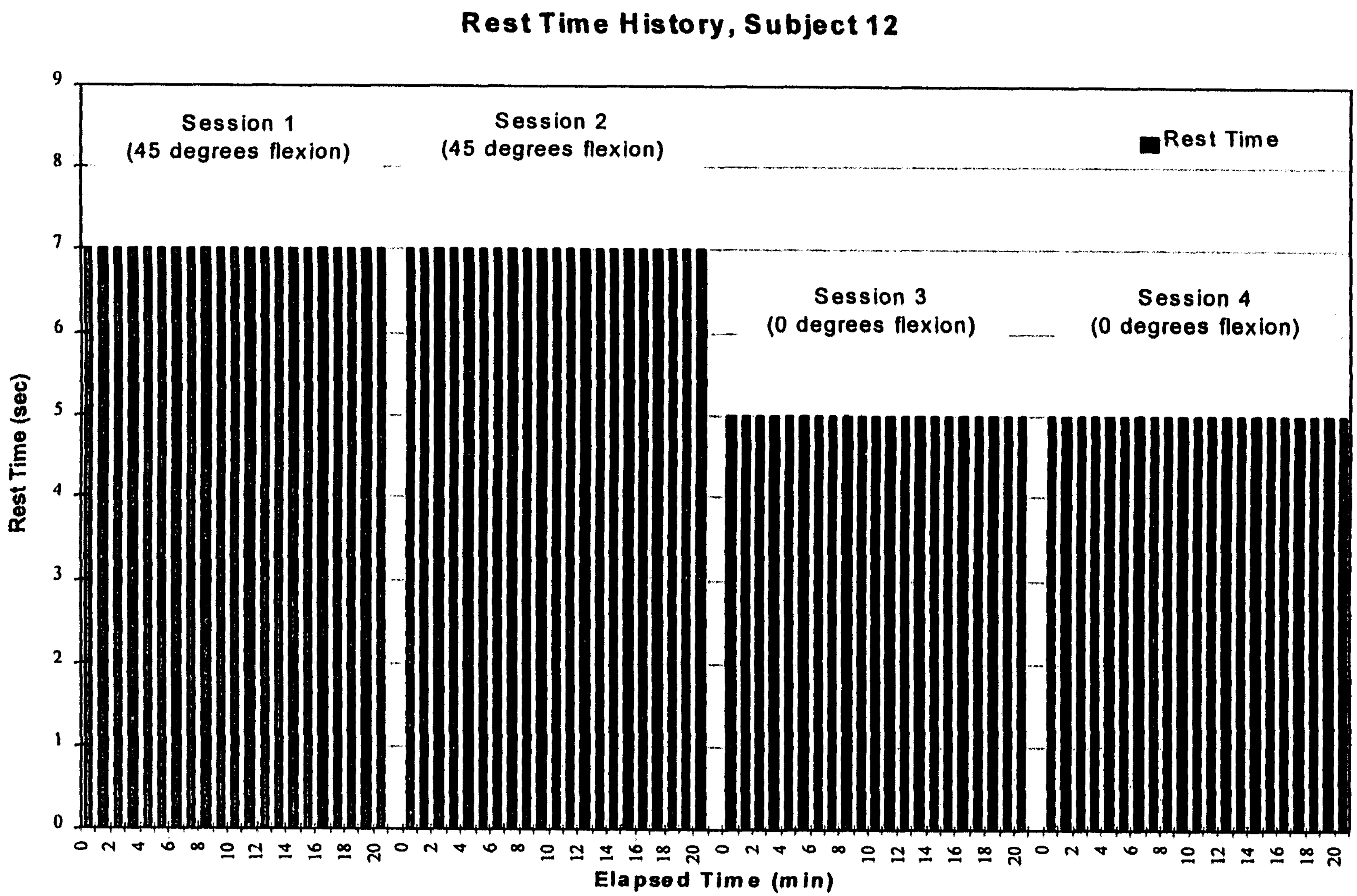


Rest Time History, Subject 10

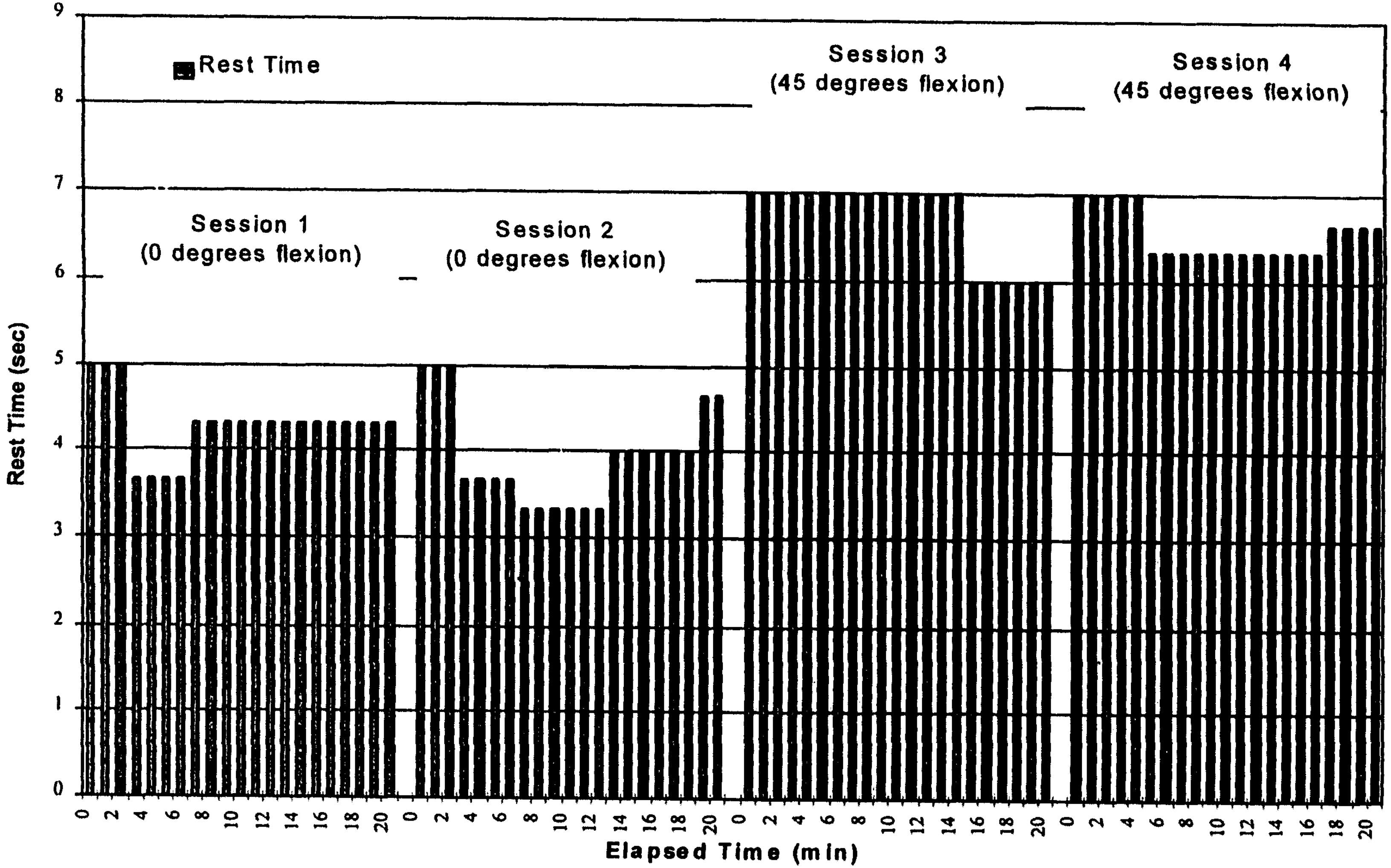


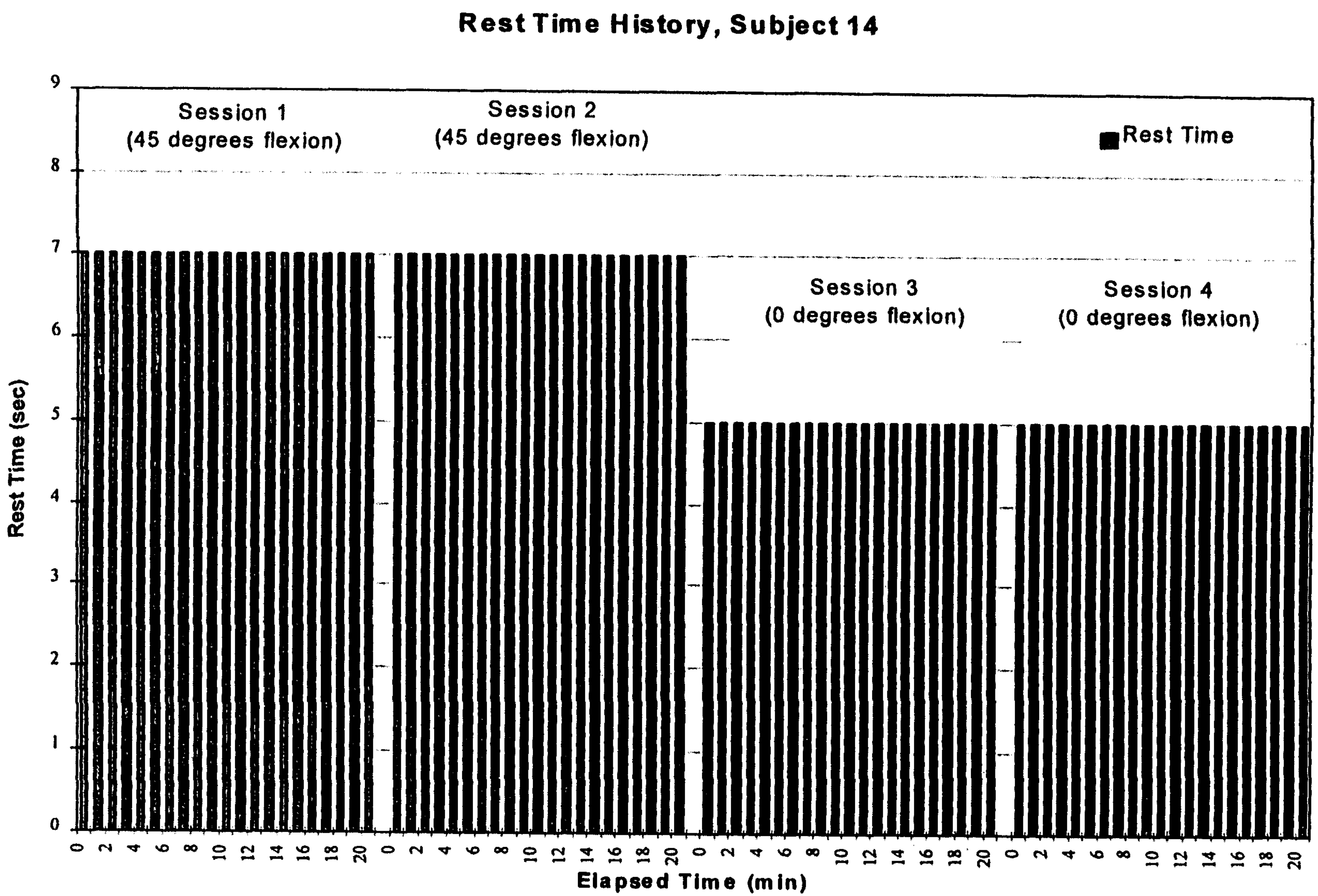


Rest Time History, Subject 11
Session 1
(45 degrees flexion)
Session 2
(45 degrees flexion)
Session 3
(0 degrees flexion)
Session 4
(0 degrees flexion)
Rest Time
Rest Time (sec)
Elapsed Time (min)

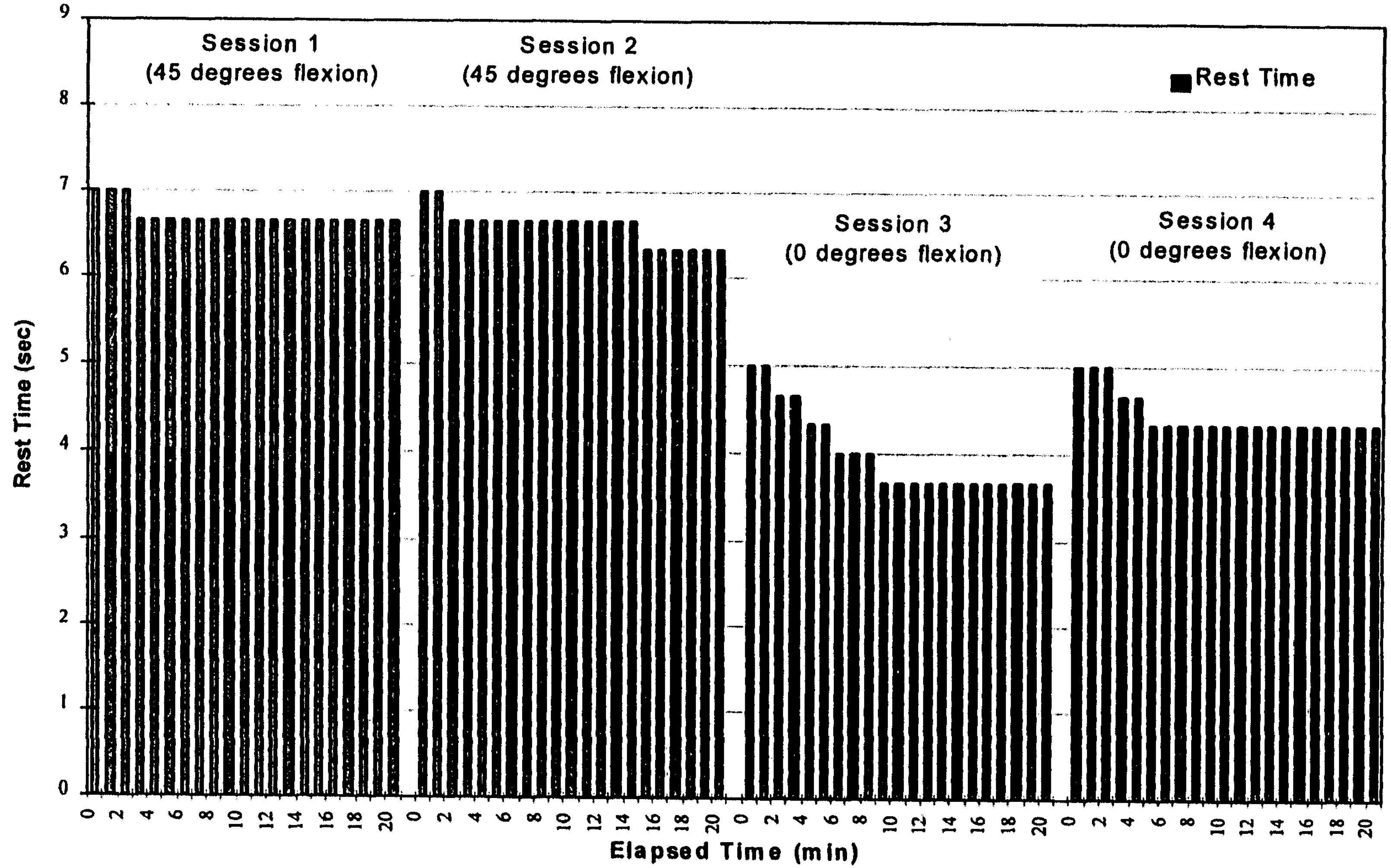

Rest Time History, Subject 12
Session 1
(45 degrees flexion)
Session 2
(45 degrees flexion)
Session 3
(0 degrees flexion)
Session 4
(0 degrees flexion)
Rest Time
Rest Time (sec)
Elapsed Time (min)
0
1
2
3
4
5
6
7
8
9
0
2
4
6
8
10
12
14
16
18
20

Rest Time History, Subject 13

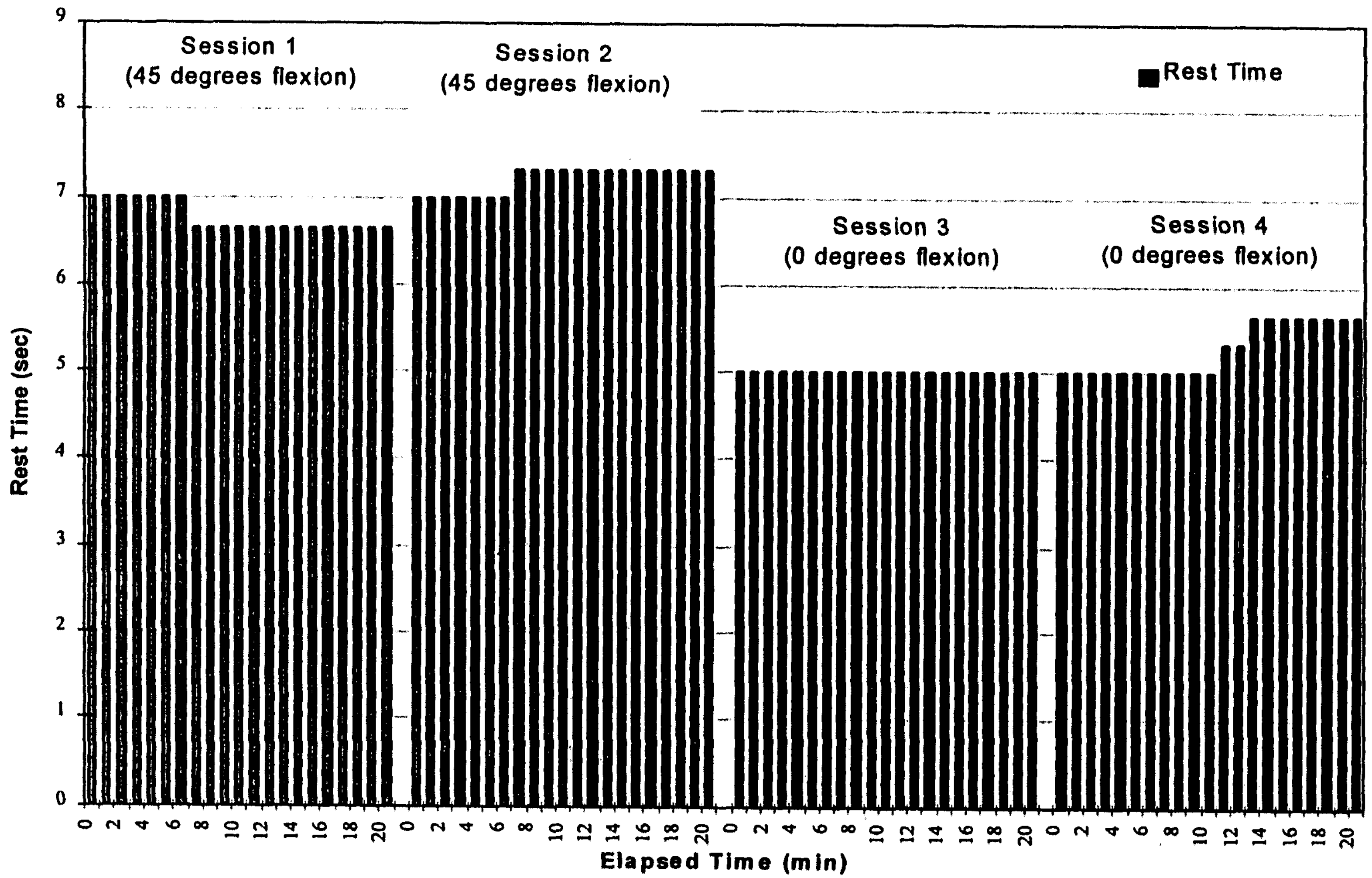


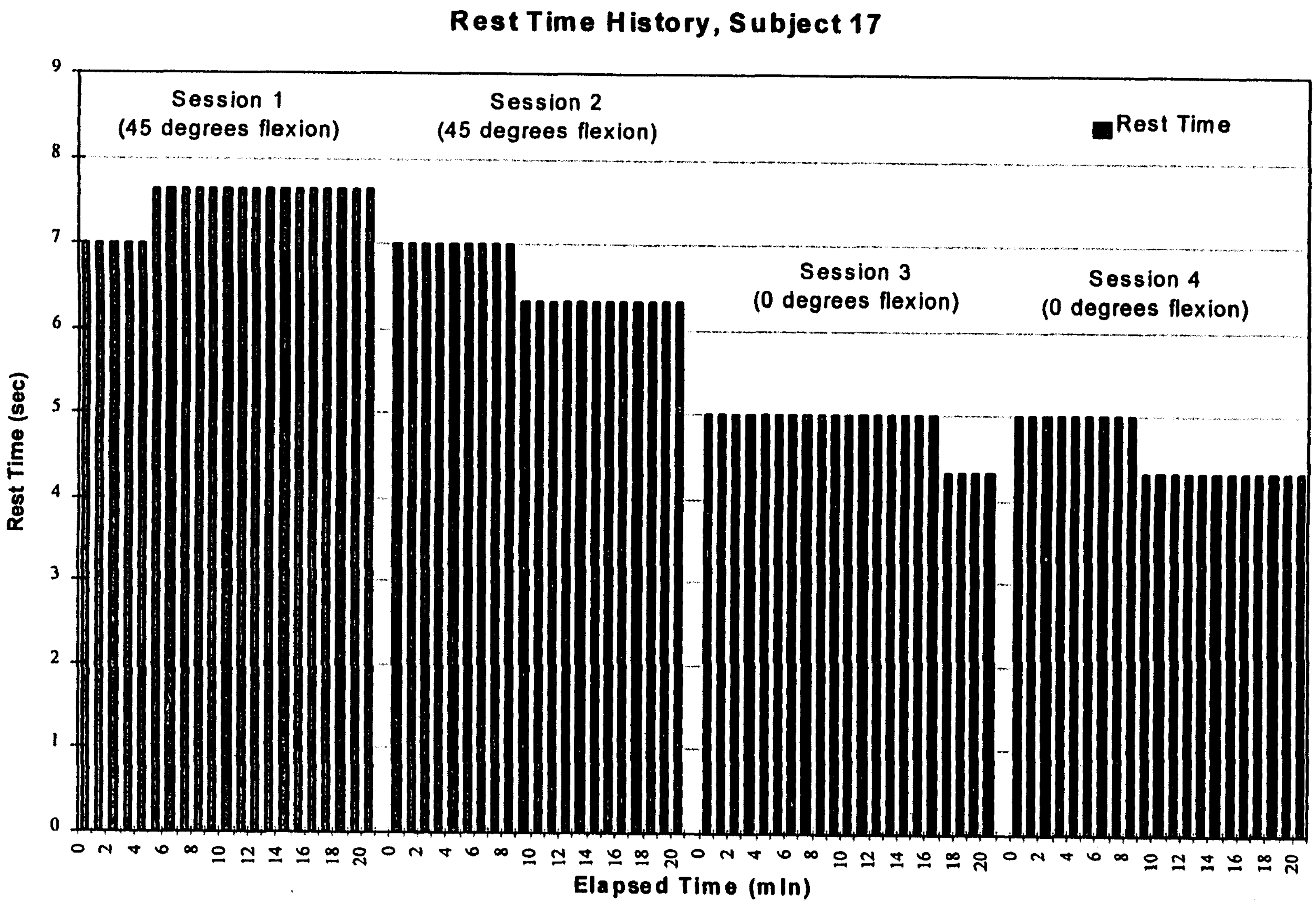

Rest Time History, Subject 14
Session 1
(45 degrees flexion)
Session 2
(45 degrees flexion)
Session 3
(0 degrees flexion)
Session 4
(0 degrees flexion)
Rest Time
Rest Time (sec)
Elapsed Time (min)
0 1 2 3 4 5 6 7 8 9
0 2 4 6 8 10 12 14 16 18 20

Rest Time History, Subject 15

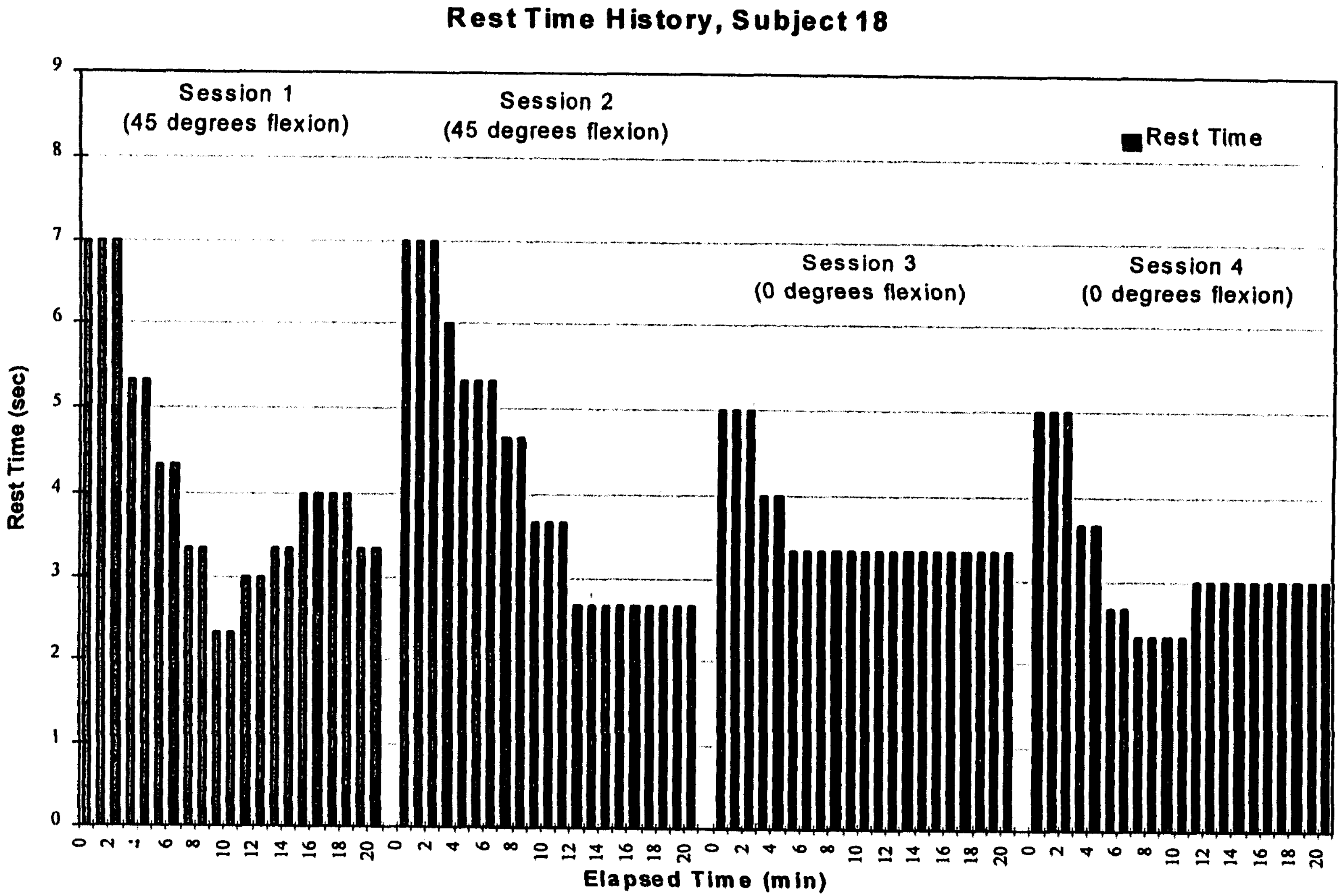


Rest Time History, Subject 16





Rest Time History, Subject 17
Session 1
(45 degrees flexion)
Session 2
(45 degrees flexion)
Session 3
(0 degrees flexion)
Session 4
(0 degrees flexion)
Rest Time
Rest Time (sec)
Elapsed Time (min)
0
1
2
3
4
5
6
7
8
9
0 2 4 6 8 10 12 14 16 18 20


Rest Time History, Subject 18
Session 1
(45 degrees flexion)
Session 2
(45 degrees flexion)
Session 3
(0 degrees flexion)
Session 4
(0 degrees flexion)
Rest Time
Rest Time (sec)
Elapsed Time (min)
0
1
2
3
4
5
6
7
8
9
10
12
14
16
18
20