# BIOMECHANICAL LOADING WITH PSYCHOPHYSICALLY DETERMINED ACCEPTABLE TORQUES DURING IN-LINE SCREW RUNNING: EFFECT OF CYCLE TIME AND DUTY CYCLE

by

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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Kinesiology

Waterloo, Ontario, Canada, 1999

0-612-44775-8

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# ABSTRACT

Adjustment type psychophysical methodology has been used to develop guidelines for repetitive upper limb movements. The acceptability of adjustment type psychophysical methodology for upper limb tasks has not been examined both in terms of the biomechanical loading of the tissues at risk and in terms of the ability of workers to determine loads presented. There is a growing recognition that repetitiveness includes not only frequency of exertion (cycle time), but also the duration of exertion within the cycle time (duty cycle). These two dimensions of repetitiveness are not always controlled for in psychophysical studies. This thesis used adjustment type methodology, under different conditions of cycle time and duty cycle, to determine acceptable torque for an industrial task, in-line screw running. This task was chosen to add to the large library of workplace specific tasks that will be required for psychophysical guidelines to be useful. It also provided a task that requires response to external force generation typical of powered hand tool use as opposed to many existing studies where muscle activity causes the initial activity to occur.

Eight female workers performed a simulated screw running task consisting of grasping a 46 mm diameter handle driven by a computer controlled torque motor, simulating an in-line screw runner. The women worked for 15 days: 3 days of training, 11 days of adjustment type psychophysical data collection and 1 day of more detailed biomechanical data collection. The participants were trained to prevent the handle from turning while the motor repetitively applied a torque. During psychophysical data collection different conditions of duty cycle (25, 50, and 83% of time) and cycle time (3, 6, 12 and 20 s) were used and the women were instructed to adjust the torque level such that they were working as hard as they could without undue discomfort. Electromyographic (EMG) signals from extensor carpi radialis brevis (ECRB), flexor digitorum superficialis (FDS), flexor carpi radialis (FCR), and trapezius was recorded every hour during a test contraction to study muscle fatigue. Biomechanical measures taken on the last day for each condition at both the psychophysically determined acceptable torque and a reference torque included EMG, wrist angle, tool angular movement, hand torque, and hand grip force.

Duty cycle was found to significantly affect the amount of torque selected. With duty cycle controlled, cycle time was no longer found to have any significant effect on acceptable torque. Psychophysically determined acceptable torques (PDAT) for 25, 50 and 83% duty cycle were 1.09, 0.9, and 0.73 Nm. Discomfort and stiffness were concentrated on the back of the hand and the thumb web. While there was a significant difference with duty cycle for hand force and EMG during the "operating" phase of the cycle, there was no difference averaged over the whole cycle. This was due to the biomechanical duty cycles for force and EMG becoming longer than the applied motor duty cycle. At the 83% motor duty cycle the biomechanical duty cycle for EMG was above 90% leading to static muscle loads greater than 1% MVC.

Despite having no effect on the PDAT and discomfort, decreased cycle time was associated with increased flexor muscle fatigue. The results would suggest that muscular

fatigue was not a primary sensation used in selection of acceptable torque. The fatigue could be the result of reduced amount of time available for the muscle to completely shut off (i.e. fewer gaps).

This thesis gives psychophysically developed guidelines for a workplace specific task requiring response to an externally generated force typical of powered hand tools. It is concluded that: 1) Duty cycle is an important factor in psychophysical adjustment studies of highly repetitive upper limb tasks and needs to be included to generalize results, 2) Participants appear to choose the load based on time weighted hand grip force or muscle activity, 3) Participants are able to estimate the load being adjusted according to Steven's Law in such a way that they under estimate low loads and over estimate high loads, 4) The PDAT didn't appear to be based on muscle fatigue, which may limit its use in preventing muscle pain 5) Biomechanical duty cycle is longer than that implied by the task 6) A task duty cycle of 83% with high repetition tasks may lead to static muscle loads of greater than 1% MVC and 7) Based on psychophysical data collection methods, for the monotask of highly repetitive in-line screwrunning, it is recommended that the torque not exceed 1.06 N.m with 25% duty cycle or 0.79 N.m with a 50% duty cycle.

# ACKNOWLEDGMENTS

I would like to thank the many people who supported the completion of this work. My supervisor, Dr. Richard Wells, was a constant source of support throughout the ups and downs of life. Ideas that went into our meetings as a spark, always came out as a flame, generating the energy to keep going. I would also like to thank my committee members: Dr. Donald Ranney who in addition to his expertise, also provided medical supervision for the participants, Dr. Robert Norman who believed enough to provide funding, and Dr. Fran Allard who always had time to provide the perceptual view point.

I would like to thank the many fellow graduate students and staff who provided help, support and feedback particularly Ken Strawbridge and Wendell Prime whose technical support was invaluable, Pia Amping who made sure all the programs worked and Ruth Gooding who always made sure I was on top of things.

To Chris and Drew who managed to grow up with Mommy's thesis spread out over every spare surface. Thanks for making sure I knew what the important things in life are.

Most of all, I thank David who shared in all the thrills of discovery and tears of defeat. Thanks for all the hugs, the talks, the time and the encouragement.

This work was partially supported by General Motors of Canada Ltd, Woodbridge Foam Company and A.G. Simpson. An adjustable workstation was donated by Arbill Inc. Burlington, ON.

# DEDICATION

To Dad. You taught me to love science.

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# Chapter 1

## INTRODUCTION

Cumulative Trauma Disorders (CTD), Repetitive Strain Injuries (RSI), Occupational Overuse Injuries, Sprains and Strains or Work-related Musculoskeletal Disorders (WMSD), by whatever term used, chronic injuries of tendons, muscles and nerves constitute a significant problem in jobs that require repeated loading of particular soft tissues. Occupational factors that have been implicated in the development of CTD's of the upper limb include highly repetitive or monotonous work, high forces, extreme postures, use of vibrating tools, use of gloves and abrupt changes in workload or unfamiliar work (Armstrong and Silverstein, 1987). Currently there are few objective guidelines available for use in minimizing risk of upper limb CTD's in task design or analysis. There are many reasons for this: the lack of tissue tolerance data to repetitive low level loading, the number of different tissues involved, the difficulty of estimating tissue loads in a workplace setting, the existence of multiple injury mechanisms leading to complex dose-response relationships, confounders such as psycho-social factors in the workplace, age, gender, and other personal factors, the multiple degrees of freedom in the upper limb and the time required to develop these disorders making the needed prospective studies difficult and costly. Despite these difficulties, researchers have been using several different approaches to tackle the problem of CTD's in order to eventually provide objective guidelines for reducing the risk of CTD's.

Moore et al. (1991) proposed a profile of biomechanical measures which describe different aspects of mechanical loading on selected tissues in the forearm and wrist. Their approach was to use proposed etiologies for CTD's of different tissues, and predict associated mechanical loading of those tissues over time from time course records of the hand and wrist posture and force requirements. While this approach seems logical for linking the established external risk factors (force, posture, movement, time) to the injuries that occur, it is limited to use as a comparative tool until tissue tolerance to low level cumulative loading or epidemiological data are available.

A different approach utilized by Snook et al. (1995) has the advantage of translating directly into a proposed workplace guideline. The psychophysical approach involves having experienced manual workers perform a set repetitive manual task at given frequencies. While working, the subjects can adjust their own workload and are given instructions to "work as hard as they can without developing unusual discomfort in the hands, wrists and forearms". The problems with this approach when applied to repetitive upper limb tasks include: 1) A large library of common industrial tasks would be required to be useful, 2) Currently there is no epidemiological verification of the approach, 3) It is unclear whether there is any relationship between the loads chosen and loads on the tissues at risk for WMSD and 4) There is no verification of the ability of workers to estimate the magnitude of the load being adjusted (Stevens, 1957).

High repetition tasks have been defined as having a cycle time of 30 seconds or less or a repetitive sub cycle occupying more than 50% of the cycle (Silverstein et al. 1986). Load adjustment type psychophysical studies have found that even within high repetition tasks, there is a significant drop in the load accepted with shorter cycle times (Snook et al., 1995). However it is also clear that repetitiveness not only includes aspects of cycle time, but also other factors including duty cycle (time of tissue loading with respect to whole time) and similar loading on tissues (Moore and Wells, 1992; Kilbom, 1994; Radwin and Lin, 1993). Unfortunately, Snook et al. (1995) did not control for or report duty cycle therefore making it impossible to estimate the work:rest ratio for the task performed. Current work:rest ratio guidelines come from a range of sources including physiological data (e.g. blood flow and blood chemistry; Bystrom, 1991), endurance time (Rohmert, 1973), muscular fatigue (e.g. Wood et al., 1997), psychophysical time adjustment studies (e.g. Dahalan and Fernandez, 1993) or strain in tendons (Goldstein, 1981; Fisher et al., 1993). Unfortunately, for short cycle time tasks, there is a wide variation in both acceptable load levels and direction of change (e.g. time adjustment psychophysical studies have a positive slope with cycle time, endurance studies have a negative slope with cycle time). For load adjustment psychophysical studies the following issue needs to be addressed: 1) how do both cycle time and duty cycle combined affect the load chosen?

Repetitive hand tool use has been linked to development of WMSD (Silverstein et al., 1987; Cannon et al., 1981). The muscle responses to short term use of various powered screw runners (in-line and pistol grip) and nut runners (90 degrees) have been studied (Armstrong et al., 1993, Kihlberg, 1994; Radwin et al., 1989) showing high muscle response to even low torques which can be affected by build up rates and the shut off mechanism. However, while our understanding of the effect of powered hand tool use on the musculoskeletal system grows, there is still a need for guidelines in the form of external torque guidelines for use in industry. Also, the role of cycle time and duty cycle on repetitive hand tool use particularly on biomechanical variables representative of loading in the upper limb has not been well explored.

**Thesis Overview**

This thesis is comprised of seven chapters, four of which represent manuscripts resulting from different aspects of the study. Together, these papers address the goals of this thesis. These goals are:

1. To establish load adjustment type psychophysically determined values for acceptable torque (PDAT) during in-line screw-running,
2. To examine the effect of duty cycle and cycle time on PDAT,
3. To test the psychophysical relationship between torque and perception over different conditions.
4. To examine the role of torque, duty cycle and cycle time on selected biomechanical variables representative of mechanical loading of the upper limb which may lead to WMSD, and
5. To examine the effect of load adjustment psychophysical study on fatigue and discomfort

over the course of a working day and over different duty cycles and cycle times.

The Chapters cover:

*Chapter 2.* *Review of Literature*

This chapter is a brief review of literature which encompasses the project as a whole. It is designed to provide background and rational behind the goals as stated. The review is intended to augment the reviews provided in the manuscripts themselves.

*Chapter 3.* *Psychophysically determined acceptable torques for in-line screw running: effect of cycle time and duty cycle.*

Load adjustment type psychophysical determination of acceptable loading has been used to develop guidelines for lifting in industry. Similar methods are now being applied to repetitive upper limb movements (Snook et al., 1995). To be useful, acceptable loads for a large library of tasks found in industry are required. Such tasks include repetitive hand tool use. To add to this library, a load adjust study was performed using a simulated in-line screw runner. Repetitiveness, includes components of frequency (i.e. cycle time) and duty cycle. While different task frequencies have been used in the past in such studies, duty cycle is not often controlled. The task performed here is controlled for both cycle time and duty cycle. This chapter addresses goals 1 and 2. It is hypothesized that both cycle time and duty cycle will affect the acceptable torques chosen.

*Chapter 4.* *Perceived versus actual torque on psychophysical variables during in-line screw running.*

The ability of the participants to detect torque could affect their ability to adjust the torque. Rated torque versus actual torque should follow a linear log-log relationship (Stevens, 1957). This chapter addresses goals 3 and 4. It is hypothesized that the rated torque versus actual torque follows a linear log-log relationship and that duty cycle and cycle time will alter the slope of that relationship.

*Chapter 5. Fatigue and discomfort with simulated in-line screw-running.*

Central to the ability of psychophysical adjustment methodology to produce effective guidelines for the prevention of WMSD is the ability of the participants to respond appropriately to prevent injury to the tissues at risk. One commonly injured forearm tissue is muscle (Ranney et al., 1995). Changes in the electromyographic (EMG) signals from the muscles at risk can be used to indicate local muscle fatigue. To examine this, test contractions were done every hour during a load adjust study, where participants choose work loads for an in-line screw running task done at different cycle times and duty cycles. EMG from 3 forearm muscles was collected and frequency and amplitude measures were calculated. This chapter addresses goal 5. It is hypothesized that the participants adjusted the torque such that there was minimal forearm fatigue with the different conditions of duty cycle and cycle time.

*Chapter 6. Relationships between psychophysically chosen torque and biomechanical variables for in-line screw running.*

Hand force has been implicated in development of WMSD (Silverstein et al., 1986, 1987). Muscle load as indicated by EMG has also been linked to development of WMSD. Average hand force and average muscle load are theoretically sensitive to duty cycle, with a less understood cycle time role. Total wrist and tool movement are theoretically sensitive to the number of times a task is performed per time (i.e. cycle time). However, the role of duty cycle is unknown. Also unknown is how the psychophysically determined loads will affect hand force, muscle load, wrist and tool movement and possible risk of injury. These issues were examined by having participants work at a simulated in-line screw runner at both a reference torque and the psychophysically determined acceptable torque for each of 3 different duty cycles and 4 different cycle times. While working, linear envelope EMG from 3 forearm muscles plus a shoulder muscle was monitored, as well as hand grip force, hand torque, wrist angle and tool angle. Calculated measures included Amplitude Probability Distribution Function (APDF) of the EMG, total EMG gap time (time below 0.5% Maximum Voluntary Contraction, MVC, for at least 0.2 s), physiological duty cycles for EMG and force, and cumulated wrist and tool movement. This chapter addresses goal 4. It is hypothesized that participants adjusted the torque such that cumulative hand torque, cumulative hand force and average EMG for the forearm muscles monitored are no longer affected by the condition tested. It is also hypothesized that reduced loads will reduce the amount of cumulative tool and wrist movement.

*Chapter 7. Discussion and Conclusions*

This chapter is designed to unify the findings of the different chapters based on the goals. It serves to discuss the implications of the findings with respect to hand tool use in industry and summarize the conclusions.

# Chapter 2

# REVIEW OF LITERATURE

The purpose of this chapter is to provide a review of literature to provide a background and rational behind the goals of this thesis. The chapter is intended to augment the reviews provided in each of the manuscripts themselves.

Goal 1: To establish load adjustment type psychophysically determined values for acceptable torque (PDAT) during in-line screw-running.

**Work-related Musculoskeletal Disorders of the Upper Limb**

Work-related musculoskeletal disorders (WMSD) of the hand, wrist, forearm and shoulders include injuries to nerves (e.g. Carpal Tunnel Syndrome, Thoracic Outlet Syndrome), tendons (e.g. tendinitis, tenosynovitis, peritendinitis, rotator cuff tendinitis), and muscles (e.g. tension neck syndrome, forearm muscle pain) (Silverstein, 1985; Luopajärvi et al., 1979; Ferguson, 1971; Ranney et al., 1995). Different etiologies for development of different disorders (e.g. tenosynovitis: force of tendons on sheath, movement of tendon with respect to sheath or friction between tendon and sheath) have been proposed (Moore et al., 1991). Several studies have found a relationship between work and the development of WMSD's (Silverstein et al., 1986, 1987; Stock, 1991). These disorders have been linked to jobs that are repetitive, require high forces, and require continuous or repeated extreme or awkward postures (Armstrong and Silverstein, 1987). A preliminary dose-response relationship has been demonstrated between WMSD's and force, repetition (Silverstein et al., 1986, 1987), static muscle load (Aaras and Westgaard, 1987), and the movement of the tendons through the carpal tunnel (Wells et al., 1992a). *The physical and social costs of these disorders precipitates the need for simple, but effective ergonomic evaluation tools and guidelines for use by ergonomic practitioners and design engineers in order to balance the need to obtain maximum work output from minimum staff while maintaining health.*

**Psychophysical Studies in Ergonomics**

One method frequently used to evaluate different workplace situations is psychophysics. Two broad types of psychophysical studies are used in ergonomics research. The first is to present a number of different working situations to the participants and have them rate the jobs based on their perception of exertion, effort, discomfort, etc. These are often rated on some form of Borg scale (Borg, 1982) or visual analogue scale (e.g. Ulin et al., 1990). This rating approach allows comparisons between different situations so that rules of what is perceived better or best can be developed. While a function between, for example, perceived exertion and load for a given posture and frequency can be established, it is difficult with this approach to address what load may be the acceptable limit for working without unusual pain and discomfort.

Snook (1978) addressed this problem by using an `adjustment' psychophysical approach where participants were given a specific task (e.g. lifting from floor to knuckle height). The participants were told to work as hard as they could without feeling unusual discomfort (e.g., fatigued or overheated or out of breath). The participants then performed the task for a set duration while being allowed to adjust one factor (either load weight or frequency). The results of these studies for a number of different low back intensive tasks, frequencies and participants are compiled in the well-known Snook tables for lifting, lowering, pushing and pulling (Snook, 1978; Snook and Ciriello, 1991). These tables present the load a given percentage of the population perceive they can lift (10th, 25th, 50th, 75th, and 90th percentiles) for a given task description and worker gender.

The validity of this approach was examined by investigating 191 cases of low back injury (Snook, 1978). The specific act associated with the injury (if acute) was compared with the tables. It was found that workers were 3 times more susceptible to low back injury if working greater then the maximum acceptable weight of lift (MAWL) for 75% of the population. Snook (1978) suggests, therefore, that use of the tables can reduce low back injuries to a third. Herrin et al. (1986) did both a psychophysical and biomechanical analysis of 55 jobs with 6912 incumbent workers and tracked dispensary visits 2 years retrospectively and 1 year prospectively. Overexertion injuries studied included contact injuries, back injuries and other musculoskeletal sprains and strains. Both biomechanical (maximum disk compression: BC.MAX) and psychophysical (minimum population that can perform the task: PSY.MIN) measures associated with the most acute task in a job were found to be related to both incidence and severity of overexertion injuries. Acute and chronic risk jobs and injuries were not separated out. This may explain why indices which averaged the job stresses from all the tasks did not exhibit any relationship to injury.

Therefore, while it appears that guidelines based on psychophysical analyses have the ability to reduce injury, it is not clear whether the sensations used to determine MAWL are directly related to injury or whether the physical act of providing some guidelines will naturally remove jobs that are high risk based on their high biomechanical or physiological loads. Snook (1985) lists the subjective nature of the method as well as problems with lifting at high frequency (high metabolic loads) and in sensitivity to bending and twisting (high local tissue loading) as disadvantages of psychophysical studies. He points out that the method will likely be replaced "when and if more objective methods are available" (Snook, 1985). *That is, before conclusive studies are available which give clear and encompassing guidelines based on the appropriate injury mechanisms, psychophysical studies remain a strong alternative since they are based on realistic simulation of industrial work, are good for intermittent tasks, are consistent with the idea of occupational work capacity, are reproducible and (in lifting studies) appear to be related to low back pain (Snook, 1985).*

***Psychophysical Studies in Repetitive Manual Tasks***

Given these fairly positive results in lifting tasks, and with the emergence of WMSD's of the upper limb as an increasing problem in industry, the adjustment type of psychophysical methodology is now being applied to upper limb repetitive movements (Snook et al., 1992a, 1992b; Krawczyk et al., 1992). The psychophysical approach in repetitive manual tasks poses some different challenges than found in lifting. First, the degrees of freedom of movement in the upper limb make for many more different tasks and task combinations then found in lifting. Snook et al. (1992a, 1992b) used 3 fundamental wrist movements (wrist flexion with a power grip, wrist flexion with a pinch grip and wrist extension with a power grip), Krawczyk et al. (1992), used a transfer task, namely the transfer of an object from one location to another. It is unclear at this point whether it is possible to generalize the results from one movement to another. *It is likely that a large number of different movements, including tasks that require response to external force generation typical of powered hand tool use, will have to be studied to achieve a useful database.*

Next, it is unclear what sensations are used in participants' perceptions of discomfort. In lifting, the relationship between physiological and psychophysical measures are usually studied using global physiological measures such as heart rate and $VO_2$. Wiker et al. (1990) found that in repetitive lifting overall aerobic-cost (as indicated by heart-rate) dominated perceived strain compared to local tissue loads such as disc compression. With repetitive manual tasks, local not global physiological distress is likely more of a concern (Larsson et al., 1988,1990; Dennett and Fry, 1988). Also the hand has a large number of mechanoreceptors and nociceptors. This may mean that tactile discomfort instead of loading of the soft tissues that get injured (muscles, tendons, tendon sheaths, and nerves) may be the overriding sensation used in determining maximum acceptable load. In fact, both Snook et al. (1992a) and Wiker (1991) found that most of the symptoms (soreness, stiffness and numbness) were found in the fingers/thumb area. It is unclear whether this will constitute a safety margin for all tissues or not. It may not be as Snook et al. (1992b) had a shift of soreness symptoms to hand/wrist and forearm after increasing the exposure to 5 days per week (which decreased the acceptable load). Finally, there is the question of how to present results. Snook et al. (1992b) had their participants do primarily a wrist movement while adjusting the torque. Since the moment arm for applying the load to the handle was constant, the results are presented as a force. As the output of the musculoskeletal system at the wrist is a torque, and a given task may not have the same moment arm, it is likely more appropriate to leave the results as a torque.

Despite these unknowns, psychophysical studies may be a useful starting point in developing preliminary guidelines for repetitive manual tasks. There is a definite interaction between load and frequency as found in epidemiological studies of WMSD's (Silverstein et al., 1986, 1987). In both Snook et al. (1992a, 1992b) and Krawczyk et al. (1992), all tasks would be considered high frequency based on Silverstein et al. (1986, 1987). The force data are not directly comparable in the forms presented. However, all the results from Krawczyk et al. (1992) would be classed low force as the preferred weights for just the lift portion of the cycle were all below 6 kg. *Therefore, psychophysical studies may be able to distinguish loads even within the confines of tasks which are already considered highly repetitive.*

***Factors affecting Psychophysical Studies***

Maximum acceptable weights of lift determined through psychophysical studies have been found to be reproducible (Gamberale et al., 1987; Legg and Myles, 1985). Their validity, however is affected by many factors. Ayoub (1989) reviewed the factors affecting the results of psychophysical studies in manual material handling. These include the worker (age, gender, experience, strength, anthropometrics, etc), the task (quality of simulation, frequency, posture, weight of lift, range of lift), container characteristics (size, shape, means of coupling), and environmental components (heat, noise, light etc). Also of importance is study design factors (presentation of the load, duration, instructions to participants). Factors that may be of importance in studies of repetitive upper manual tasks will be further discussed.

i. Frequency

In lifting, the effect of frequency on MAWL is considered non-linear (Ayoub, 1989). That is at very low frequency lifts (e.g. 1 per 8 hours) the primary limitation is strength. For this reason, the psychophysical results for infrequent lift can pose a risk from a biomechanical point of view. At the other end of the spectrum for continuous high frequency lifting, the psychophysical results tend to be higher then suggested from a physiological point of view (Ayoub, 1989). With upper limb intensive repetitive tasks, we are really only concerned with the effect of high frequency. Since these jobs tend not to be whole body movements, the physiological concerns are more related to local metabolic crisis and local tissue strain as opposed to more global measures such as heart rate and $VO_2$. An examination of the results of upper limb studies performed to date indicate a linear inverse relationship between maximum accepted force and frequency (Snook et al. 1992b, Krawczyk et al., 1992).

Correspondingly, studies using rating scales in upper limb intensive tasks have found linear increases in RPE with increased frequency (Krawczyk and Armstrong, 1991; Ulin et al., 1993; Genaidy et al., 1990b). Interestingly, the participants in both Snook et al. (1992) and Krawczyk et al. (1992), while accounting for the increase in frequency with decreased loads, still had higher RPE (Krawczyk et al.) or number of symptoms (Snook et al.). This would indicate that at higher frequencies the psychophysical approach may overestimate the acceptable load in upper limb tasks as was found in lifting. However, for the tasks used, an increase in the frequency may also have increased the duty cycle. *This makes it is unclear whether the results are due to the number of cycles or the amount of rest per cycle, or both.*

ii. Duration

Legg and Myles (1985) found that soldiers could lift the weight they personally selected over 40 minutes for over 8 hours. There was no significant difference in heart rate over the day, however feelings of fatigue and perceived exertion increased significantly over the day. Mital (1983) found a decrease (35% males, 15% females) in the weight chosen when the participants could adjust the load over an eight hour period compared to a 25 minute period. However, Snook and Ciriello (1991) report no significant difference using 4 hours per lifting condition compared to 40 minute per condition, although in both cases the workers were working for 4 hours/day. In the upper limb studies, Krawczyk et al. (1992), with the participants working for 8 hours/day, found a significant change between the first 4 hours and last 4 hours. From the data presented, the changes within the last 5 hours do not appear significant. Snook et al. (1992a, 1992b), with the participants working for 7 hours/day, found a significant difference between the first and seventh hour. However there was no significant difference in the last three hours. *These results would suggest that at least 5 hours per day is necessary for repetitive upper limb tasks in order to achieve a value representative of an 8 hour working day.*

iii. Participants

The common wisdom in psychophysical methodology is that if the task simulated is industrial, then the participants should be industrial workers (Ayoub, 1989). Several studies have shown an effect on the weight chosen by the background of the participants. Gamberale et al. (1987) found a decrease in the weight chosen by warehouse workers vs office workers, yet the ability of Steven's power law to describe perceived work load was independent of the group tested. Snook (1978) reported testing 15 female industrial workers and 16 female household managers. He found higher levels of loads chosen for the females who worked in industrial settings. *Overall, these results would indicate experience is not necessary to rate relative work situations, but it is important in perceiving what is a reasonable level to work at on a long term basis.*

To account for gender associated differences in anthropometrics and strength, males and females are generally tested separately in lifting studies (e.g. Snook and Ciriello, 1991). Krawczyk et al. (1992) tested 8 males and 8 females and found no significant gender effect in weight chosen. However there was a gender/distance lifted interaction where women rated the longer distance more strenuous then men did. Snook et al. (1992a,b) only studied women. Wiker et al. (1990) also found that strength did not affect the onset of perceived fatigue or discomfort in light manual tasks done above shoulder height. *Therefore, the effect of gender is not clear. Testing using one gender will allow for examining specific research goals without* *having to account for interactions. However the results will not be as generalizable.*

iv. Task/Instructions

Several factors have been shown to affect the loads the participants choose. Slight differences in the instructions to the participants has been shown to bias the results (Gamberale et al., 1987). The presentation of the initial load has also been shown to bias the results (Krawczyk et al., 1992), although not always significantly (Legg and Myles, 1985). If the initial load is above what the participant feels they can handle they tend to choose a higher load than if the initial load is below what the participant feels he/she can handle. In lifting studies this has been handled by doing 2 trials; one starting high and one starting low. If the results are within 15% of each other then the 2 results are averaged. If not the results are thrown out and rerun (Snook and Ciriello, 1991). In the upper limb studies the loads are altered at regular intervals (e.g. 1 hour). They are alternately set high and then low by a random amount and the results averaged (Snook et al., 1992a, b; Krawczyk et al., 1992). *Since the results have shown no significant difference after the fourth hour, the combination of collecting for 5 hours and alternately setting the values high and low and averaging should account for the effect of the presentation of the initial load.*

**Hand Tool Use**

Hand tools have been found to account for 9% of compensable occupational injuries in the USA (Aghazadeh and Mitel, 1987) and 6% in Sweden (as reported in Bobjer et al., 1993). Of these, approximately one quarter are WMSD (AIHA, 1996). Epidemiological studies have found use of tools, particularly highly repetitious or forceful, is linked to development of WMSD (Cannon et al., 1981; Silverstein et al., 1987). Use of an inappropriate tool for the job, or an appropriate tool with an inappropriate workstation can lead to extreme postures, or less than optimum postures for force generation, local pressure on the hand, muscle fatigue, and injury (AIHA, 1996; Kadefors et al., 1993). Tool features that can lead to undesirable loading on the musculoskeletal system include: mechanical output of the tool, tool mass and centre of gravity, tool dimensions, grip shape, type and surface characteristics, vibration and trigger design. Workstation/work task features of concern include work location, work orientation, gloves, frequency of operation, duration of operation, tool accessories, work methods and tool maintenance (AIHA, 1996; Mital and Kilbom, 1992; Kadefors et al., 1993) Guidelines are available for many of these features based on anthropometrics, functional limitations of the hand, and research examining maximum grip strengths, or minimum fatigue or discomfort for different grip shapes, sizes, postures and orientations (Meagher, 1986; Greenberg and Chaffin, 1977; Mital and Kilbom, 1992; Konz, 1983). In other words, given a type of tool for a job and a required mechanical output, how can it be designed to create the lowest possible musculoskeletal loads on the upper limb? What is not as clear, is, given a specific type of tool, designed to be acceptable in terms of diameter, surface, posture etc., how much mechanical output can be sustained by the upper limb without injury? Specifically, how is this affected by repetitiveness, frequency, and duty cycle of use? Mital and Kilbom (1992b) recommend a power grip force of 100 N based on hand strength data. However, high force combined with high repetitiveness (more than 4 hours distributed over the entire day or more than 30 minutes continuously or repetitively, cycle times less than 30 seconds based on the proposal by Sperling et al., 1993) is deemed unacceptable. No recommendations for how much to drop the force with high repetition demands are given. In fact, they list work:rest ratios for tool usage as an area needing further research (Mital and Kilbom, 1992). For torque producing tools, they recommend maximums of 6 Nm for in-line tools, 12 Nm for pistol grip and 50 Nm for angled tools. Ford Motor Company recommend maximum 3.2 Nm for in-line tools, 6.8 Nm for pistol grip and 267 N maximum hand force for right-angled tools (AIHA, 1996). In each case, how much hand force this represents will be a function of many factors. This includes the moment arm from the torque axis to the hand, the coefficient of friction between the tool and hand, and other force requirements associated with the tool usage including supporting the tool load and any push or feed force required to advance the bit and keep it engaged in the fastener being run down. Based on workers perceptions, Armstrong et al. (1989) found that tools between 0.9 kg and 1.75 kg were acceptable. The coefficient of friction between a hand and tool is dependent on the material characteristics of the grip, hand wetness/contamination, skin surface area, as well as the hand grip force itself (Buchholz et al., 1988; Bobjer et al., 1993). This suggests that the relationship between force required and torque produced may be non-linear. Also, with a coefficient of friction near 0.74 (sweaty hand, 50 % ridged material) and an in-line tool with a 5 cm diameter and 4 Nm torque, the hand grip force could exceed 100 N which represents a 41% MVC contraction based on mean strength values published by the American Medical Association (1990). *Hand tool use is a source of injury in working populations. Guidelines for torque producing tools cover a large range and may be inconsistent with recommendations for hand grip. The effect of high repetition and high work:rest ratios on the guidelines is not known.*

*Summary 1:*

WMSDs are a continuing problem in repetitive manual jobs. Methods are being developed to evaluate jobs for risk of injury. However, more are needed. Particularly lacking are guidelines specific to external loads for highly repetitive jobs suitable for use by industrial engineers. Adjustment type psychophysical methods are currently being used to fill this void until complete understanding of the etiologies and critical loads associated with low level repetitive work is achieved. Unfortunately, this method has a number of drawbacks. Specific to the upper limb, the multiple degrees of freedom requires a large library of tasks or movement elements. For direct applicability, guidelines for specific tasks may be more useful to an engineering community. Repetitive use of hand tools is one area which has been identified with the development of WMSD. Therefore, task specific guidelines for hand tool use may be a priority.

Goal 2: To examine the effect of duty cycle and cycle time on PDAT

**Repetition**

On the surface repetition appears to be one of the easiest factors to measure. In order to quantify an exposure, however, it is necessary to define to what it is that the worker is being exposed. As reviewed by Kilbom (1994), repetition has been defined from a number of perspectives. Those definitions that have been used range from purely output based (e.g. parts/hour, keystrokes/hour) to slightly more movement based (e.g. cycle time and the number of tasks per cycle, Punnett and Keyserling 1987; cycle times of 30 seconds or less or repeating subcycles occupying more than 50% of the basic cycle, Silverstein et al., 1986). Definitions based on the number of movements made per unit time have also been used (Kivi 1984, Genaidy et al., 1990). While this definition is more physiological, and likely more transferable between different jobs, it suffers in its current state from the lack of definition of a movement (e.g. the number of change of directions of a joint around a given axis, a given range of motion of a joint around a given axis etc).

Latko et al. (1997) developed a visual analogue scale with verbal anchors and benchmark examples. This was found to be related to both the hand exertions per second and rest per cycle, as well as prevelance of injury (Latko et al., 1997; 1999). Mathiassen and Winkel (1991) suggest that to define a task the cycle time (inverse of frequency), duty cycle, and mean load must all be stated. Ayoub and Wittels (1989) noted that Cumulative Trauma Disorders result from sustained or repetitive applications of low stress over time. Repetitive can be defined as "characterized by being done again and again" (Oxford American Dictionary). From current definitions used it is apparent that what is recognized as repetitive when viewing a job is tasks or movements done over and over. However, what leads to injury is loading of a tissue over and over.

Silverstein et al. (1987) found high repetition to be a significant factor in the prevalence of carpal tunnel syndrome. Their operational definition of less than 30 seconds or repeating sub-cycles for more than 50% of the time is currently the standard for defining high repeitition. Wells et al. (1992a) found that tendon excursion had a U shaped relationship to injury in a study of highly repetitive jobs. At one end there are jobs with little movement or constrained postures. At the other end are jobs with lots of movements or 'repetitions'. Again the combination of force and repetition together present greater risk than repetition by itself (Silverstein et al., 1986, 1987). This is consistent with the concept of fatigue in metallurgy where the number of cycles to failure decrease with increased stress per cycle. Bishu et al. (1990) used this approach in studying the maximum number of voluntary repetitions to cessation as a function of % maximum voluntary contraction for one frequency. They found a linear log-log function, although it is unknown how endurance relates to injury. In biological tissues it is likely both the number of cycles (repetitions) and the rest between cycles that impact injury. *Epidemiological evidence and biological plausibility would suggest repetition is important in the development of WMSD. However, defining repetition based on one output based measure appears insufficient in capturing all mechanisms leading to injury. Cycle time and duty cycle are two measures which give some feel for frequency and recovery aspects of a task.*

***Duty Cycle and Cycle Time with Upper Limb Psychophysical Studies***

None of the psychophysical adjustment studies reviewed controlled for duty cycle. That is, as frequency increased the amount of rest decreases. Therefore it is unclear what accounts more for the decrease in force chosen, the increased frequency or decreased rest. Wiker (1991) examined the effect of decreased rest and different pinching forces on a participants' psychophysical function. He found that changes in percent rest (from 50% to 25%) had relatively small effects and was only significant at high pinch forces (25% MVC). Not all upper limb, psychophysical adjustment studies use load as the adjustable factor. Several studies have used task frequency as the adjusted factor (Abu-ali et al., 1996; Kim and

Fernandez, 1993; Dahalan and Fernandez, 1993). Since the task duration and level of load is fixed, adjusting the frequency (which in effect is adding or removing rest) will adjust both the cycle times and the duty cycle. In these studies, which were high repetition, a positive relationship was found for cycle time and workload, which is opposite that predicted by endurance studies such as Rohmert (1973). *The results from psychophysical studies contradict those from endurance studies on the effect of cycle time. In load adjustment studies, duty cycle has not been controlled for. Therefore, it's not clear whether frequency effects are due to increased number of repetitions or decreased rest.*

### *Physiological and Biomechanical Implications of Duty Cycle and Cycle Time*

Increasing the length of rest between repetitive handgrips appears to reduce signs of local fatigue from a range of different measures including: physiological - blood flow, biomechanical - zero crossings in EMG, and psychophysical - subjective ratings (Byström and Kilbom, 1990). In their research, four duty cycles were examined, 50%, 66%, 83%, and 100%, (10+10, 10+5, 10+2, and continuous contraction) for three contraction intensities (10, 25 and 40% MVC). Only 10% contraction for 10+5 and 25% + 10% contraction for 10+10 were considered acceptable. Unfortunately, all conditions examined simultaneously changed the cycle frequency, duty cycle and length of work. Rohmert suggested that the rest required after an isometric contraction depends on the duration of the task and the force required (Rohmert, 1973). Mathieson and Winkel (1992) express concern over the use of endurance data to limit work:rest ratios in highly repetitive tasks due to its sensitivity to task factors such as muscle group and position as well as the unknown relationship between acute fatigue and injury.

Muller found that, in terms of endurance, it was the total rest given as opposed to the number of rest pauses given that was important (as reported by Bystrom, 1991). While it seems clear that reduced duty cycle is beneficial, Bystrom et al. (1991) found that compared to a continuous contraction the addition of a short rest with a large duty cycle (.93) may actually be harmful since the pause was not sufficient to allow potassium recovery but increased endurance and subjective feelings of comfort. Interestingly, the need for appropriate rest may be more important at low levels of contraction, since recovery of potassium takes longer after low level (10%) contractions (Bystrom and Sjogaard, 1991).

Moore et al. (1991) suggest that a range of biomechanical load factors are important in characterizing exposure that lead to injury. Included are a range of movement and cumulative load measures. Many biomechanical load factors, such as mean muscle load or cumulative tendon load, are unchanged by changing frequency with no change in workload or duty cycle. Factors that are theoretically affected by frequency include excursion and work of the tendons against the sheath. Many biomechanical variables are much more sensitive to decreased rest, since this increases the percentage of time the load is held (i.e. increased duty cycle), therefore allowing increased tissue creep and extended muscle activation. *Most biomechanical and physiological load measures indicative of suggested mechanisms leading to WMSD appear effected by duty cycle. Still other measures are sensitive to cycle time. The interactions between the two are not well studied in highly repetitive tasks.*

*Summary 2*

Various studies have found an association of upper limb WMSD with repetition, with repetition usually defined using cycle times or movement frequencies (Kilbom, 1994).

However, repetition involves more than cycle time/frequency (Moore and Wells, 1992b). Physiological studies have shown that with low level repetitive tasks, the amount of rest involved with a cycle can affect local muscle fatigue (Bystrom and Kilbom, 1990) and therefore be a possible mechanism in the development of muscle pain (Sjogaard and Jensen,1997). Many measures of cumulative biomechanical loading for static tasks are sensitive to duty cycle and posture. Dynamic portions of a task would be sensitive to cycle time and the range of motion involved (Moore et al., 1991). Frequency adjustment type psychophysical studies show that load can effect both cycle time and duty cycle. However, cycle time and duty cycle are not adjusted independently. Load adjustment type psychophysical studies have shown a significant effect of task frequency, even within high repetition jobs. However, duty cycle has not been controlled. Therefore it is not clear whether it is the decreased cycle time that is being adjusted for or decreased rest or both.

Goal 3: To test the psychophysical relationship between torque and perception over different conditions

**Magnitude Estimation**

Central to the psychophysical adjustment method used to determine safe loads, is the ability of the participants to perceive the load presented, interpret the load with respect to the tissues at risk, and adjust the load to a level which will not cause injury. The relationship describing perceived versus actual magnitude of a stimulus can be defined by a power function (Stevens, 1957). The exponent or the slope of the function when plotted in log-log scale is used to describe the function. The use of Steven's power function is one way of examining the ability of the participants to perceive the load presented. Gamberale et al. (1987) were among the first researchers to report on testing the assumption in conjunction with a load adjust study applied to lifting. Steven's law adequately described the relationship between perceived workload and both work pace and case weight. The slopes found were different for two different lifting situations (horizontal and diagonal lifting). Cafarelli and Bigland-Ritchie (1979) found that developing forces in a matching task was affected by muscle length.

In grasping and lifting tasks, it is found that subjects overrate the force at higher workloads (i.e. have exponents greater then 1). This was also true of the participants' rating of perceived difficulty of the task. (Gamberale et al., 1987). Stevens (1960) found an exponent of 1.7 for handgrip. Jones and Hunter (1982) found exponents in the range of 0.45-0.86 for a task exerting force with the middle finger, which is consistent with their subjects having been asked to exert the force based on a rating number, not rate the force after experiencing it.

Sensation of force during a repetitive grasping task would come from a variety of sources. Golgi tendon organs, found at the aponeurotic junction of the muscle tendon, are in series with 10-20 extrafusal muscle fibres from a range of motor units including at least one low threshold fibre. Their Ib afferent fibres have exhibited a linear relationship between force and firing rate. Several receptor structures are available in the glabrous skin of the hand to sense touch (Sinclair, 1981). Mechanoreceptors have been classified based on structure and electrophysiologic response. Slow adapting units are thought to be hederiform endings (SA I) which may detect pressure and are more common in the finger tips than palm and Ruffini type corpuscles (SA II) which are distributed over the territory of the median nerve and may be sensitive to stretch. There are also rapidly adapting units which have been thought to include Meissner's corpuscles (FA I) which may detect moving stimuli along the surface of the skin or slow vibration. Very rapid adapting units (FA II) are associated with the Pacinian Corpuscles and are extremely sensitive to mechanical deformation. However, adaptation is very rapid being most sensitive to touch at 250 Hz. In a series of papers examining response to repetitive loading normal to the skin surface, (Macefield et al., 1996 a, 1996b) FA I receptors consistently responded to loading forces, while the SA afferents were sensitive to grip force and load forces, and muscle and joint afferents can provide information regarding reactive forces. The primary structure that respond only to strong stimulation are the C fibres polymodal nociceptors. Fransson-Hall and Kilbom (1993) noted that the thumb/thenar portion of the hand was the most sensitive to external pressure, and that sensitivity to pain was affected by both duration and repetition of pressure. Tension in the muscle/tendon unit may also provide information on discomfort. However, during 30 second bouts on a cycle ergometer, Hamilton et al. (1996) found that there was a different onset of discomfort from muscular effort and that perception of muscle pain was distinct from perceptions of muscle tension and discomfort. *Initial detection of the external loading of the hand as would occur with powered tools is primarily mediated by afferent signals in the skin of the hand not the tissues at risk for WMSD. However, once loaded, muscle, tendon and joint afferents will provide load information.*

*Summary 3*

The ability to adequately perceive the stimulus provided is one step in examining the usefulness of the psychophyscial adjustment method. This has been examined for lifting tasks. For studies applied to highly repetitive upper limb tasks, this assumption has not been tested. Evidence would suggest that the time course of the external load affects the afferent information and sensation (Macefield et al., 1996a; Franson-Hall and Kilbom, 1993). Therefore, duty cycle and cycle time could affect the relationship between actual and perceived load and should be tested for.

Goal 4: To examine the role of torque, duty cycle and cycle time on selected biomechanical variables representative of biomechanical loading of the upper limb which may lead to WMSD

## Biomechanical Risk Factors for WMSD

### *Posture*

As mentioned, the main risk factors attributed to WMSD's are force, posture and repetition. Accordingly, most quantified approaches to task analysis try to quantify these factors. Posture is typically recorded from video or film (e.g. Armstrong et al., 1982) or direct measurement with a goniometer (Armstrong, 1986; Moore et al., 1991). Measuring wrist and finger postures from visual records such as video is difficult due to the multiple degrees of freedom in the upper limb, making it very difficult for the joints in question to remain in the field of view, let alone in an orientation that will allow accurate estimation of the angle. Wrist goniometers allow for continuous recording of the wrist angle along both axes. The data glove (VPL research, California) can provide similar information on finger joint movement.

However, the video record is still essential to obtain hand function information since the type of hand grip used affects the relative muscle usage between the various intrinsic (i.e. within the hand) and extrinsic (i.e. in the forearm with tendons running into the hand) muscles of the hand (An et al., 1985). It is also useful in posturally static tasks where the hand is continuously oriented in the same manner.

Wrist posture can be analyzed by examining the percentage time spent in various wrist postures (Wells et al., 1992b), the daily damaging wrist motion index (Drury, 1987) in which the number of times the wrist is not in a neutral posture is counted, or the range of motion and end point postures used (Marras and Schoenmarklin, 1991). However, posture itself has not always been found to be related to injury (Silverstein et al., 1987; Marras and Schoenmarklin, 1991). The role of posture in injury is at issue. At extreme ranges of motion, there would be passive stresses on ligaments and tendons. Marras and Schoenmarklin, however, did not find the end point postures to be a significant indicator of risk. Instead they found wrist velocity and acceleration to be more predictive. This would indicate that the coupling of posture and movement or force production may be a more important factor in injury. Posture can affect the required muscle activation for a given force requirement, it can also change the orientation of the forces on the internal structures (Moore et al., 1991). Postural stability against gravity can lead to forearm muscle loading likely independent of extreme ranges of motion (Ranney et al., 1993). *Time spent in specific wrist postures as well as movement of the wrist have epidemiological support and biological plausability in the development of WMSD. Measurements are important in psychophysical studies to detect whether changes associated with selection of psychophysical load also changed posture in a manner which reduces loads* *on vulnerable tissues.*

*Force*

Force has been quantified by several methods. It has been estimated from the weight of the objects handled (Silverstein et al., 1987). This may not reflect actual hand grip force as skin friction (Armstrong, 1986) and individual dependent over-gripping (Westgaard and Bjorklund, 1987; Moore et al., 1991) affect how much actual grip force is used. Also, this does not give continuous readings, but point loads associated with lifting the objects handled. Force can be 'matched' at a later time on a dynamometer in place of the objects handled (Drury, 1987). The results of this method would likely be affected by the similarity of the dynamometer and the objects handled. However good rank matches have been found (Wiktorin et al., 1996). Force can be directly measured by instrumenting the objects handled or each segment at the hand. Present technological constraints (cost, inaccuracy, interference with tactility and function) limit this to settings such as a laboratory where tasks are designed to employ a small number of objects or tools used in a stereotypical fashion, all of which can be instrumented. Useful in a wide range of workplace settings, is estimating the hand grip force using EMG from the extrinsic finger flexors suitably calibrated for each hand grip (Armstrong et al., 1979). This approach has the advantage of giving continuous recordings through the duration of a task. However, the inclusion of additional factors such as wrist and forearm posture may improve the estimation (Moore et al., 1992).

The role of hand grip force in injury is perhaps understandable. Force is generated by muscles and transmitted along the tendons. Therefore, the greater the force, the greater the required muscle activation and stress in the tendons. Stress on surrounding tissues might also increase with increase force dependent on the posture and movements used. For example, pressure within the carpal tunnel and hence on the median nerve, is a function of both posture and muscle activation (Rempel et al., 1992, Keir, 1996). Silverstein et al. (1987), splitting force into high and low categories based on the adjusted force (mean force + variance/mean), found force by itself not to be significant in the prevalence of carpal tunnel syndrome. However, they did find force significant in the prevalence of WMSD's in general (Silverstein et al., 1986) and the combination of force and repetition was much greater risk than either factor on its own. *Hand grip force directly affects biomechanical loading on tissues at risk for WMSD of the forearm and wrist particularly when combined with specific postures or repetition. In high repetition psychophysical load adjust studies, how does hand grip relate to loads chosen? Is handgrip force below that found by Silverstein et al. (1986) and does a gradient exist within high repetition tasks for peak or mean hand grip force?*

***Electromyography***

The electromyographic (EMG) signals from muscles have been measured from shoulder and forearm musculature as an indicator of muscle load leading to injury during repetitive manual work (Jonsson, 1988; Aaras and Westgaard, 1987; Moore et al., 1991). The time varying signals are commonly expressed statistically using a technique developed by Jonsson (1982). The amplitude probability distribution function (APDF) describes the probability of the measured signal being at or below a certain level throughout the duration of a task. Three points (static: p=.1; dynamic: p=.5; peak: p=.9) are used to describe the curve.

Moore et al. (1991) showed that in the forearm, measures from the APDF accounted for changes in force, repetition and posture in a manner consistent with the prevalence of injury in jobs of similar force and repetition. The static level has been shown to account for chronic muscle disorders in the shoulders at levels as low as 1% MVC (Aaras, 1987). Local metabolic crisis in single muscle fibres has been implicated in chronic muscle pain in the shoulders (Larsson et al., 1988, 1990). This could in part be due to 'first-on, last-off' fibres that don't receive adequate rest unless the muscle is given a chance to completely turn off (Søgaard et al., 1992; Hägg, 1991). EMG has been analyzed to look for the number of times the muscle is turned off (.5% MVC for more than 0.2 seconds). Using this 'gaps' analysis, Veiersted et al. (1990) found people with pain tended to have fewer pauses. *Pattern of muscle usage as shown by EMG APDF and gaps analyses appears linked to development of muscle pain and injury. The effect of external loading typical of hand tool use on the pattern of muscle activation could affect whether injury occurs.*

*Summary 4*

Increased risk of developing WMSD has been linked to posture, force, and muscle usage measures (e.g. Silverstein et al., 1986; Aaras, 1987; Marras and Schoenmarklin, 1991). Injury develops as a function of load on tissue. The ability of participants in a psychophysical adjustment study to adjust the load such that the loads on tissue are such that they fall below current known guidelines is an important test in the usefulness of the results.

Goal 5: To examine the effect of load adjustment psychophysical study on fatigue and discomfort over the course of a working day and over different duty cycles and cycle times.

**Muscle Fatigue**

Physical assessments of women working in highly repetitive jobs have found 23% to have forearm/hand muscle pain (Ranney et al., 1995). Muscle injury may be the result of repetitive or continuous stimulation of the same muscle fibres leading to fatigue and disruption of the muscle's physiologic state (Sjogaard and Jensen, 1997). Fatigue with intermittent sub-maximal contractions has been shown to be peripheral in origin (Bigland-Richie et al., 1986; Vollestad et al., 1988). Workers with work related muscle pain have been found to have physical changes (moth-eaten or ragged red fibres) in individual low threshold muscle fibres (Larsson et al., 1988). It has been suggested that with low level sustained or repetitive work the low threshold motor units, or so called "Cinderella fibres", get continuously/repetitively used, without having sufficient time for recovery (Hagg, 1991). This can lead to high loading, fatigue and damage of these fibres.

Decreases in median or mean power frequencies are indications of muscular fatigue (e.g. Deluca, 1983). Mean power frequency has been found to be a better indicator of change in mechanical output from shoulder muscles than changes in EMG amplitude (Gerdle et al., 1989). These measures have been used as indicators of local muscular fatigue in the shoulder musculature and were able to show signs of fatigue during a 5 hour day doing a repetitive manual task (Christensen, 1986). It is important, however, to record from a standard test contraction as there is evidence of a change in frequency level with load at low loads (Gander and Hudgins, 1985). *The use of median or mean power frequency from standard test contractions repeated throughout a 5 hour day can be used to test for fatigue during a repetitive manual task.*

*Summary 5*

Forearm muscles have been shown to be at risk for pain in populations with repetitive manual tasks (Ranney et al., 1995). Muscle fatigue with inadequate recovery has been implicated in the development of muscle pain (Sjogaard and Jensen, 1997). Undue discomfort or fatigue are factors often included in instructions in research using adjustment type psychophysical methods. It has been shown that people can rate increased discomfort with increased muscle fatigue. It has not been shown that they can adjust loads to have either no detectable fatigue, or else a consistent amount of fatigue between different conditions representing differing amounts of rest for the muscle

# Chapter 3

# PSYCHOPHYSICALLY DETERMINED ACCEPTABLE TORQUES FOR IN-LINE SCREW RUNNING: EFFECT OF CYCLE TIME AND DUTY CYCLE


**ABSTRACT**

Psychophysical methodology has been used to develop guidelines for lifting in industry. Similar methods have been applied to repetitive upper limb movements. However a large library of different work related movements and tasks is necessary to make this approach a useful tool for upper limb ergonomic assessment. While different frequencies (cycle times) are usually used, there is often no control for duty cycle. The purpose of this paper is to present psychophysically determined acceptable torques for a common upper limb task (in-line screw running), with both cycle time and duty cycle conditions set by the researcher. Eight female participants sat at adjustable workstations. A handle controlled by a torque motor simulated an in-line screw running task. The computer controlled motor applied torques every 3, 6, 12 or 20 s with duty cycles of 25, 50, and 83%. The participants worked with one set of conditions each day and self selected the most torque that they felt was acceptable without developing undue pain and discomfort. Duty cycle was found to significantly affect the amount of torque selected. With duty cycle controlled, cycle time was no longer found to have any significant effect on acceptable torque. Acceptable torques for 25, 50 and 83 % duty cycle were 1.09, 0.9 and 0.73 N.m. Discomfort and stiffness were concentrated on the back of the hand and on the thumb web. These findings may imply that increased incidence of Work-related musculoskeletal disorders (WMSD) with increased frequency (decreased cycle time) are related to decreased rest/recovery time for muscles and other tissues.

Key Words: Psychophysical, RSI, Hand, Wrist, Screw Driving, Duty Cycle, Cycle Time, Muscle

## INTRODUCTION

Repetitive use of hand tools has been associated with the development of work related upper limb musculoskeletal disorders (WMSD). These disorders include soft tissue injuries to muscle, tendon and nerves in the hand, wrist, forearms and shoulders. Risk factors identified include repetition, force and postures, with the combination of both high force and high repetition having been found to have a multiplicative effect (Silverstein et al., 1986, 1987). The physical and social costs of these disorders precipitated the need for simple, but effective ergonomic evaluation tools and guidelines for use by ergonomic practitioners and design engineers in order to balance the need to obtain maximum work output from minimum staff while maintaining health.

One method of developing such a tool is the "psychophysical" adjustment approach. This approach led to a commonly used tool in the fight against the development of work related low back pain (Snook and Ciriello, 1991). In essence, participants with industrial experience were asked to manually handle loads under a variety of conditions (e.g. different frequencies, heights, locations, and movements: lift, lower etc.). While working, the participants were encouraged to adjust the weight of the load until they found a load that they felt was as heavy as they could handle over the time given without developing any undue pain or discomfort. The results were then published in tabular format by population. Validation of this assessment tool was limited to an analysis of past records of insurance claims for low back pain. Snook himself expressed concern that the approach only be used until research provided another "more objective method" (Snook 1985). The tables are still widely used in conjunction with biomechanical and physiological information.

Recently similar methods were used to provide data on acceptable forces and moments for upper limb tasks (eg. Snook et al., 1995, Krawczyk et al., 1992, Kim and Fernandez, 1993). The approach is attractive since it creates an assessment tool that can be applied in industry, uses external exposure measures (e.g. torque and frequency), and uses working populations. It is limited, however, because the large number of degrees of freedom available in the upper limb mean a large library of different movements and postures is required. A concern is that the relationship between the perceived capability and injury and fatigue are unknown, and upper limb epidemiological verification is unavailable. Snook et al. (1995) chose to study a specific wrist movement (wrist flexion and extension during grasp and pinch, with the forearm pronated). While this movement may be an element of many jobs, the data are not necessarily easily used when examining the risk associated with many industrial jobs. Data specific to a common industrial task such as hand tool use would be a useful addition to the "psychophysical library" of tasks.

Use of hand tools is associated with 9% of all work-related compensable injuries (Aghazadeh & Mital, 1987). A portion of these are due to over exertion. Repetitive hand tool use has been linked to development of WMSD (Silverstein et al., 1987; Cannon et al., 1981). The muscle responses to various powered screw runners (in-line and pistol grip) and nut runners (90 degrees) have been studied (Armstrong et al., 1993; Kihlberg, 1994; Radwin et al., 1989) showing high muscle response to even low torques which can be affected by build up rates and the shut off mechanism. The effects of hand tool interface (e.g. diameter, gloves, shapes) on maximum torque capability have also been studied (e.g. Hall, 1995; Shih and Wang, 1996). However, while our understanding of the effect of powered hand tool use on musculoskeletal system grows, there is still a need for guidelines in the form of external measures for use in industry. Psychophysical methods have been shown to be a useful approach (Snook et al., 1995; Kim and Fernandez, 1993).

One area in the use of hand tools (and in work in general) which requires more research is the work-rest regime (Mital & Kilbom, 1992). In previous psychophysical studies the participants were able to control the force of the movement which was done at different frequency conditions. Frequency was found to significantly affect the amount of force the participants chose. The higher the frequency (i.e. the shorter the cycle time), the lower the force chosen. Silverstein et al. (1986) found that jobs with a cycle time less then 30 seconds or repeating subcycles occupying 50% of the basic cycle had a higher prevalence of WMSD.

All of the frequencies studied by Snook et al. (1995) would be classed as high frequency. The risk factor of repetition incorporates a number of components (Moore and Wells, 1992b; Kilbom, 1994; Radwin and Lin, 1993). Frequency, or its inverse cycle time, is usually one component. Duty cycle (%time working) and similarity (i.e. use of the same tissues over and over) are other components. Length of rest between cycles in repetitive hand grips appears to reduce signs of local fatigue as evidenced by a range of measures including blood flow, EMG and subjective ratings (Bystrom and Kilbom, 1990). Rest required after an isometric contraction has been shown to depend both on duration of the task and the force required (Rohmert, 1973). Mathiassen and Winkel (1991) suggest that to define a task, cycle time, duty cycle and mean load must all be defined.

The role of the two factors of cycle time and duty cycle within a psychophysical adjustment method is not clear. Where frequency has been adjusted for different work loads and work durations, an effect of duty cycle and cycle time has been shown (Abu-Ali et al., 1996; Kim and Fernandez, 1993; Dahalan and Fernandez, 1993). In adjustment studies where load is adjusted, duty cycle hasn't been controlled for.

The purpose of this paper is to present the results of psychophysically determined maximum allowable torque using a simulated in-line screw-running task, where both frequency and duty cycle are changed. The effects of duty cycle and cycle time on psychophysically chosen maximum allowable torque during this high repetition task are studied.

## METHODOLOGY

Eight women (Table 3.1), with industrial experience, were recruited from a temporary industrial employment agency. Prior to participation, the women completed a questionnaire detailing their employment and health history. They were also screened by a physician for the presence of any musculoskeletal disorders of the hand, wrist or forearm on their right upper limbs. Two women participated at the same time. The women worked for fifteen days, which were completed within a four week period. The fifteen days included 3 days of training, 11 days of psychophysical data collection and 1 day of biomechanical data collection (Table 3.2). This paper will concentrate on the eleven days of psychophysical data collection. A typical work day is shown in Table 3.3. The participants worked for 5 hours per day with a 20 minute lunch break after hour 3. Snook et al. 1995 found that the levels chosen leveled off after 4 hours. The participants worked continuously for 50 minutes of each hour. The remaining time was used to fill in discomfort scales, record electromyographic signals during a fatigue test contraction (to be reported on later) and take a short break during which torque levels were reset. Throughout each day the participants worked at one of eleven test conditions (Table 3.4) chosen at random. The two women working concurrently used the same test condition. However, any preset torques were different.

**Table 3.1** Anthropometric data of the 8 female participants. Mean (range)

| Age (years) | Weight (kg) | Height (m) | Strength (N) |
|---|---|---|---|
| 33 (20-51) | 74.8 (59.4-96.5) | 1.63 (1.53-1.80) | 197.6 (107.9-323.7) |

**Table 3.2** Schedule of days

| Day | Hours Worked | Activity |
|---|---|---|
| 1 | 2 | Informed consent, questionnaire, medical screening, 1 hour training/work hardening session |
| 2 | 3 | Training/work hardening session, torque perception recorded |
| 3 | 4 | Training/work hardening session |
| 4-14 | 5 | 1 combination of duty cycle (25, 50 or 83%) and cycle time (3, 6, 12 and 20 sec) presented each day |
| 15 | 5 | Biomechanical Data at each condition recorded (not reported here) |

**Table 3.3** Work Schedule (days 4-14).

| Time | Activity | Data Collected |
|---|---|---|
| 9:05-9:10 | Set Up, EMG Test contraction, Questionnaire | discomfort scale, EMG from test contraction |
| 9:10-10:00 | Screw running, selecting torque | Final Selected Torque |
| 10:00-10:10 | Questionnaire, EMG Test Contraction, Break | discomfort scale, EMG from test contraction |
| 10:10-11:00 | Screw running, selecting torque | Final Selected Torque |
| 11:00-11:10 | Questionnaire, EMG Test Contraction, Break | discomfort scale, EMG from test contraction |
| 11:10-12:00 | Screw running,selecting torque | Final Selected Torque |
| 12:00-12:05 | Questionnaire, EMG Test Contraction | discomfort scale, EMG from test contraction |
| 12:05-12:25 | Lunch | |
| 12:25-12:30 | EMG Test Contraction | EMG from test contraction |
| 12:30-1:20 | Screw running, selecting torque | Final Selected Torque |
| 1:20-1:30 | Questionnaire, EMG Test Contraction, Break | discomfort scale, EMG from test contraction |
| 1:30-2:20 | Screw running, selecting torque | Final Selected Torque |
| 2:20-2:35 | Questionnaires, EMG Test Contraction, EMG MVC's, clean up | discomfort scale, Specific discomfort scale, EMG from test contraction, EMG MVC |

**Table 3.4** Test conditions used. Note, 3 s 25% condition was not performed due to pre-testing results.

| Condition # | Cycle Time (s) | Duty Cycle (% Time) | Work Time (s) | Rest Time (s) |
|---|---|---|---|---|
| 1 | 20 [b1,b3] | 25 | 5 | 15 |
| 2 | 20 [b1] | 50 | 10 | 10 |
| 3 | 20 | 83 | 16.6 | 3.4 |
| 4 | 12 [s] | 25 | 3 | 9 |
| 5 | 12 [s] | 50 | 6 | 6 |
| 6 | 12 [s,b1, b3] | 83 | 10 | 2 |
| 7 | 6 [s, k] | 25 | 1.5 | 4.5 |
| 8 | 6 [s, k] | 50 | 3 | 3 |
| 9 | 6 [s, k] | 83 | 5 | 1 |
| 10 | 3 [s, k] | 50 | 1.5 | 1.5 |
| 11 | 3 [s, k] | 83 | 2.5 | .5 |

[s] Cycle time used in Snook et al., 1995.
[k] Cycle time used in Krawczyk et al., 1992.
[b1] Frequency and duty cycle used in Bystrom and Kilbom (1990).
[b3] Cycle time and duty cycle used in Bystrom (1991).

The work performed was a simulation of a screw running task (i.e. using a powered screw driver where the axis of torque production is in-line with the axis of a cylinder when grasped). The worker grasped a 46 mm cylindrical handle with a 3/4" socket mounted in the bottom and prevented the handle from turning. Grip force was measured with a force transducer located inside the handles. The socket fitted over a nut that was mounted on a shaft which included a torque transducer (Chatillon) and a pulley that was driven by a belt from a computer controlled torque motor (Figure 3.1). Each participant sat at an adjustable workstation in an adjustable chair. The participants were taught how to adjust both, and asked to adjust them until her arm was comfortably resting at her side while holding the handle. A cushion was provided to rest the forearm to minimize any stresses related to gravitational

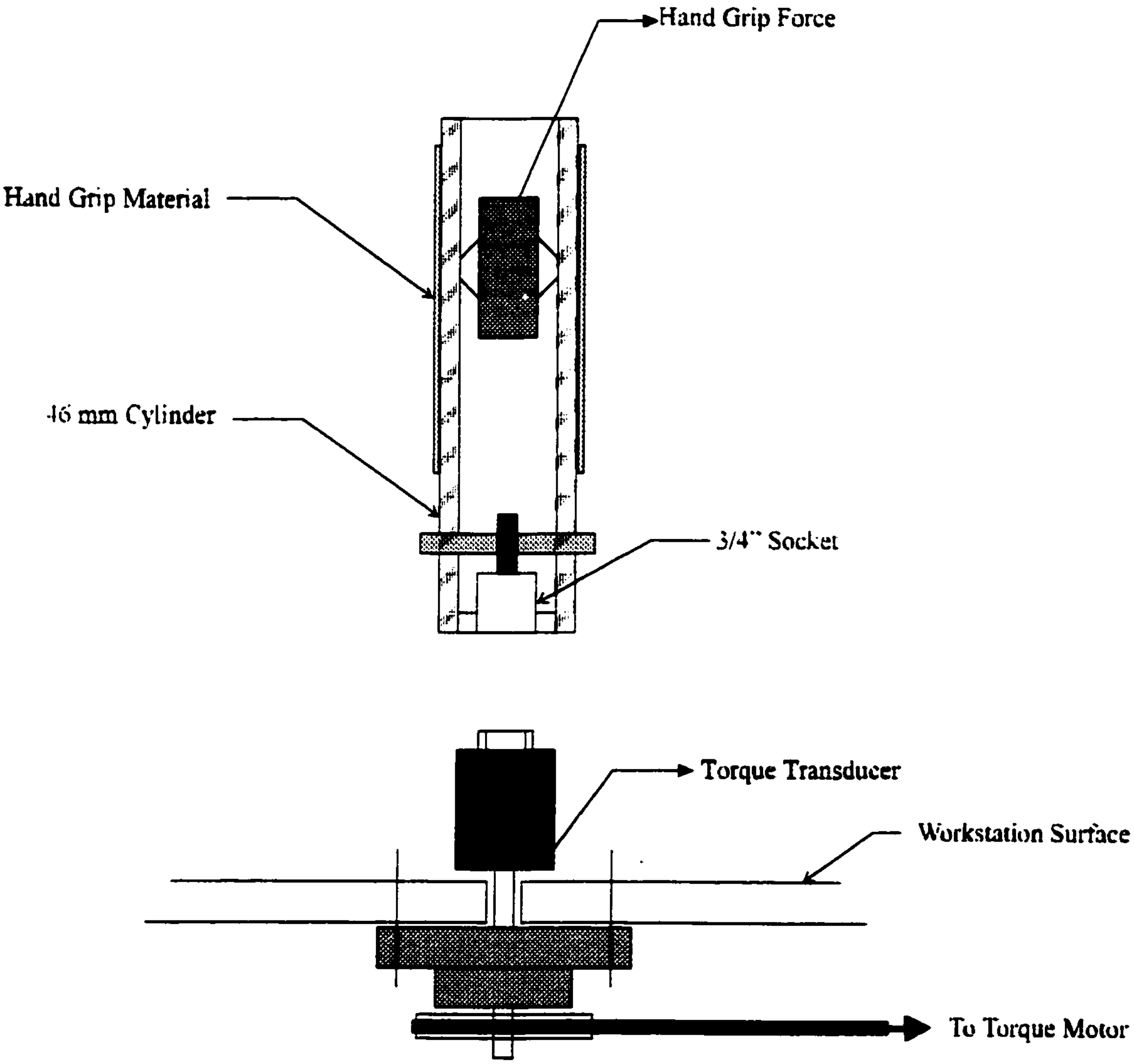



**Figure 3.1** Side view of simulated screw runner.

support of the arm or forearm.

The torque motor was programmed to repetitively apply a torque (figure 3.2) at a set cycle time (3, 6, 12, or 20 s) and duty cycle (percentage of time on; 25%, 50%, 83%). The amount of torque output by the motor was preset randomly alternately high or low at the beginning of each hour. The participants could then control the torque based on the instructions given, using a two button mouse with a plus button (more torque) or a minus button (less torque). A schematic of the workstation is shown in Figure 3.3. A set rise rate of 10 N.m/s was used to avoid eliciting a muscle reflex response (Armstrong et al., 1993).

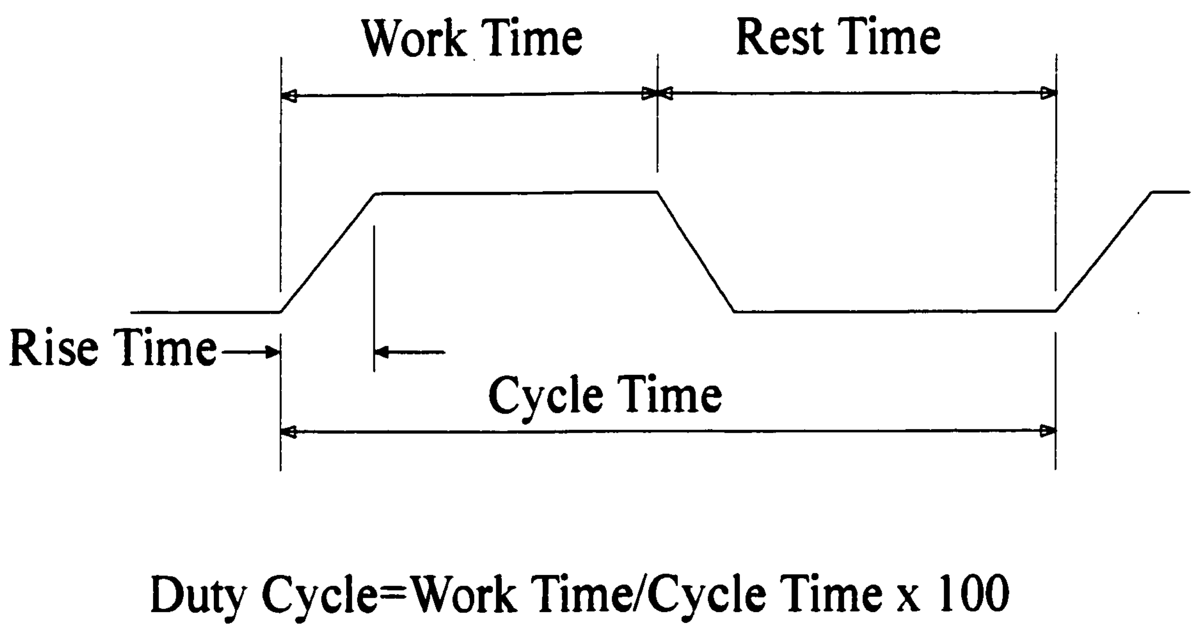



**Figure 3.2** Time profile of a cycle of the torque motor

Participants were given instructions to use the mouse to choose a torque level such that they were working as hard as they could without undue discomfort (Snook et al., 1995). This sheet (Appendix A) was posted on the wall in front of the participants. At the end of each hour the torque chosen was recorded and the torque level randomly reset alternatively higher or lower. At the end of the day a two page discomfort survey was administered, detailing the type and location of any discomfort in the hand and forearm as well as an overall discomfort level (Appendix C). Since the participants were instructed to choose a level that would cause little or no discomfort, if they reported any discomfort at the "somewhat" (2) or "very" (3) level they were reminded of the instructions. If this was repeated, they were asked to withdraw from the study for their own safety. One participant completed all but 2 conditions due to concerns about discomfort and these data are included. Two participants failed to complete the protocol, one because she developed high levels of discomfort and the other due to a vehicular accident after 9 days. A randomized block design was used with time as a repeated measure. Statistical analyses were done using a generalized linear model utilizing the SAS statistical software package on a Unix platform.

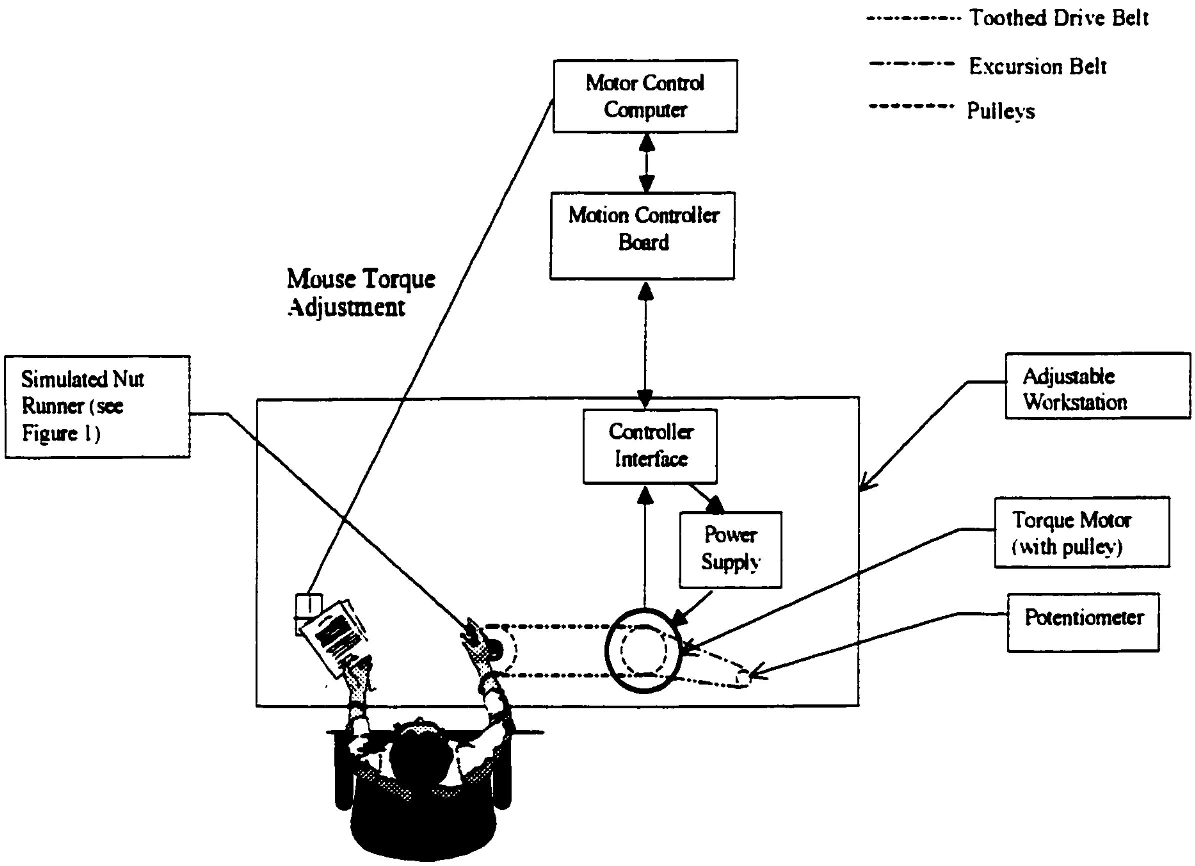



**Figure 3.3** Schematic of the Workstation.

**RESULTS**

Figure 3.4 shows the mean results for all subjects over each of the conditions of duty cycle and cycle time. It clearly shows that as the duty cycle increases (i.e. less rest time) the torque chosen is reduced. This was the case for most conditions for every subject. In fact, duty cycle was a significant factor in choosing torque ($p<0.05$). Cycle time, however, showed no statistically significant effect and no interaction between cycle time and duty cycle was found. Table 3.5 lists the psychophysically selected acceptable torque by duty cycle. The range of acceptable torques for the 8 participants is shown in figure 3.5.

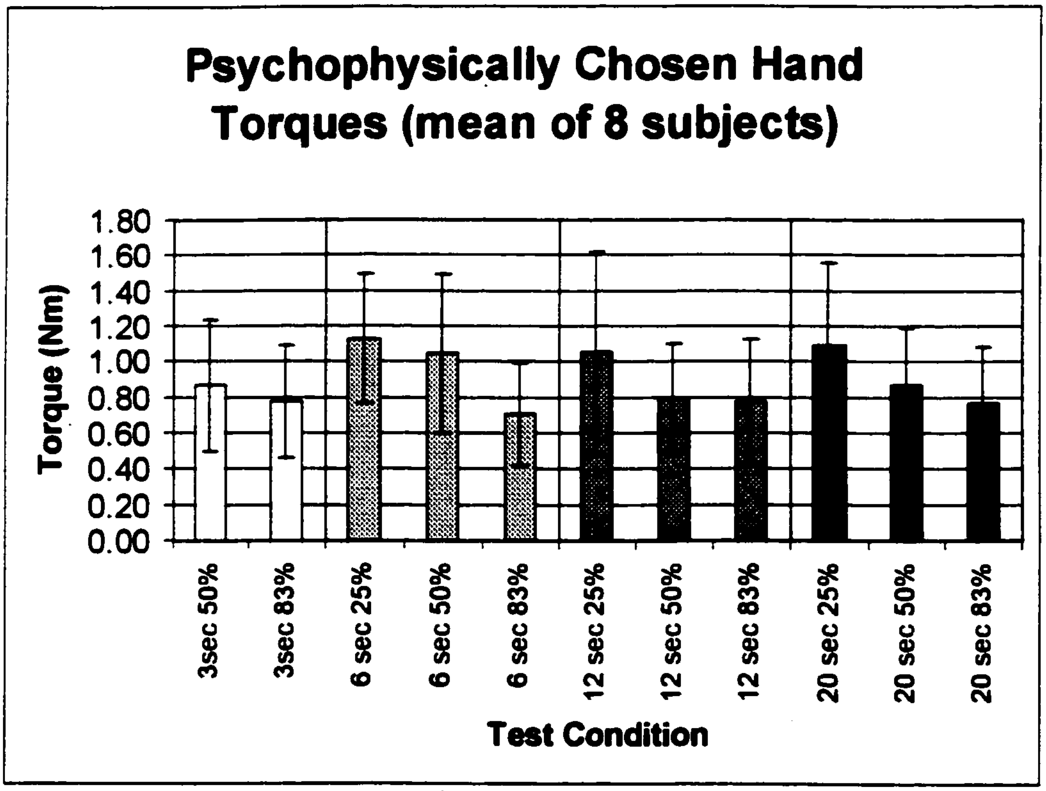



**Figure 3.4** Graph of the torques chosen by the workers (mean, standard deviation of 8) for each of the different cycle time and duty cycle conditions. Results are grouped by time (3, 6, 12 and 20 s) and within each group are the different duty cycles (25, 50 and 83%).

**Table 3.5** Acceptable torque based on psychophysical selection.

| Duty Cycle (% Time) | Measure | Torque (N.m) |
|---|---|---|
| 25 | mean (std dev) | 1.09 (.45) |
| | median | 1.06 |
| | range | .36-1.96 |
| 50 | mean (std dev) | .90 (.36) |
| | median | .79 |
| | range | .33-1.65 |
| 83 | mean (std dev) | .75 (.3) |
| | median | .73 |
| | range | .27-1.18 |

The mean value of the 7 point overall discomfort scale over all subjects and days (total 86) is 1.8 for both front and back. There was no significant effect of cycle time nor duty cycle. The number of different discomfort categories marked at the end of the day for each of the

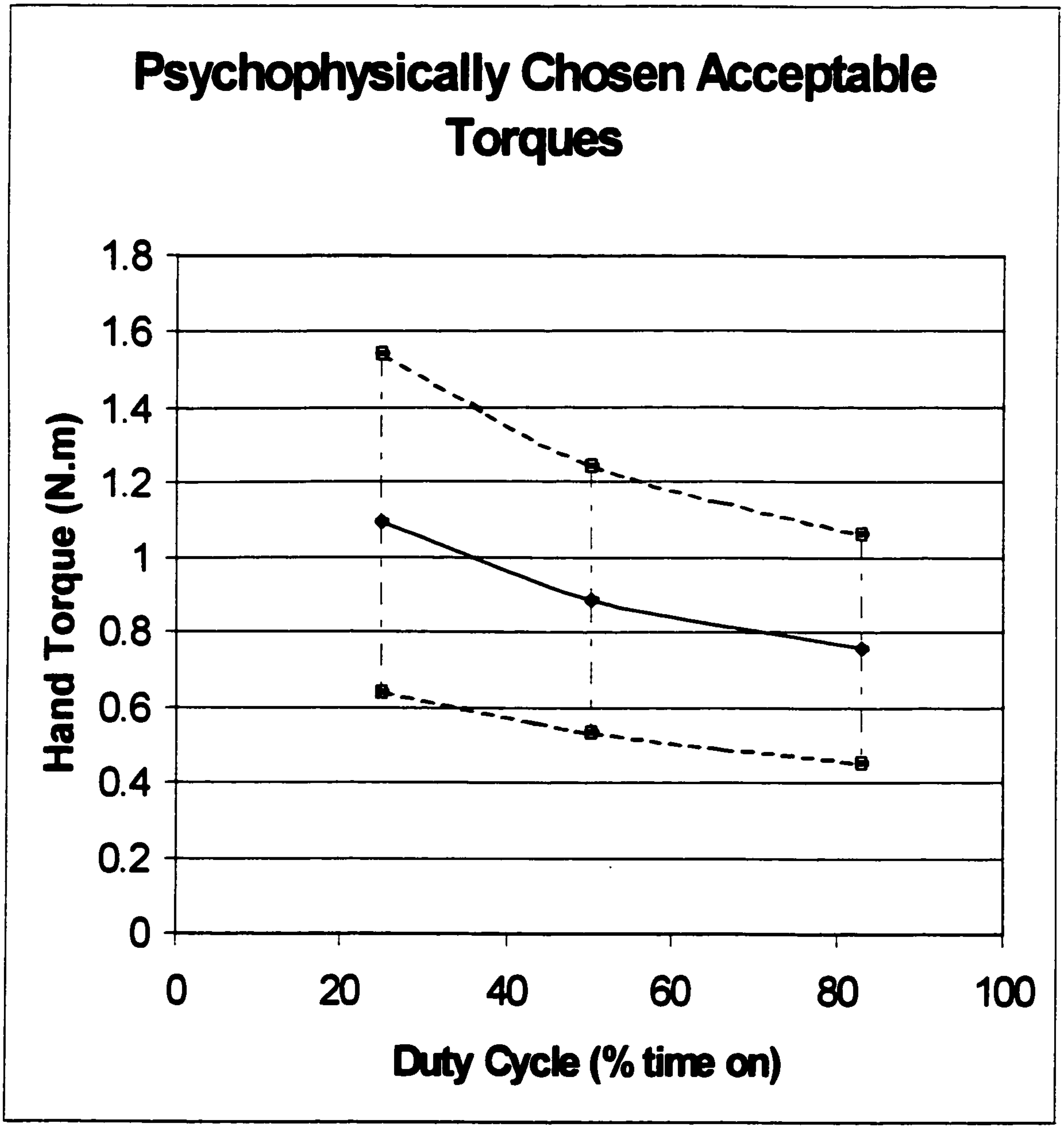



**Figure 3.5** Range of Torques Chosen by Duty Cycle

conditions of duty cycles and cycle time is shown in figure 3.6. The distribution of the reports of discomfort is shown in figure 3.7. In most cases, there are more reports on the back of the hand. The most notable exception is the area between the thumb and index finger (the thumb web and thumb MCP joint area). The back of the thumb itself followed by the area between the thumb and index finger had the greatest number of reports of discomfort. Stiffness was the largest reported type of discomfort. Discomfort in the fingers was usually reported as stiffness. Most of the reports of discomfort in the fingers were marked directly on the IP joints.

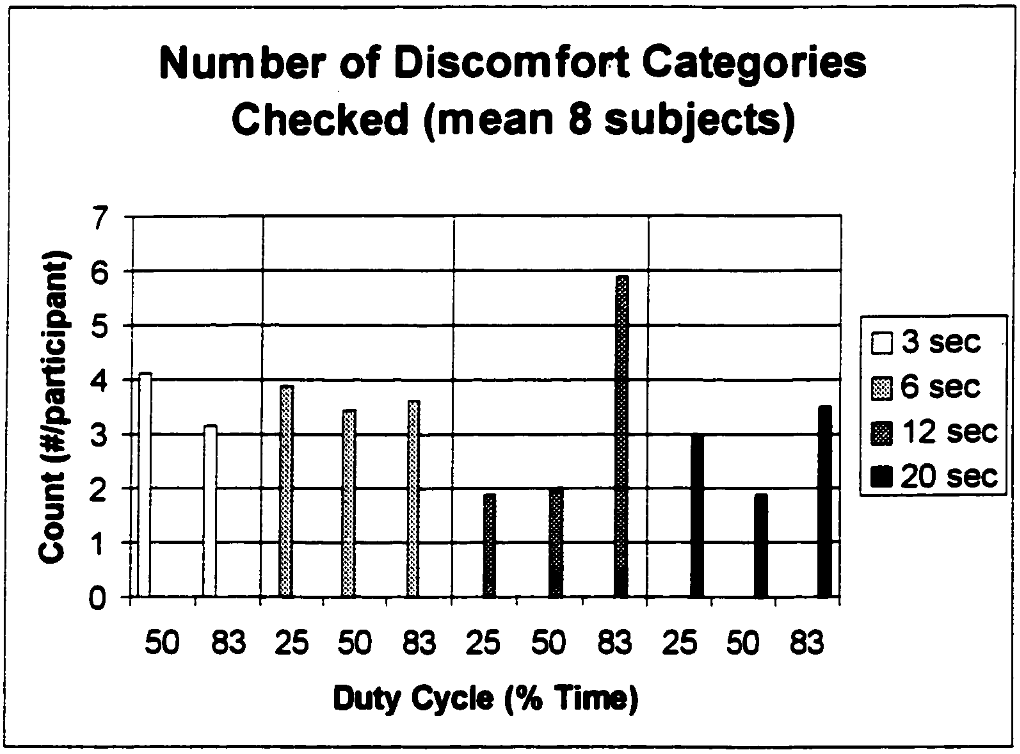
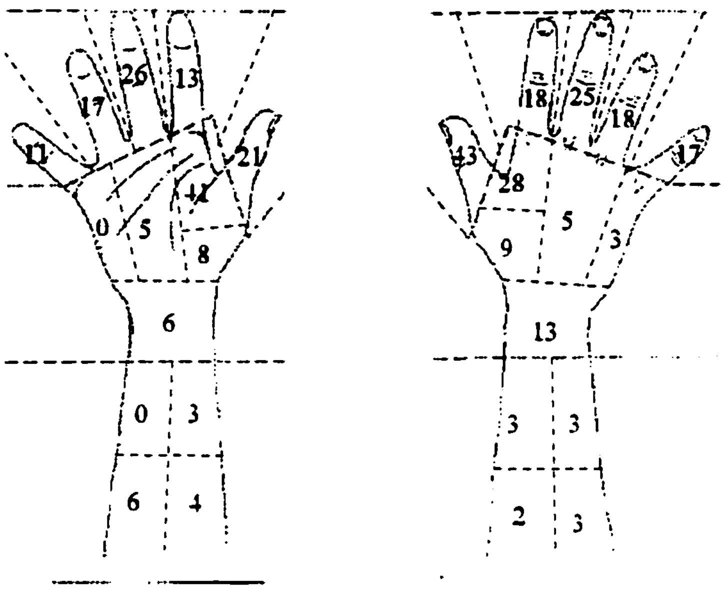



**Figure 3.6** Graph of the total number of discomfort categories checked off by the workers (out of a possible 18) for each of the different cycle time and duty cycle conditions (mean 8). Results are grouped by time (3, 6, 12 and 20 s) and within each group are the different duty cycles (25, 50 and 83%).

a)




b)

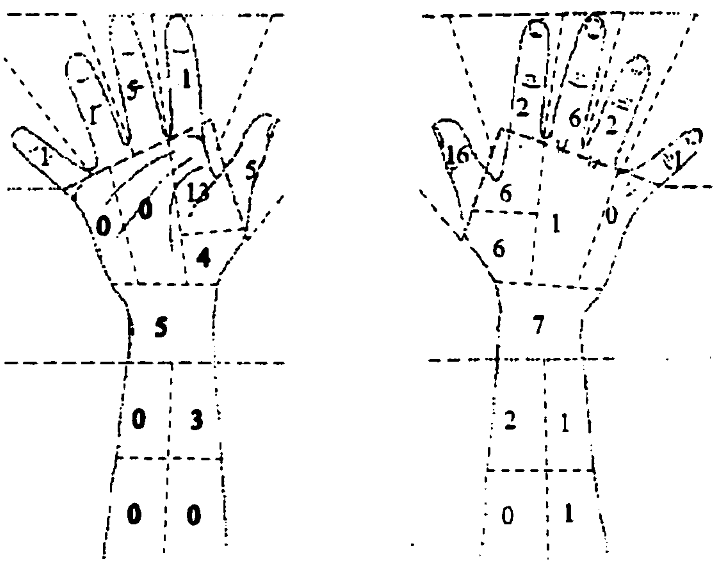
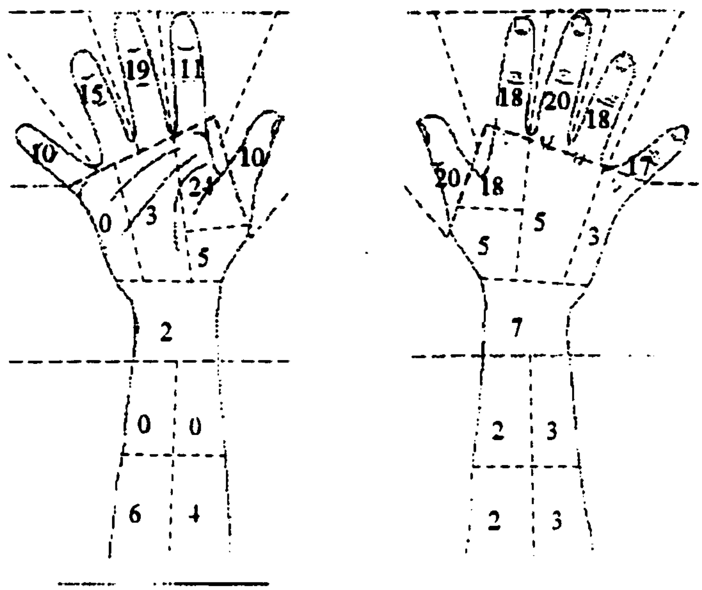



Figure 3.7 Sites of reports of discomfort at the end of the day. Total count over all days and participants (maximum score 86). a) number of reports of a form of discomfort of any type, b) number of reports of soreness, c) number of reports of stiffness, and d) number of reports of numbness.

c)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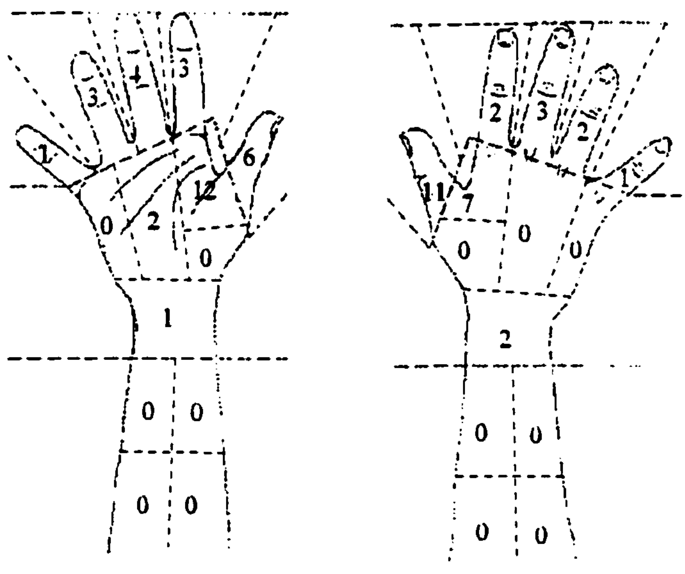
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**DISCUSSION**

Frequency has been reported to be significantly related to the force level chosen in psychophysically determined limits for upper limb repetitive task (Snook et al., 1995). However, when the frequency of a task was changed, there was no control of the duty cycle. Increased frequency could very well mean increased duty cycle if the participants did not

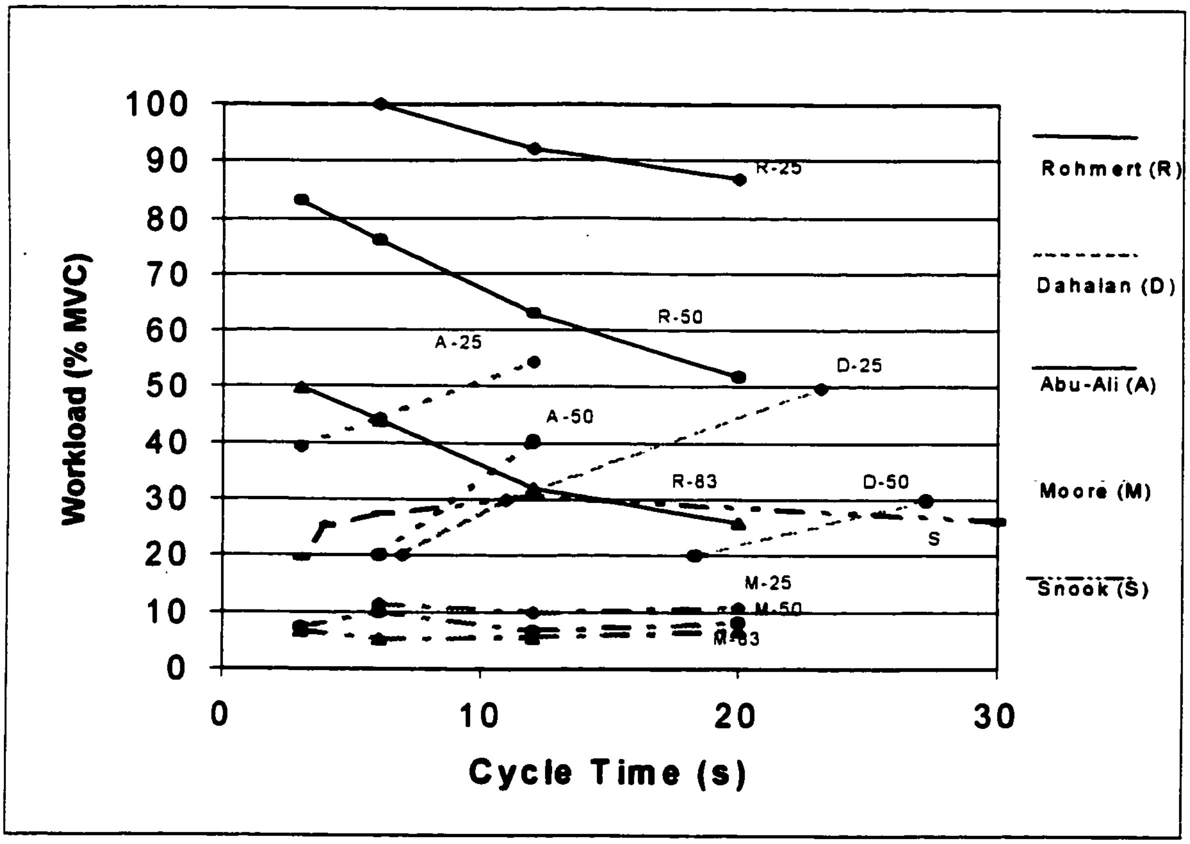



**Figure 3.8** Comparison of "Acceptability" of workload for different cycle times by different approaches. Abu-Ali et al. (1996) and Dahalan and Fernandez (1993) use psychophysical frequency adjust, Moore et al. and Snook et al. (1995) based on psychophysical load adjust (note Snook et al. based on the wrist extension with a power grasp) and Rohmert (1973) is based on endurance time. ♦ = 25% Duty Cycle, ● = 50% Duty cycle, ▲=83% Duty Cycle and ▬ = Duty Cycle is not controlled for.

change the speed of the actual movement in relationship to the decrease in cycle time. The increased frequency would then remove relatively more rest from the total cycle. For example if the movement was done in 2 seconds on average with a 12 second cycle time the duty cycle would be 17%. However, if the same movement was done in 1.5 seconds with a 3 second cycle time, the duty cycle would now have risen to 50%. This may account for the sharp decrease in workload chosen in Snook's results with short (3 s) cycle times (Fig 3.8). The results found here would suggest that it is the increased duty cycle (i.e. percent of time working) that is more important in the choosing of an acceptable work load rather than the frequency at which the task is performed for the high frequency efforts used here.

Along with controlling the duty cycle, this study differed from previous load adjust psychophysical studies by using a task in which the hand is responding to external loading instead of being initiated by internal muscle contraction. This is a useful addition to the psychophysical library as many powered hand tool tasks exist in industry. However, the results may differ from other tasks as it is likely more eccentric contractions are required. Also, defining the duty cycle based only on the task may not be correct as there will be time required for the hand to prepare for the initiation of the tool.

Abu-Ali et al. (1996) and Dahalan & Fernandez (1993) controlled both the workload and work time and allowed the participants to adjust the cycle time. Comparisons of the studies are shown in table 3.6. In both cases there was a significant effect of workload and work time on cycle time. In both studies examined, there is a reduction in acceptable load as duty cycle increases and cycle time decreases. There were, however, different interactions between cycle time and duty cycle (figure 3.8). There are several possible reasons for the differences from this study found in the magnitude and cycle time effects. First, both frequency adjustment studies were only done for a short period of time. Krawczyk et al. (1992) found a significant difference between the first four hours and the last four hours in a psychophysical study. No significant difference was found over the day in this study (table 3.7). However, measures weren't taken at times as short as 40 min. On top of this, Snook et al. (1995) found a 36.3% decrease in maximum acceptable torques by working 5 days per week as opposed to 2 days per week. Second, adjustment by frequency may lead to different results than adjustment by workload. Psychophysical adjustment studies have been shown to be sensitive to task features as well as the question asked (Karwowski et al., 1999). This may extend to the factor being adjusted. Direct comparison is also difficult since with frequency adjustment, the participants vary both their cycle time and duty cycle. Third, this study covered different ranges for the various conditions (table 3.6). None of their participants chose 83 % duty cycles, nor did any of the participants in this study choose 70% work loads. The results of Snook et al. (1995) are slightly higher than the results presented here in terms of workload (Figure 3.8). However that may be due to differences in task.

**Table 3.6** Comparison of this study to Abu-Ali et al. (1996), Dahalan and Fernandez (1993) and Snook et al. (1995).

| Study | Task | Testing Time | Measure Adjusted | Range Duty Cycle | Range Cycle Time | Range Workload |
|---|---|---|---|---|---|---|
| Moore and Wells | In-Line Screw Running | 5 hours | workload | 25-83% Time | 3-20 s | 5.2-11.4%* |
| Abu-Ali et al | gripping | 40 min | frequency | 20-63% | 2.5-14.8 s | 25-50% |
| Dahalan and Fernandez | gripping | 25 min | frequency | 9-43% | 6-31 s | 20-70% |
| Snook et al | wrist extension with grasp | 7 hours | workload | Not controlled | 3-30 s | 11-17.5% (adjusted for 5 days per week) |

* Based on Extensor Carpi Radialis Brevis muscle activity during the work period

**Table 3.7** Hourly results for acceptable torque. Mean (std dev) 8 participants, all cycle time and duty cycle conditions.

| Time: | 10:00 am | 11:00 am | 12:00 noon | 13:30 pm | 14:30 pm |
|---|---|---|---|---|---|
| Torque (N.m) | .91 (.40) | .90 (.44) | .93 (.43) | .89 (.40) | .90 (.40) |

The finding that reports of discomfort are not significantly related to cycle time or duty cycle suggests that the participants were successful in choosing a torque level for each test condition that did not create undue discomfort. The source of sensation which may act as the limiting factor in selection of the maximum acceptable torque is difficult to speculate upon. Sources could include mechanical pressure on the hands, sustained loading on the joints and tendons or muscular fatigue. Sensory inhibition due to stress on the skin has been shown to limit muscle strength. The stress on the skin during this task would be a combination of normal and shear stresses. Fransson-Hall and Kilbom (1993) noted that the thumb/thenar portion of the hand was the most sensitive to external normal pressure. The discomfort we found at the base of the thumb could be the result of stretching of the skin between the thumb and index fingers or due to possible intrinsic muscle pain (thenars or first dorsal interosseus). If pressure alone was responsible for the discomfort in the hand and fingers, it would be expected that there would be more discomfort on the palmar side than the dorsal side, particularly in the middle phalanx of the middle finger since this was found to be the location of most pressure while grasping a 50 mm cyclinder (Hall, 1995). This was not the case. For the fingers, the greatest reports of discomfort, were reported as stiffness in the back of the fingers. Sensitivity to pain in the hand has been found to increase with both repetition and duration of pressure (Fransson-Hall and Kilbom, 1993). Therefore both cycle time and duty cycle could have affected any threshold levels for discomfort.

In psychophysical studies of lifting it was found that cardio-pulmonary stress had more relative importance in perception of discomfort than local muscular stress (Wiker, 1992). However, upper limb repetitive tasks limited to forearm muscle groups similar to the one used in this study do not show significant effects on heart rate (Dahalan & Fernandez, 1993). The task used here involved a grasping motion by the finger flexors to exert pressure on the handle in order to develop sufficient frictional force to oppose rotation of the cylindrical handle. Simultaneous activation of the wrist extensors were required to both hold the wrist at an optimum position for grasping against the moment developed in the wrist due to the finger flexors and the twisting action of the handle (Moore et al., 1991, Snidjers et al., 1987).

Therefore, the primary muscle groups responsible would be the forearm finger flexors and the forearm wrist extensors. The lack of reported pain in the forearm could suggest that the workload was kept low enough such that muscle damage sufficient to cause cell membrane disruption did not occur or it was not sufficient to be detected. One possible muscle injury mechanism is the repetitive eccentric contraction that occurs at the start of each cycle. This could lead to delayed onset discomfort, particularly for the very short cycle time conditions. An attempt was made to look at this, and nothing significant was found. However, this analysis was complicated by weekends and missing data from the end of the study. It is also possible that 15 days was not sufficient for the development of discomfort.

Using muscular endurance data, the duration of a task (work time) has been associated with the amount of rest required in static work (Rohmert, 1973). Interpolating from the graphs provided by Rohmert (1973) and graphing by cycle time and duty cycle, it is clear that there is a large discrepancy between those results and the results presented here (figure 3.8). There is a negative slope between cycle time and workload (figure 3.8) with much higher acceptable loads (e.g. almost 83% MVC for 3 second cycle and 50% duty cycle, versus 7.2 % MVC found here). Based on an exponential function, short cycle times lay at the bottom of the curve, hence there is a large jump in acceptable load. The drawbacks in using endurance data for highly repetitive tasks has been expressed elsewhere (Mathieson and Winkel, 1992). The results here would suggest that the results of Rohmert (1973) could lead to workloads that are much higher than perceived acceptable when used in highly repetitive jobs.

Work related musculoskeletal disorders include injuries to soft tissues due to stress placed on them from working. These would include muscles, tendons, nerves and tendon sheaths. Risk factors include force, repetition, and posture. The interaction between the various risk factors can affect which tissue may have higher mechanical loading and therefore be at risk of injury (Moore et al., 1991). The participants in this study appear to have traded off between cumulative time and force. This should limit the perception of muscle fatigue and cumulative loading on tendons and nerves. However, what of other tissues? The task performed involved little movement. All the subjects kept their fingers clasped loosely around the handle during most rest periods. While the wrist was generally held in slight extension, there was generally a flexion movement at the start of each cycle. There should, therefore, be a greater amount of wrist movement for tasks with shorter cycle times. Excursion of the tendons through the wrist and the frictional work between the tendons and tendon sheaths have been used to characterize loading in the wrist that may lead to tenosynovitis and secondary development of carpal tunnel syndrome (Moore et al., 1991). The lack of significant effect by cycle time would suggest that either the participants do not detect risk factors associated with the task frequency, or in this case the effect was not perceived.

While the temporal pattern of work is important (Bystrom and Kilbom, 1990), there are other factors that affect workload when using powered screwdrivers. These include posture, material and screw characteristics, grip design, trigger design, screw direction, vibration, weight of the tool, wear etc. (Cederqvist and Lindberg, 1993). This study concentrated on temporal characteristics with no trigger and a relatively optimal posture for a seated worker with an in-line tool (Ortengren et al., 1991). The tool diameter (46 mm) was near optimum based on hand grip force and preference studies (40mm Hall, 1995; 50 mm Johnson, 1988; >44.5 mm for females Shih and Wang, 1996). An attempt was made to use optimal postures through the use of adjustable workstations and training. It is possible that lower torques may be required where extreme or awkward postures are required. The torque profiles utilized are of necessity idealized for this study. The hand force required in real power screwdriving is a combination of push force, tool support, trigger activation and torque reaction force depending on the tool utilized, the tool orientation and the workstation design. The rise time used was kept lower than that known to elicit muscle reflexes (Armstrong et al., 1999). The effect of rates fast enough to create a muscle reflex was not examined here.

In summary, the maximum acceptable torque in in-line screw running was determined using psychophysical adjustment methods for different conditions of cycle time and duty cycle. Duty cycle was found to have a significant effect on the torque chosen whereas cycle time did not.

# Chapter 4

# PERCEIVED VERSUS ACTUAL TORQUE DURING IN-LINE SCREW RUNNING


## ABSTRACT

The use of the psychophysical adjustment method for developing guidelines for use by industry to design jobs with reduced risk of injury due to manual materials handling, has recently been extended to upper limb intensive, highly repetitive tasks. The ability to perceive the load being adjusted has been studied for lifting tasks using Steven's Power Law. The purpose of this paper is to use similar methods applied to an upper limb repetitive task. Fifteen participants (11 females, 4 males) performed a simulated in-line screw running task. The task involved grasping a cylindrical handle. A computer controlled torque motor applied torques every 3, 6, 12 or 20 seconds for 25, 50 or 83% of the time. Within each test condition, 5

torques from 0.4 to 2.4 N.m were presented. The participants were asked to rate the strength the handle turned in their hand based on a reference torque presented at the start of each of the 12 conditions. The slope of the log actual vs log perceived was determined for each cycle time/duty cycle combination. It was found that the participants were able to estimate the magnitude of the torque according to Steven's Law. The overall mean slope was 1.85. The participants tended to underestimate the low torques and overestimate the higher torques. The slope got significantly greater with longer cycle times. A subset of 8 females performed a psychophysical adjustment study, in which they worked at the same task for a day at each condition. They were instructed to adjust the torque throughout the day to select a level that would cause little or no discomfort. Using the relationships derived, perceived torques were calculated. No significant differences were found for the perceived torques, despite a statistically significant effect of duty cycle on the torques chosen.

## INTRODUCTION

Work Related Musculoskeletal Disorders (WMSD) involve injury to the soft tissues of the upper limb due to exposure to certain types of jobs and work factors (Kuorinka et al., 1995). Injuries to muscles, tendons, and nerves have been linked to jobs with high repetition, and high force (Silverstein et al., 1986) and extreme or awkward postures (Kuorinka et al., 1995). The development of WMSD is suggested to be the result of local physiological disturbances and/or tissue strain due to physiological or biomechanical loading of the tissues at risk without adequate recovery.

Given this, prevention of WMSD should ultimately come with increased knowledge on the physiological response to repeated or sustained loading of each of the tissues at risk. In the mean time, the psychophysical adjustment method popularized by Snook et al. (1981) for producing guidelines for prevention of low back injury during lifting, have been applied to repetitive upper limb movements (Snook et al., 1995; Krawczyk et al., 1992; Abu-Ali et al., 1996; Dahalan and Fernandez, 1993). Central to this method is the ability of the participants to perceive the load presented, interpret the load with respect to the tissues at risk, and adjust the load to a level which will not cause injury.

The function describing the perceived versus actual magnitude of a stimulus can be defined by a power function (Stevens, 1957). The exponent or the slope of the function when plotted in log-log scale is used to describe the function. The ability to perceive the load being adjusted according to Steven's Law is usually assumed in studies using the psychophysical adjustment method. Gamberale et al. (1987) were one of the first researcher groups to report on testing the assumption in conjunction with a load adjust study applied to lifting. Steven's law adequately described the relationship between perceived workload and both work pace and case weight. The slopes found were different for two different lifting situations (horizontal and diagonal lifting). For studies applied to highly repetitive upper limb tasks, this assumption has not been tested. The purpose of this study was to test this assumption for a highly repetitive upper limb task.

## METHODS

Fifteen participants (11 females, 4 males; age: 20-51) performed a simulated in-line screw running task. Each participant sat at a workstation, adjusted so that the elbow was near 90 degrees of flexion with the upper arm comfortably at the side. The task involved grasping a vertical cylindrical handle and preventing the handle from turning around the vertical axis. The handle was turned by a toothed belt and pulley that was driven by a computer controlled torque motor. The torque motor was programmed to repetitively apply torques at a set duty cycle (percentage of time working: 25%, 50%, 83%) and cycle time (turns on every 3, 6, 12 or 20 seconds). These 12 conditions were presented to the participants in a randomized block design. At the start of each block, a ten second, non-cyclical reference level was presented. The reference level strength and value was the same for all blocks and participants (1.06 N.m). Within each block, five randomly spaced different torques (0.4-2.4 N.m) were presented in a random order. Each torque/duty cycle/cycle time combination was presented for two minutes at which time the participant was asked to rate the "strength the handle turned in their hand" based on the reference value given.

The slope of the log actual versus log perceived was determined for each block and for each subject using the regression procedure using the SAS statistical software. The slopes were then used as input to a 3 x 4 ANOVA.

A subset of eight female participants also subsequently performed a psychophysical adjustment protocol. The methods have been reported previously (Moore, chapter 3). To summarize, however, the participants worked at the same work station, as reported here, for five hours a day, performing one combination of duty cycle and cycle time each day. While working, they were asked to adjust the torque either up or down based on the instructions "to work as hard as you can without straining your hand, wrist or forearm." At the end of each hour, the torque they were working at was recorded, and the torque reset alternately higher or lower by a random amount. The mean of the torques recorded for the last two hours was determined and defined as the psychophysically determined acceptable torque (PDAT).

## RESULTS

The overall mean slope was 1.85. There was a significant effect of cycle time, with the shorter cycle times having the lower slopes (Table 4.1). The effect of duty cycle was mixed (Figure 4.1), although there was a tendency for the 83% duty cycle to have the largest slope. There was a significant difference for the intercept with duty cycle. There was a significant

**Table 4.1** Slope defining the relationship between actual torque and perceived torque. Mean of 15 participants, 3 duty cycles. * $p<0.05$

| Cycle Time (s) | Mean Slope* (std dev) | Range of Slopes |
|---|---|---|
| 3 | 1.69 (.66) | .24-2.8 |
| 6 | 1.84 (.51) | 1.02-4.17 |
| 12 | 1.93 (.58) | .75-3.1 |
| 20 | 1.95 (.59) | .79-3.27 |

difference between participants. However, there did not appear to be any difference between the group that participated in the adjustment portion of the study and those who didn't. In almost all cases the slope was significant and in most cases $r^2$ was greater than 0.95. Three of the one hundred and eighty slopes were eliminated due to obvious error in recording the value.

The perceived torques associated with the PDAT chosen by the 8 participants who continued on into the adjustment study were determined from the actual torques for each condition and the results for their particular regression equation for that condition. The effects of cycle time and duty cycle were then examined. No significant difference was found for either cycle time or duty cycle.

For a subset of 6 women from the adjustment study, they not only rated each torque/cycle time/duty cycle combination based on the magnitude of the perceived torque, but also based on the difficulty of doing that task combination all day using a visual analogue scale anchored with no difficulty and extreme difficulty. Similar analyses were performed. However, not as many of the slopes were significant. The results for 3 second cycle time, 25% duty cycle were particularly poor with $r^2<0.4$. There was also no significant differences between slopes. Duty cycle did significantly affect the intercept.

**DISCUSSION**

The results show that the participants were able to estimate the magnitude of the torque according to Steven's Law. This was also found in lifting tasks (Gamberale et al., 1987). On average, the exponents found were consistent with those expected for grasping (1.7, Stevens, 1960). As in grasping and lifting tasks, the relative increase in perceived torque gets larger as the actual torque gets larger. This was also true of the participants rating of perceived difficulty of the task.

The differences in the relationship between perceived and actual torques for different conditions suggests that participants could choose torques that they perceive the same which are actually different. For low torques (below approximately 1.25 N.m), participants tended to underestimate the torque magnitude particularly for short cycle times and short duty cycles (Figure 4.2). This is the area of the curve where most of the torques chosen by the subset who participated in the adjustment study fell (Moore, chapter 3). This could be one explanation for the finding that while participants chose higher torques for shorter duty cycles, there was no significant difference between the perceived chosen torques. Cafarelli and Bigland-Ritchie (1979) found that developing forces in a matching task was affected by muscle length. It is possible that changes in perceived magnitude could be related to differences in posture associated with the different conditions.

During the adjustment phase, the women's instructions included the instructions to adjust torque to "not strain their hand wrist or forearm" and to "not go home experiencing any unusual discomfort". In psychophysical studies of lifting, cardio-pulmunary stress has been found to be of more relative importance in perception of discomfort than local muscular stress (Wiker, 1992). However, upper limb repetitive tasks of similar workloads as here have been shown to not have a significant effect on heart rate (Dahalan and Fernandez, 1992). Hamilton et al. (1996) found that during 30 second bouts on a cycle ergometer there was a different onset of discomfort from muscular effort and that perception of muscle pain was distinct from perceptions of muscle tension and discomfort. The results here suggest that perceived difficulty in performing the task all day may be related directly to the duty cycle condition, distinct from the estimation of torque level.

In conclusion, Steven's law did adequately describe the relationship between perceived and actual torque. However, the factors describing the relationships were affected by duty cycle and cycle time, such that the torques chosen in adjustment type psychophysical study may not have been perceived as different.

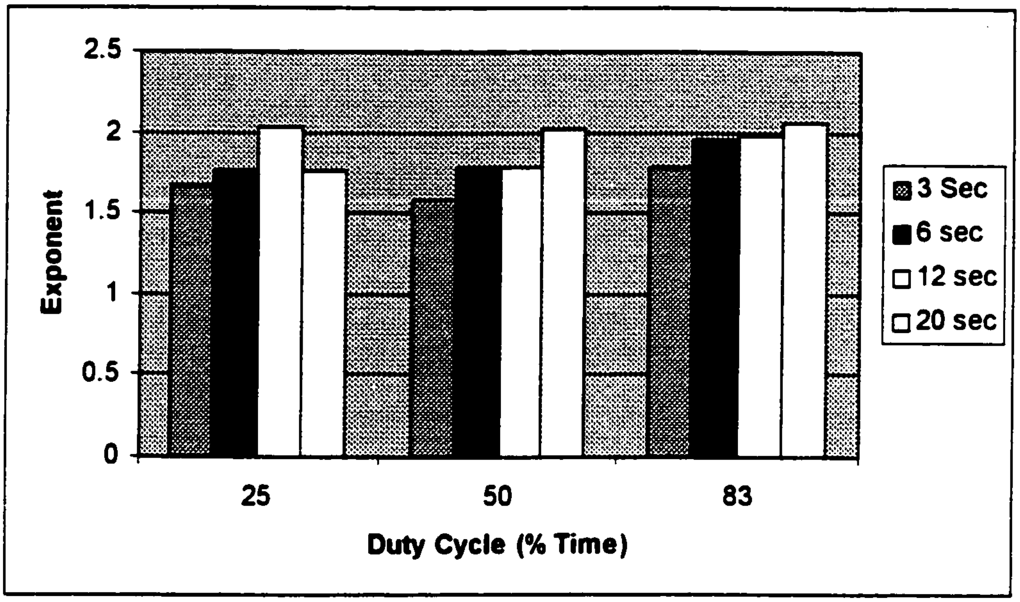
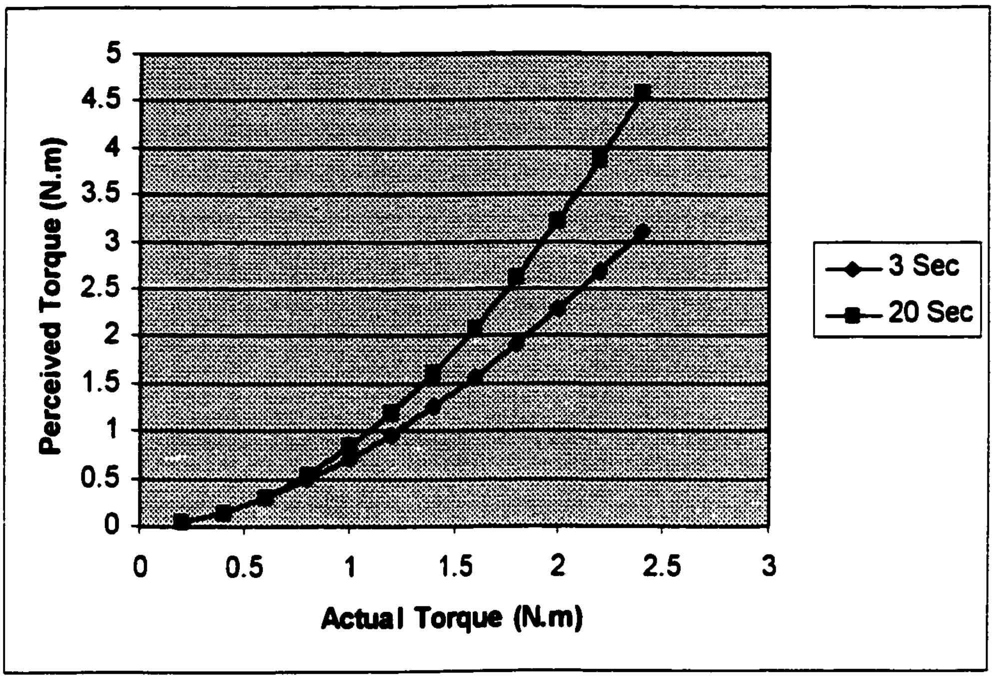



**Figure 4.1** Exponents for Steven's power law by test condition. Mean of 15 participants.

a)




b)

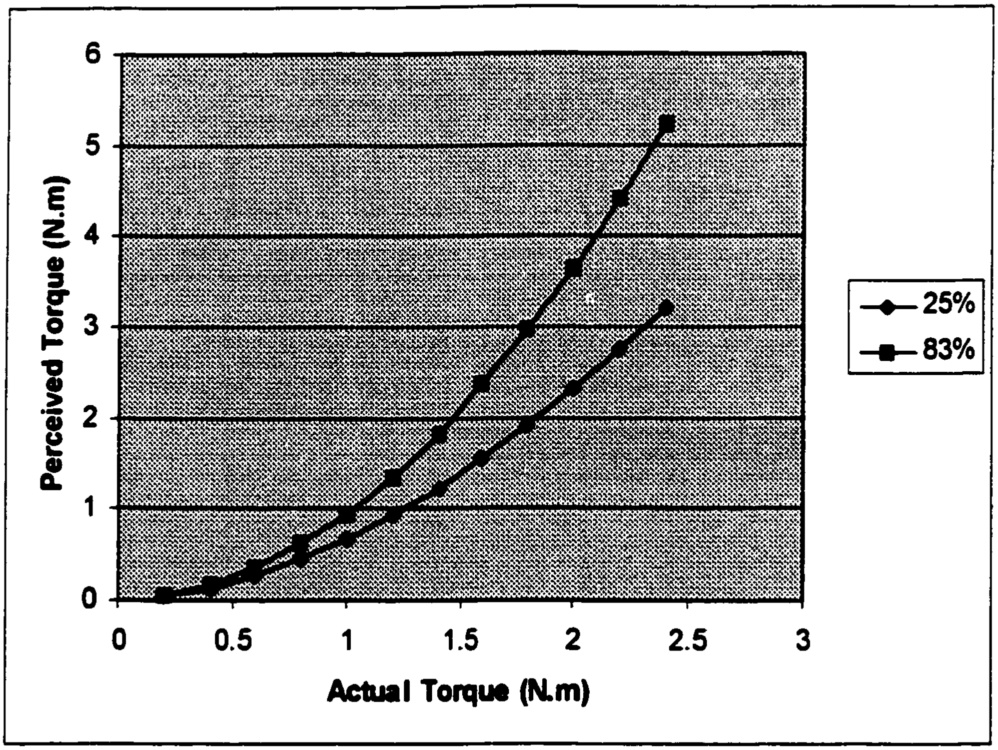



**Figure 4.2** Comparison of perceived versus actual torque based on Steven's Law for a) 3 second and 20 second cycle times and b) 25 % and 83% duty cycles (mean of 15 participants).

# Chapter 5

# FATIGUE AND DISCOMFORT WITH SIMULATED IN-LINE SCREW-RUNNING

## ABSTRACT

Work related musculoskeletal disorders of the upper limb include pain and injury to different tissues in the upper limb, including muscle. Adjustment-type psychophysical methodology is being used to develop guidelines for repetitive upper limb tasks in industry. With this type of methodology, it is unclear what type of information is used by participants to chose the load selected. The time course of fatigue and discomfort over a working day during which acceptable loads are chosen using psychophysical methods, may give insight. Were the participants able to adjust loads such that different conditions of duty cycle and cycle time did not have a differential effect on fatigue and discomfort? Eight female participants sat at adjustable workstations. An in-line screw running task was simulated using a cylindrical handle driven by a computer controlled torque motor. The motor applied torques every 3, 6, 12 or 20 s with duty cycles of 25, 50, and 83%. The participants chose maximum acceptable torques for each day long condition. Before work and after every hour of work, the participants held the handle for a 20 second period at a preselected constant torque level during which raw electromyographic (EMG) data from flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), and flexor carpi radialis (FCR) sites were collected. Measures of EMG that have been useful in the study of muscle fatigue, namely average EMG (AEMG), median frequency (MF), and mean power frequency (MPF), were calculated. On a subset of 6 participants discomfort was reported hourly throughout the day using a visual analogue scale (VAS). While the participants reported significantly greater discomfort at the end of the day, no significant increase in fatigue, as shown by EMG, was found over the course of a day. However, cycle time and duty cycle were found to have a significant effect on the EMG fatigue measures and no effect on discomfort. In the FDS muscle site there was evidence of muscle fatigue with shorter cycle times. Both flexor sites, had evidence of fatigue with shorter duty cycles. Since the participants chose to work at lower torque levels with greater duty cycles, it appears this has the effect of limiting fatigue in the flexor muscles. However, they also did not make any significant changes with cycle time, appearing to ignore flexor muscular fatigue. The results would suggest that muscular fatigue on the flexor side of the forearm was not a primary sensation used in selection of the psychophysically determined acceptable torque level.

Key words: RSI, Hand, Wrist, Screw Driving, Muscle, Fatigue, EMG

## INTRODUCTION

Work related musculoskeletal disorders of the upper limb include pain and injury to different tissues in the upper limb including muscle. In a cross sectional study of a population working in repetitive upper limb tasks, Ranney et al. (1995) found that forearm muscle pain was one of the most prevalent upper limb disorders, especially on the extensor side. Muscle injury may be the result of repetitive or continuous stimulation of the same muscle fibres leading to fatigue and disruption of the muscle's physiologic state (Sjogaard and Jensen, 1997). Fatigue with intermittent sub-maximal contractions has been shown to be peripheral in origin (Bigland-Richie et al., 1986; Vollestad et al., 1988). Workers with work related muscle pain have been found to have physical changes (moth-eaten or ragged red fibres) in individual low threshold muscle fibres (Larsson et al., 1988). It has been suggested that with low level sustained or repetitive work the low threshold motor units, or so called "Cinderella fibres" get continuously/repetitively used, without having sufficient time for recovery (Hagg, 1991). This can lead to high loading, fatigue and damage of these fibres.

Electromyography (EMG) is frequently used as a non-invasive method for documenting fatigue effects in muscle. The effect of muscle fatigue on the electromyographic signal has been documented (e.g. Deluca, 1985). Specifically, there is a shift of the frequency content as documented by lower mean power frequency or median frequency. This is accompanied by an increase in amplitude for the same muscle force level.

The independent role of duty cycle and cycle time on muscle fatigue during low level repetitive tasks is poorly understood. Several studies have shown that muscle fatigue does occur during intermittent sub-maximal contractions (e.g. Hagg and Milerad, 1997; Jorgensen et al., 1988; Bystrom and Kilbom, 1990), likely due to changes in extracellular Potassium levels (Sjogaard et al., 1988; Jorgensen et al., 1988; Bystrom and Fransson-Hall, 1991). Unfortunately, however, in vivo studies tend not to independently modify the cycle times and duty cycles studied, often adjusting the total length of the total work time. In working isolated rat diaphragm muscle, Stephens et Syme (1993) found fatigue depended more on cycle time than duty cycle.

Adjustment-type psychophysical methodology is being used to develop guidelines for repetitive upper limb tasks in industry (e.g. Snook et al., 1995). In this method, a group of workers is presented with a task where most of the task features are fixed, with the exception of one. While the workers perform the task, they are asked to adjust this one feature such that they are working as hard as they can without experiencing any discomfort. With this type of methodology for low level repetitive manual tasks, it is unclear what type of information is used to settle on the load chosen. Most psychophysical adjustment studies do not monitor muscle fatigue to determine if the participants have been able to control fatigue while choosing their acceptable loads. With highly repetitive manual tasks, this is important since, as discussed, muscle is at risk for development of pain and injury. The purpose of this paper was to study the time course of muscle fatigue and discomfort over a working day during which loads are chosen using psychophysical methods. Also of interest was whether different conditions of duty cycle and cycle time have an effect on any muscle fatigue experienced or discomfort reported.

**METHODOLOGY**

Eight women (ages 20-51) with industrial experience were recruited from a temporary industrial employment agency for participation in a study on the repetitive use of hand tools. Prior to participation, the women were screened by a physician for the presence of any musculoskeletal disorders of the hand, wrist or forearm on their right upper limbs and completed a questionnaire detailing their employment and health history. The women worked for fifteen days which included 3 days of training and one day of detailed biomechanical data collection (i.e. wrist posture and posture changes and hand grip forces) that will be reported on later. For the remaining 11 days, the participants performed a simulated screw running task throughout the day. While working, the participants chose maximum acceptable torques for the simulated screw runner using an adjustment psychophysical methodology. Details of the task and workstation as well as the torques chosen are presented in Moore (Chapter 3). Briefly however, the worker sat at an adjustable work station (Figure 5.1) and with her right hand grasped a cylindrical handle with a socket mounted in the bottom. The socket fit over a nut on a shaft that was driven by a computer controlled torque motor through a toothed belt pulley system. The participants were trained to resist the applied torque as when using a power in-line screw driver, while the torque motor repetitively applied a torque at a set duty cycle (25, 50 and 83% of time on) and cycle time (3, 6, 12 and 20 s), chosen randomly for the day. The participants were instructed to adjust the torque level such that they were working as hard as they could without undue discomfort. They worked 5 hours per day with a 20 minute lunch break after hour three.

Submaximal test contractions were performed 7 times per day: before work, after lunch and after every hour of work (Figure 5.2). The test contraction consisted of the participants holding the handle for a 20 second period at a constant torque level of 1.4 N.m. During the last 16 seconds of the contraction raw electromyographic (EMG) data from three right forearm muscle sites, flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), and flexor carpi radialis (FCR) were collected. EMG signals were collected using silver/silver-chloride disposable surface electrodes at a 2 cm spacing. For FDS this was midway on a line between the medial epicondyle and the radial styloid while the forearm was in mid pronation. For the ECRB site, electrodes were placed on the extensor muscle mass just distal to the lateral epicondyle and for FCR just proximal to the FDS electrodes. Signals were collect at 1000 Hz using the battery operated ME3000P (MEGA electronics Ltd, Finland) Muscle Tester (CMRR 110 dB, 15-500 Hz). Fast fourier transforms (FFT) using overlapping 1024 samples were done every 0.5 seconds for the last 16 seconds of the test contraction. For each FFT the average EMG (AEMG), median power frequency (MF), and mean power frequency (MPF) were calculated and the results averaged. The results were normalized to the first measurement of the day.

On a subset of 6 participants, discomfort throughout the day before work and after each hour of work was reported using a 16 cm visual analogue scale (VAS) anchored at each end with "no discomfort" and "extreme discomfort". A randomized block design was used with time as a repeated measure. Statistical analyses were done utilizing the SAS statistical software.

## RESULTS

Figure 5.3 shows the raw EMG from a typical test trial. The mean contraction level at 9 am was 29%MVC for ECRB, 21% MVC for FDS and 15% MVC for FCR. The change of MPF, MF, and AEMG over the work day is shown in Figure 5.4. No significant trends were found over the day on any of the measures. The only point at 2:30 pm that was significantly different than 9:00 am was the AEMG for FCR.

Cycle Time was found to have a significant effect on the FDS muscle site (Figure 5.5). With shorter cycle times the two frequency measures (MF and MPF) were reduced while the amplitude measure (AEMG) was raised, indicating evidence of muscle fatigue. Both flexor muscle sites, particularly FCR, showed evidence of less fatigue at higher duty cycles (Figure 5.6). An opposite trend was found at the extensor site.

Typically, the participants reported significantly higher values for discomfort as the day progressed (Figure 5.7). One participant reported their highest levels first thing in the morning which dropped off and leveled off within an hour. There was no significant effect of duty cycle or cycle time on either the mean level or the slope of the recorded discomfort levels over the day.

## DISCUSSION

With shorter cycle times, participants did not choose significantly different torque levels (Figure 5.8) yet there was evidence of increased muscle fatigue, particularly in the FDS. This leads to two main questions; what causes the increased fatigue and why was it not adjusted for? The increased fatigue may be the result of biomechanical, perceptual or physiological effects.

Increased muscle activation levels and time of activation may result from shorter cycle times. With decreased cycle times, even with the same work duty cycles, there is the increased likelihood of increased muscle duty cycles above the computer controlled setting (i.e. there is a fraction of time before and after the portion of the cycle that the torque is on, in which the participants were still gripping the handle). The finding that the subjects did not adjust for these may be because either the magnitude was not sufficient to have a significant effect or the increased number of rest pauses decreased the perception of fatigue. The addition of small pauses has been shown to increase the endurance time in submaximal contractions (Bystrom et al., 1991) and decrease discomfort in the second hour (Sundelin, 1993). This suggests that adding more frequent pauses gives the perception of greater comfort or reduced fatigue despite increased loading and physiological evidence of fatigue.

The screw running task leads to complex loading on the upper limb. The handle is prevented from turning by having sufficient friction developed between the right hand and handle. The force used for gripping the handle, thereby increasing the friction forces, is developed by the forearm finger flexor muscles. At the same time, the counter-clockwise rotation of the handle creates a tendency for the wrist to flex. In order to maintain the wrist at an optimum angle for appropriate flexor muscle length, the wrist extensors must counteract both the effect of the handle as well as the effect of the finger flexors crossing the wrist. The result is a tendency for a small flexion/extension of the wrist at the start and end of each cycle time, although the speed of this was kept low enough to prevent reflex activity (Armstrong et al., 1993 ). This will mean the muscles will be working under eccentric loading,. This will occur more often through the day on conditions with short cycle time. Repetitive eccentric loading even at low levels has been shown to negatively effect muscle function (Hargens et al., 1989 as reported in Sjogaard and Jensen, 1997).

The participants did not adjust the load to account for the increased fatigue, and therefore either did not detect it or did not perceive the amount of fatigue as leading to discomfort. This limits their ability to guard against overload. Increased potassium concentration in the interstitial space has been suggested as a method of perceiving fatigue (Sjogaard, 1990). However, possibly at low force levels with the same small number of fibres continuously firing, the concentration build up is too localized to be perceived and goes undetected until overload occurs causing pain. Alternatively, with shorter cycle times there is greater diffusion throughout the muscle area minimizing the chance of detection. The 5 % drop in frequency found here is small compared to the roughly 25% drop found during maximum fatigue. It is unclear whether this represents a level which may eventually lead to injury. The prevalence of forearm muscle pain in working populations would suggest that muscle is at risk (Ranney et al., 1995). Demonstrated physical changes in the low threshold fibres (Larsson et al., 1988) would suggest overuse of these particular fibres is a risk factor for injury. Mechanisms for muscle injury based on fatigue and overuse have been developed (Sjogaard and Jensen, 1997). However linking the three with a particular dose of fatigue has not been demonstrated. This has been hampered by the difficulty in measuring fatigue in low level repetitive work. Further study is therefore required to determine if the amount of fatigue found here is sufficient to develop forearm muscle pain over a longer term of working.

With increased duty cycle, participants reacted by reducing the acceptable torque (Moore, chapter 3). The results here would suggest that this may actually have a protective effect on the flexor muscles for the highest duty cycle (83%). An opposite (but not significant) trend was found for the extensor muscles. This could be due to the finding that the extensor muscles are working at a larger % MVC. This is consistent with the results of Hagg and Milerad (1997) who found the extensors more susceptible to fatigue with repetitive gripping. They also found increased signs of fatigue with increased duty cycle. However, it is impossible to directly compare, as duty cycle and cycle time changes are not independent, nor is work duration. Since the participants did adjust the torque based on duty cycle, yet could not account for fatigue with cycle time, it is possible that more dominant perceptions used for the torque chosen are time dependent afferent signals from the tendons, ligaments or skin.

The test condition was a submaximal contraction. Therefore, there may be some shift in the relative values of each muscle used. However, at these moderate level contractions, it would be expected that increased amplitude would be accompanied by similar or increased frequency levels (Gander and Hudgins, 1985). In the case of FDS with shorter cycle times as well as changes at all sites with 83% duty cycle, the frequency and amplitude levels are clearly moving in opposite directions as would be expected with fatigue. The increased amplitude of the FCR late in the day may represent a change of muscle activation strategy since no concurrent decrease of frequency was noted.

There was a statistically significant increase in discomfort reported as the day progressed and no significant increase in EMG evidence of muscle fatigue nor any significant difference in discomfort between cycle time or duty cycle conditions. This would suggest several things. First, any development of muscle fatigue could have been fairly rapid and may have approached some form of steady state as the day progressed whereas feelings of discomfort were slower to develop. This is consistent with other studies (Hagg and Milerad, 1997; Bystrom and Kilbom, 1990). Second, since the participants did not distinguish between the different duty cycle and cycle time conditions on perceived discomfort, then presumably the source of the perceived discomfort was equalized by use of the torque adjustment.

In conclusion, shorter cycle times were found to be associated with increased local muscle fatigue. This was not adjusted for by the participants, which would suggest that the psychophysical adjustment method may not be effective in correcting for local muscle fatigue that may lead to muscle pain and injury during highly repetitive manual tasks.

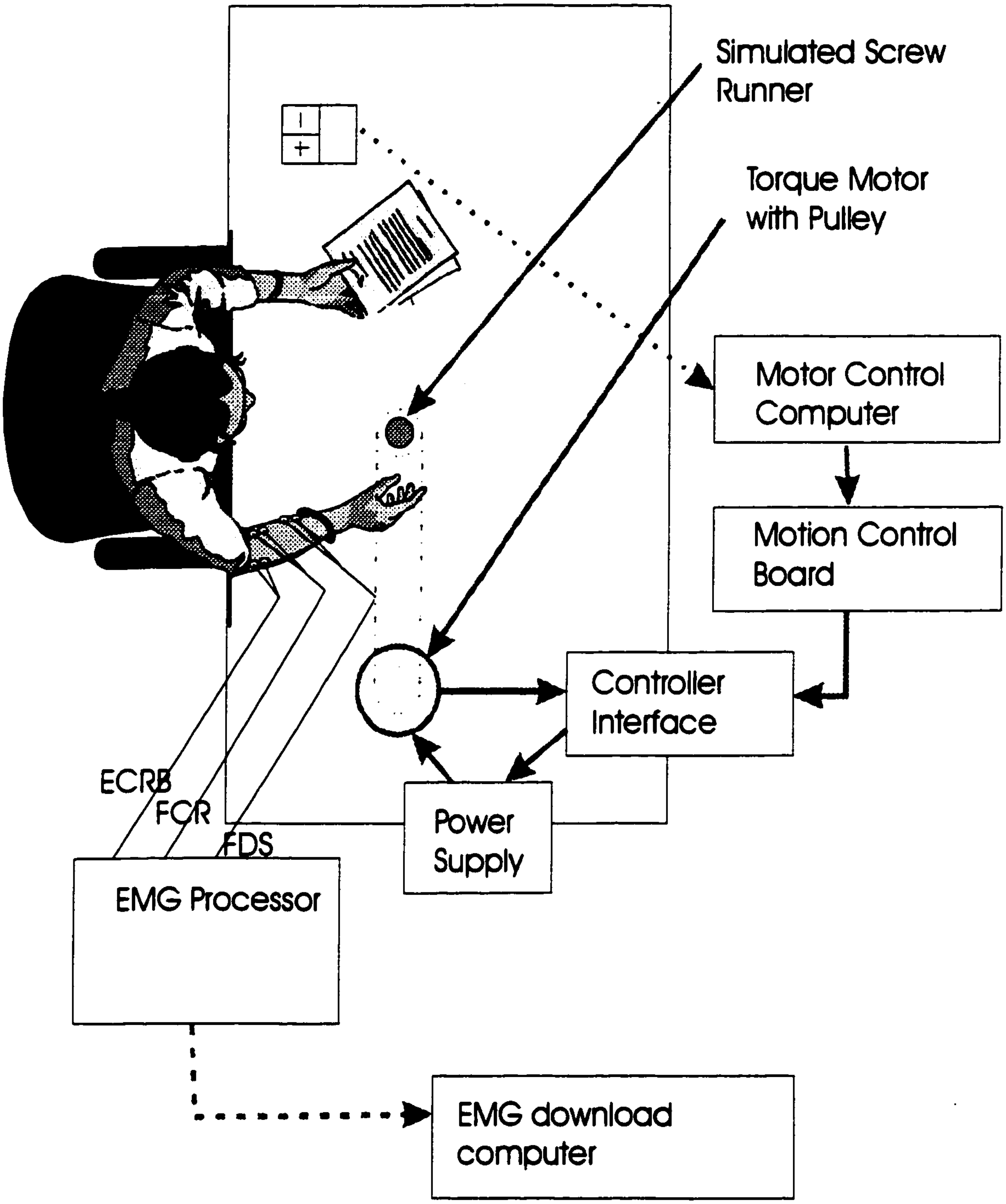



**Figure 5.1** Workstation and EMG collection system set up

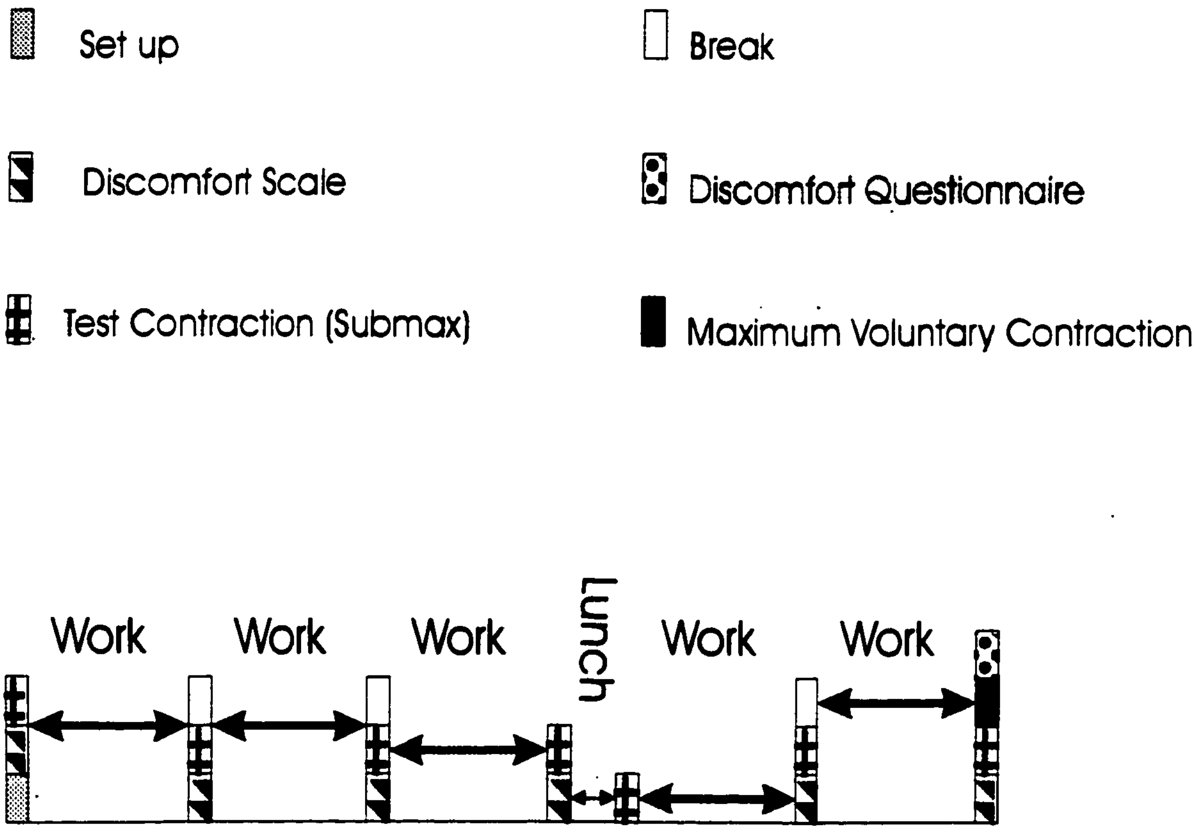



**Figure 5.2** Schedule of test contractions and discomfort scales over the work day. Work periods were 50 minutes with a twenty minute lunch. Test contractions were done immediately following the work periods.

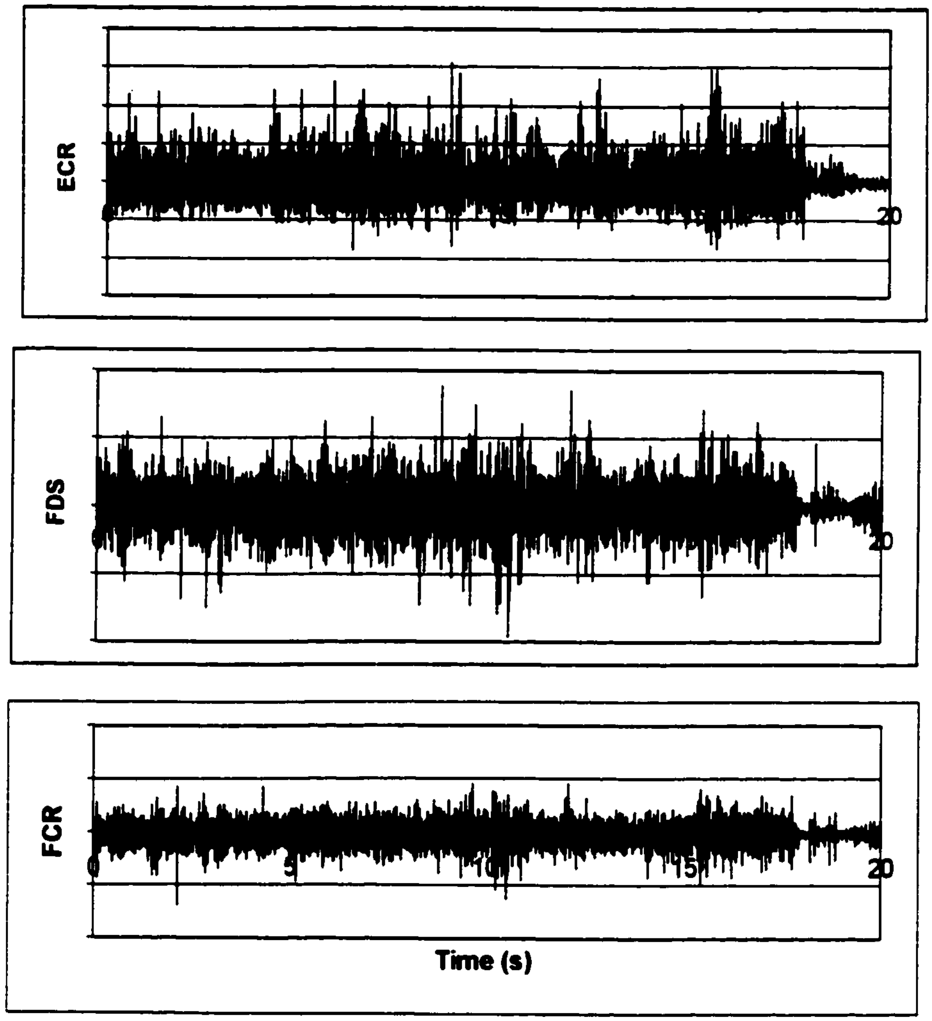



**Figure 5.3** Typical EMG test contraction.

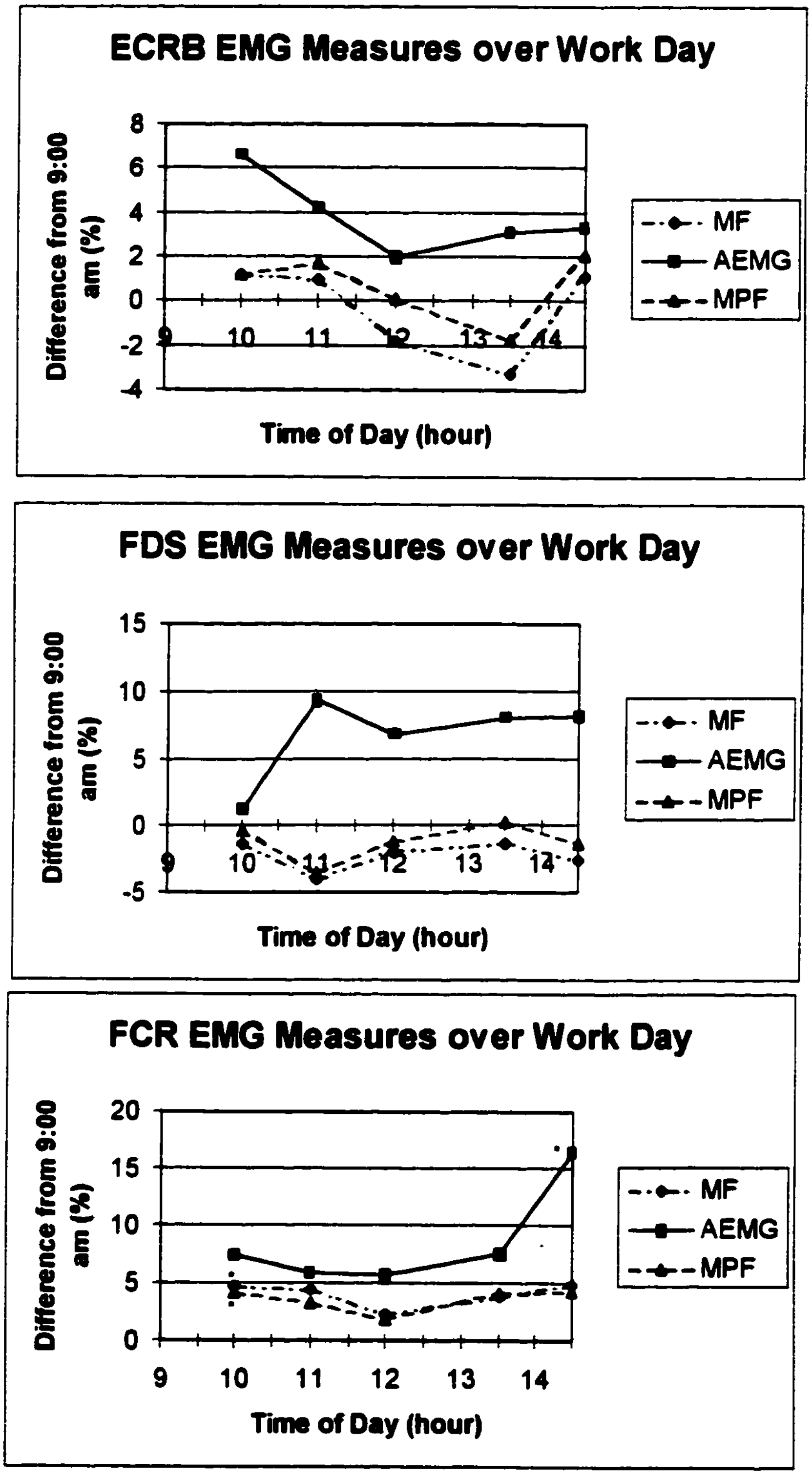



**Figure 5.4** EMG results per muscle over time. Means of 8 participants over 11 days. *=significantly different from 9:00 am ($p<0.05$).

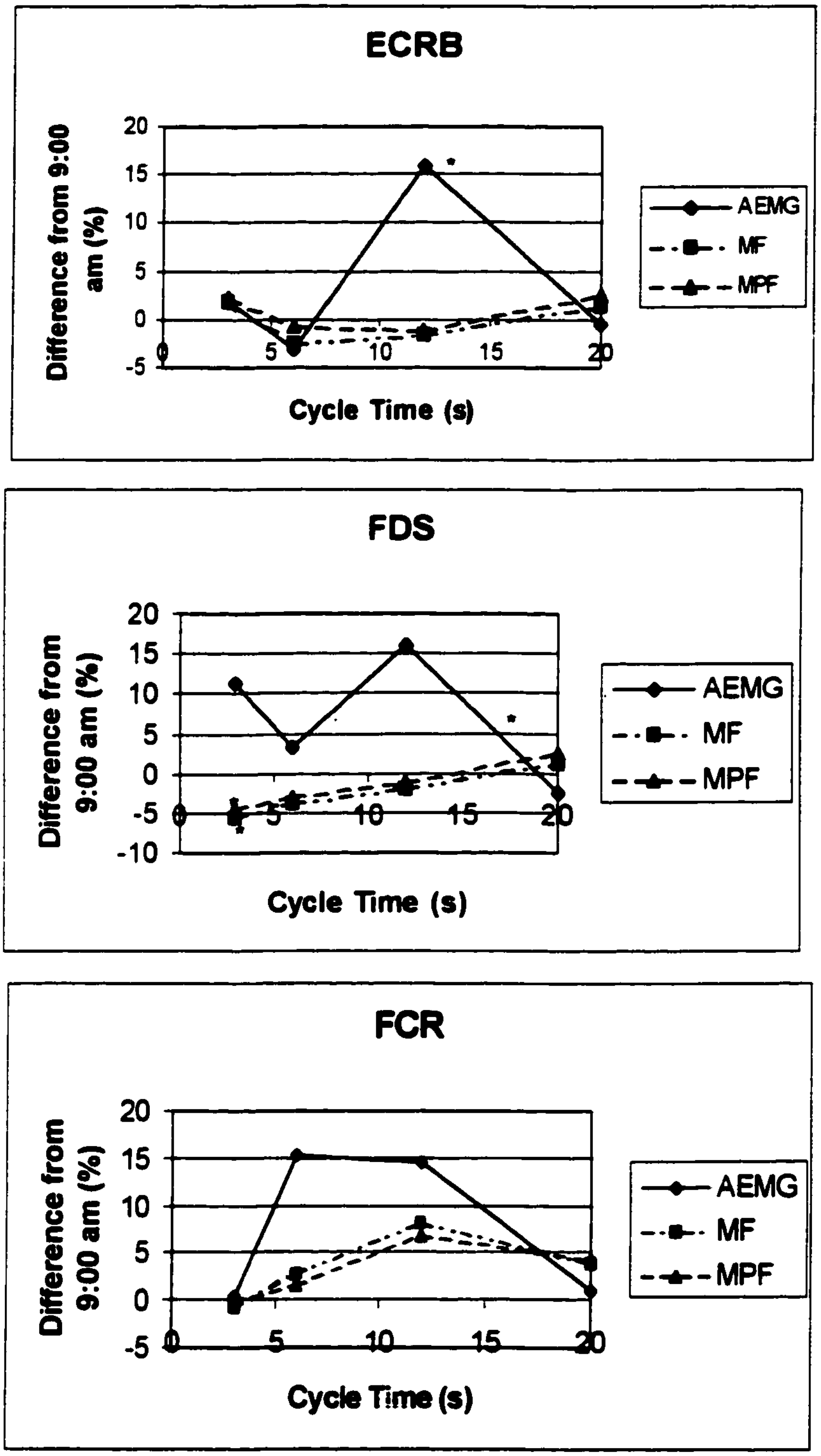



**Figure 5.5** EMG results per muscle over cycle time. Means of 8 participants for 5 hours (immediately after work periods) over 11 days. *=significant effect ($p<0.05$).

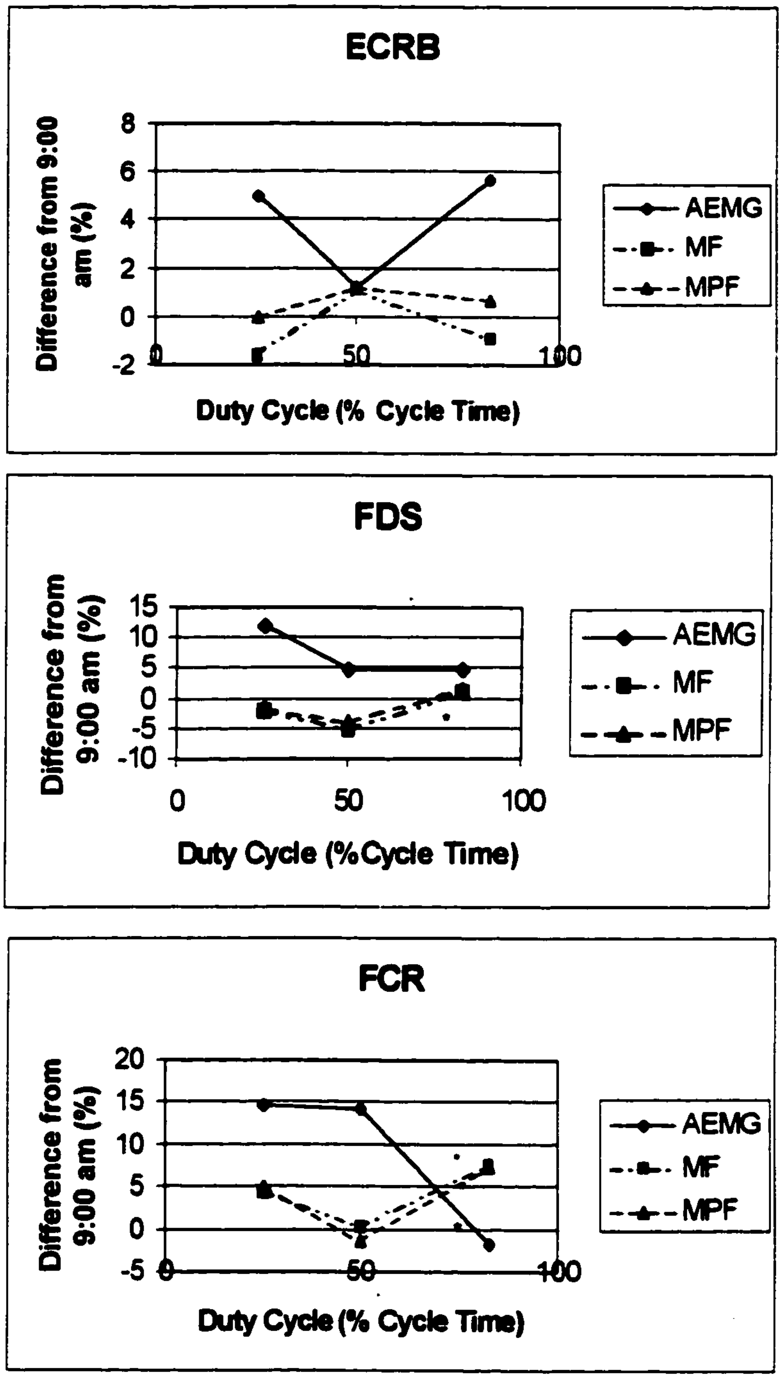



**Figure 5.6** EMG results per muscle over duty cycle. Means of 8 participants for 5 hours (immediately after work periods) over 11 days.

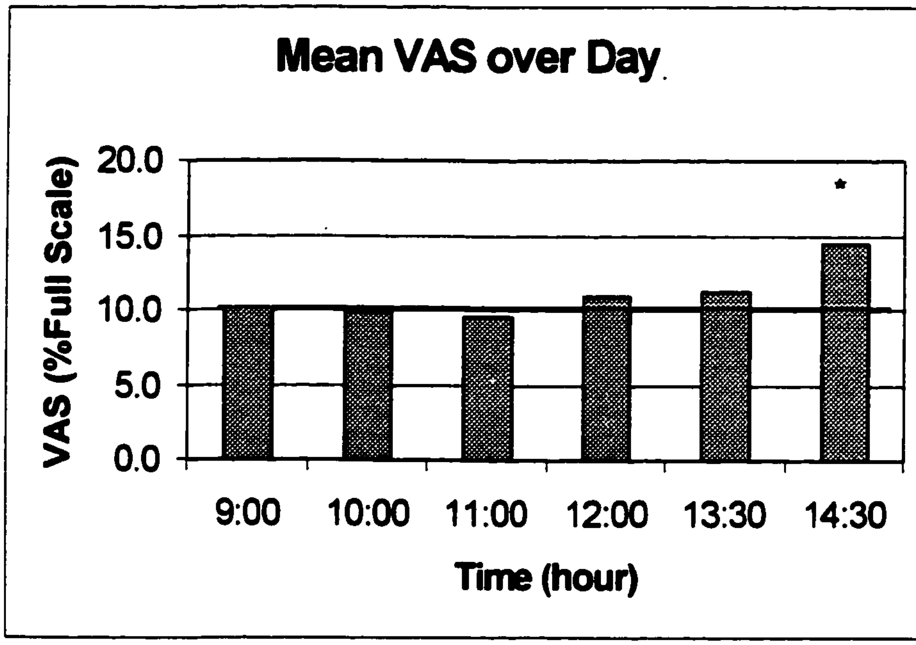



**Figure 5.7** Visual Analogue Discomfort Scale over time. Mean of 6 participants over 11 days. *=significant $p<0.05$.

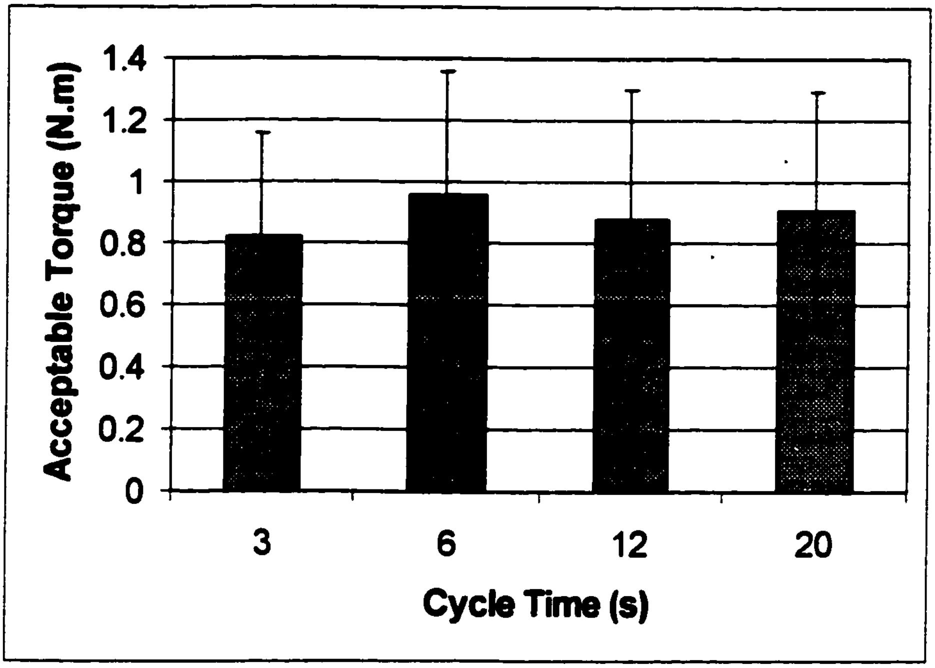



**Figure 5.8** Effect of cycle time on psychophysically determined acceptable torques (adapted from Moore, chapter 5).

# Chapter 6

# RELATIONSHIPS BETWEEN PSYCHOPHYSICALLY CHOSEN TORQUE AND BIOMECHANICAL VARIABLES FOR IN-LINE SCREW RUNNING


## ABSTRACT

Highly repetitive tasks as well as repetitive hand tool use have been implicated in the development of work related musculoskeletal disorders of the upper limb. Proposed injury mechanisms to the various tissues in the upper limb are based on excessive or inappropriate biomechanical or physiological loads required in order to perform the task. Adjustment type psychophysical methods have been introduced as a way to develop guidelines for use in evaluating jobs in industry. However, it is not known what type of exposure workers may be sensitive to when choosing loads (e.g. cumulative, peak, movement based). It is also unknown whether loads chosen using these methods are consistent with current knowledge on acceptable

hand forces, postures and muscle activation patterns. This study was performed to examine biomechanical measures during highly repetitive use of a simulated hand tool task using torques established using adjustment-type psychophysical methods. The task used a simulated in-line screw runner consisting of a cylindrical handle driven by a computer controlled torque motor. Eight females worked at three duty cycles (25, 50 and 83% of the cycle time) and four cycle times (3, 6, 12 and 20 s). For each combination of cycle time and duty cycle, they worked at two torque levels. The first one was a constant reference torque (REF) of 1.4 N.m and the second one was a level chosen at a previous time as the Psychophysically Determined Acceptable Torque (PDAT) using psychophysical adjustment methods. While working, measures of hand torque, hand grip force and tool movement were made from instrumentation within the simulated tool. Simultaneous measures were made of wrist angle and electromyographic (EMG) signals from four muscles in the right upper limb: Extensor Carpi Radialis Brevis (ECRB), Flexor Digitorum Superficialis (FDS), Flexor Carpi Radialis (FCR), and the upper fibres of the Trapezius (Traps). Average measures were made over a number of cycles and over the "work" portion of the cycle. The Amplitude Probability Distribution Function (APDF) and total Gap Time (time below 0.5% MVC for at least 0.2 s) were calculated for the EMG. The results showed that the torques chosen by the psychophysical methods were not only significantly different during the "work" portion for different duty cycles, but also as a mean over the whole file. However, there was no significant difference between mean hand force and forearm EMG over the whole file, despite no significant difference between force/torque and EMG/torque during the "work" portion. The finding is due to changes in the duty cycles for EMG and force. These "biomechanical" duty cycles are longer than the nominal duty cycle, as applied by the torque motor. At 83% duty cycle, the amount of muscle recovery time can be under 10%. With very short cycle times (<6 s) and higher torques the amount of time available for the muscle to completely shut off (i.e. gaps) is much reduced. With shorter cycle times there is significantly more total tool and wrist movement over time, but less per cycle. There is more tool movement with longer duty cycle. However, the choice of PDAT appears to equalize the wrist movement with duty cycle. It is concluded that the PDATs chosen, tend to equalize average hand force and muscle activation. However, the changes are not sufficient to bring the 83% condition into an acceptable level for muscle activation as suggested by existing static EMG guidelines of 1% MVC.

Keywords: RSI, Hand, Wrist, Screw Driving, EMG, Duty Cycle, Cycle Time, Grip Force

## INTRODUCTION

Work related musculoskeletal disorders of the upper limb are a continuing problem in highly repetitive jobs including those involving hand tools. High repetitiveness and high hand force have been implicated in the development of these injuries to muscles, nerves and tendons in the hand, wrist and shoulder with the interaction of both being multiplicative (Silverstein et al., 1985, 1986). These result suggest that with highly repetitive tasks, there is a maximum allowable hand force level, below which the risk of injury is reduced for the population of workers performing this job. To expand the force guidelines available for highly repetitive tasks, Snook et al. (1995) used the psychophysical adjustment technique popularized in tables for low back lifting (Snook and Ciriello, 1991) to determine hand force levels for wrist flexions and extensions during grasp or pinch at different movement frequencies. It is not known, however, what type of loading exposure workers may be sensitive to when choosing loads (e.g. cumulative, peak, movement based).

As mentioned, WMSD include injury to a range of tissues in the upper limb. Moore et al. (1991) suggested that knowledge of the possible injury mechanisms specific to the tissues at risk are important to measuring exposure of the tissues to loads that may lead to injury while working. Mean, peak, and cumulative biomechanical measures that integrate the effects of force, posture, and repetition were found to differentiate the exposure to tissue loading in a manner that reflected the increased odds of injury with high/low repetition and high/low force. With psychophysically determined acceptable load levels, it is not clear how the loads chosen affect the biomechanical loading on the tissues at risk. It is unknown whether loads chosen using these methods are consistent with current knowledge on acceptable hand forces, postures and muscle activation patterns.

Although all frequencies tested by Snook et al. (1995) would be classed as high repetition, there was still a statistically significant lower perceived acceptable force level chosen for jobs with higher frequencies. Using a similar methodology applied to a simulated in-line screw running task, but controlling both cycle time (i.e. frequency) and duty cycle, Moore (chapter 3) found that the effect of duty cycle was significant on the torque chosen while cycle time was not. However, using frequency analysis of EMG test contractions, Moore found that there was evidence of greater muscle fatigue with shorter cycle times (Moore, chapter 5). This may be the result of different hand grip levels or muscular activation duration and magnitude with different cycle times. The effect of shorter cycle times on muscle activation patterns during repetitive hand tool use is unclear.

The purpose of this study is to examine biomechanical variables representative of mechanical loading of the upper limb which may lead to WMSD such as muscle activation patterns, hand grip force, hand torque and wrist and tool deviation and study how they are affected by cycle time, duty cycle, and changing tool torque levels determined through adjustment type psychophysical methods.

## METHODS

For a study on repetitive use of hand tools, eight female participants (age 20-51) with industrial experience were recruited from a temporary industrial employment agency. A physician screened the women for the presence of any musculoskeletal disorders of the hand, wrist or forearm on their right upper limbs. They also completed a questionnaire detailing their employment and health history. The women worked for 15 days which included 3 days of training, 11 days of adjustment type psychophysical data collection (reported on previously) plus one day of more detailed biomechanical data collection (reported on here). Details of the workstation and task are presented previously (chapter 3). Briefly, the participants sat at an adjustable work station (Figure 6.1) and grasped a cylindrical handle with a socket mounted in the bottom using their right hand. The socket fit over a nut on a shaft that was driven by a computer controlled torque motor through a toothed belt pulley system. The participants were instructed to prevent the handle from turning while the torque motor repetitively applied a torque. During each of the 11 days of psychophysical data collection, a different condition of duty cycle (25, 50, and 83% of time) and cycle time (3, 6, 12 and 20 s), was used and the participants were instructed to adjust the torque level such that they were working as hard as they could without undue discomfort. The average of the final torque chosen over the last 2 hours was designated the psychophysically determined acceptable torque for the given condition of duty cycle and cycle time.

On the final day the participants worked at each condition of the duty cycle and cycle for two periods of 5 minutes each. For one period the torque motor was set at 1.4 N.m. During the other period the torque motor was set at the level chosen by the participant as the psychophysically determined acceptable torque (PDAT) for the given condition. While working, data were collected on wrist angle, hand force, hand torque, movement of the handle, and electromyographic (EMG) activity from 4 muscles (flexor digitorum superficialis - FDS, extensor carpi radialis brevis - ECRB, flexor carpi radialis - FCR, and upper fibres of the trapezius). Force was collected using a commercially available load cell (Transducer Techniques, Temecula, CA) mounted inside the handle. The signal was amplified and conditioned using a strain gauge amplifier (Daytronics, Miamisburg, Ohio). Hand torque was measured using a commercially available torque gauge (Chatillon, Greensboro, NC). The strain gauge based gauge was placed in line with the simulated tool handle and the signal conditioned and amplified (Daytronics). A potentiometer recorded rotation of the shaft of the torque motor. Wrist angle was collected using commercially available wrist goniometers (Penny and Giles, Blackwood Ltd, Blackwood, Gwent, UK). Cross talk from pronation/supination inherent with this goniometer was minimized by using custom order goniometers with shorter beams. Also, the task done involved very little pronation/supination, and the goniometers were calibrated with the forearm in the same position as used during tool use. Linear envelope EMG signals were collected using silver/silver-chloride disposable surface electrodes at a 2 cm spacing. For FDS this was midway on a line between the medial epicondyle and the radial styloid while the forearm was in mid pronation. For the ECRB site, electrodes were placed on the extensor muscle mass just distal to the lateral epicondyle and for FCR just proximal to the FDS electrodes. For trapezius, electrodes were placed over the upper fibres just distal to the neck. The EMG and goniometer signals were amplified and filtered using a custom built battery operated system (EMG: Bandwidth 10-1000 Hz, CMRR 80 dB, input impedance 10 Mohm, full wave rectified and low pass filtered at 3 Hz; Goniometer: bridge instrumented channels bandwidth 0-10Hz). All signals were A/D converted and collected at 50 Hz.

All signals were digitally calibrated and filtered using a 10 Hz dual low pass Butterworth filter. All files were windowed such that an even number of cycles were included in the sample. Also for each trial, the middle half of the "work" portion of 3 cycles chosen from the beginning, middle and end were windowed out. Mean values were calculated for all signals for each file. For each of the EMG signals for each 5 minute period, the Amplitude Probability Distribution Function (APDF) was calculated (Jonsson, 1978) and the static ($10^{th}$), dynamic ($50^{th}$) and peak ($90^{th}$) percentile values determined. A gap analysis was performed which calculates both the number of times and total time the EMG drops below 0.5% MVC for 0.2 seconds or longer (Veierested et al., 1990). For the wrist flexion/extension angle and the tool angular movement signals, a cumulative movement factor was determined both per minute and per cycle. Finally, "biomechanical" duty cycles were calculated for the force, FCR, ECRB, and FDS. This calculation modeled each signal as a square wave. The "biomechanical" duty cycle was then calculated using the mean of the whole file divided by the mean of the "work" portion.

## RESULTS

The results from a typical reference (REF) and a psychophysically determined acceptable torque (PDAT) trial are shown in Figure 6.2. Typically, the reference torque level is higher than the PDAT chosen. The cyclic nature of the task is apparent on all signals except trapezius, with the reference trials more distinctive than the PDAT trials. The tool rotation signal indicates cyclical movement of the tool which shifts in the direction of the torque after several cycles. Typically, corrections are occasionally made during rest portions. Of the three forearm muscles monitored, ECRB has the highest level exertions and visually matches the torque cycle the best. The postural role of trapezius is evident as the activity is fairly low without a cyclic nature, with bursts of activity indicating postural shifts.

### *Hand Torque*

As expected, based on the psychophysically determined acceptable torques chosen by the participants, the "work" torques are lower as the duty cycle increases. However, the reduction in torques chosen does not match the increase in duty cycle. There is actually an increase in mean torque with increased duty cycle. Cycle time did not have a significant effect.

***Hand Force***

Table 6.1 shows the results of hand grasp force. Again as expected the hand force during the "work" period significantly reduces with increased duty cycle for the psychophysically determined acceptable torque (PDAT) trials. However, the force does not decrease enough to create a significant effect on the mean for the whole trial. The hand grasp forces for the reference conditions represent around 10% maximum handgrip force based on the maximum power grasp strength for females (241 N, American Medical Association, 1990). The range for the PDAT trials range from 4.6 to 6.8% maximum handgrip force depending on duty cycle. Cycle time did not significantly affect the hand grasp force. The ratio of hand torque to hand force during the "work" portion was not significantly affected by cycle time or duty cycle condition.

***Wrist Angle and Tool Movement***

During PDAT tool usage, the mean wrist angle was 18.7 degrees extension, with a slight ulnar deviation (3.8 degrees). During the torque application, the tool tends to move the wrist towards flexion. With the short (3 s) cycle time the participants maintained significantly more wrist extension.(Figure 6.3). Duty cycle had no significant effect. With the higher torque level with the reference torques, the wrist extension significantly increases (24.1 degrees) and the wrist moves into slight radial deviation (1.0 degree).

The amount of tool movement is significantly correlated with wrist movement both per minute and per cycle. As expected, there is more total movement per minute with shorter cycle times for both the wrist and tool (Figure 6.4). However, there was significantly less movement per cycle for shorter cycle times (Figure 6.5). There was significantly more wrist and tool movement over time with longer duty cycles for the reference level (Figures 6.4 and 6.5). However, at the psychophysically determined acceptable torque, duty cycle no longer has a significant effect on wrist movement for movement per minute or movement per cycle. By varying both cycle time and duty cycle both "work" time and "rest" time are varied. The relationship between wrist and tool movement and both "work" and "rest" time is significant both per minute and per cycle. However, movement per minute is more sensitive to "rest" time and movement per cycle is more sensitive to "work" time (figure 6.6).

*EMG*

Mean values for EMG can be found in Table 6.2. The three forearm muscles monitored follow a similar pattern of relationship between duty cycle and level. The trapezius EMG level is low and shows no significant effect of cycle time, duty cycle or level. ECRB had the highest level of EMG. This would reflect its role in preventing the wrist from going into flexion both due to the activation of the extrinsic finger flexion muscles and due to the counter clockwise torque of the tool. The values for the "work" portion of the FDS are consistent with the hand grip force level (PDAT: mean FDS 3.7-6.2 % MVC, mean force 4.6-6.8 % Max). Of the three forearm muscles, FCR shows the least difference between mean of the "work" portion and the whole mean indicative of more of its activity occurring during the rest portion and torque initiation/completion. The "work" portion of the EMG is related to the torque level, with a significant effect of duty cycle during the PDAT trials (longer duty cycle, lower EMG), and no effect during the Reference trials. For the whole trial, the EMG was significantly higher with longer duty cycles for the Reference trials. However, unlike hand torque the EMG was not significantly related to duty cycle during the PDAT trials.

The APDF results for the three forearm muscles are shown in figure 6.7. With the Reference trials, there was a significant effect of duty cycle at the 10$^{th}$ and 50$^{th}$ percentile level. There was no significant effect with the PDAT trials. For the 10$^{th}$ percentile values, the 25% and 50% duty cycles are low but for the 83% duty cycle there was a significant jump. Cycle time had no effect on APDF levels or mean values.

Both gap time/minute and number of gaps/minute for the 3 forearm muscles were significantly higher for the PDAT level then the Reference level. Neither duty cycle nor cycle time significantly affected the PDAT gap time or number of gaps. However, the gaps per cycle were significantly related to the "rest" time per cycle particularly for the Reference level.

*Duty Cycle*

The set duty cycles tested (25, 50 and 83% of the cycle) reflect the driving torque of the torque motor. The corresponding calculated "biomechanical" duty cycles for the hand torque, hand force and the three forearm muscles are shown in figure 6.8. There is a significant effect of duty cycle but not cycle time.

## DISCUSSION

The effect of a counter clockwise torque while grasping an in-line tool with the right hand requires the activity of the wrist extensors as indicated by ECRB. To prevent rotation of the tool, the finger flexors (FDS) activate to create friction between the hand and the tool. The wrist extensors have to activate to prevent wrist flexion due to the FDS moment at the wrist thus preventing undesired shortening of the flexor muscles. Additionally, the extensors must prevent the flexion of the wrist/rotation of the tool due to the torque of the tool. The FCR had the lowest activity of the 3 forearm muscles monitored. However, it is still cyclic in nature and varies with the level of torque used.

The adjusted hand force values found for the PDAT condition are below the 6 kg value defined by Silverstein et al. (1987) for a mixture of work tasks. Therefore, during the PDAT condition the task would be classed as low force, high repetition. Since the participants had no control on the amount of repetitiveness of the task, the finding that they choose levels that are classed as low force is important since the risk associated with the two factors together are multiplicative (Silverstein et al., 1986). The role of the duty cycle was not examined in that study. However, in this study the PDAT and hence the "work" portion of the hand force is significantly affected by duty cycle.

The results reflect the difference between the motor and biomechanical duty cycle. With the reference level, the overall mean of the hand torque increases with increased duty cycle. The psychophysically determined acceptable torque levels decrease with the duty cycle, however, not enough to overcome the effect of duty cycle on the overall mean. More angular impulse is handled with the higher duty cycle despite the lower "work" torque. However, this duty cycle effect on the overall mean is not found for the hand force and EMG levels. In both cases, the force/torque and EMG/ torque (ECRB and FDS) remain relatively constant despite torque level. Therefore, they should reflect the same effect with Duty Cycle as hand torque.

The reason they don't appears to be the effect of motor duty cycle on EMG and force duty cycle. Linear regressions of the measured duty cycles versus the motor duty cycle for all torque levels are shown in figure 6.8. As can be seen, the slope for hand torque is very close to 1.0 with an intercept close to zero. However, with the muscle activation and force measures, the slope of the regression goes down and the intercept goes up. The change in slope of the activity is likely due to activity present only when there is time to do it (e.g. Muscle activation due to other hand activity during "rest" time, holding handle throughout etc. for which there is more opportunity to do at 25% than 83%) or activities that are done more slowly when there is more time to do it (e.g. longer preparation time for onset of torque). The increase in intercept values reflect activities that have a set minimum time of activity likely due to initiating grasping and releasing the tool.

The finding that the participants chose a psychophysically determined acceptable torque such that the overall mean of hand force or EMG is not significantly affected by duty cycle or cycle time, does imply a tissue loading basis for the levels chosen. It does not, however, suggest that the tissue loaded is necessarily the tissue at risk for upper limb work related musculoskeletal disorders. Forearm muscles, particularly on the extensor side are at risk during highly repetitive jobs (Ranney et al., 1995) as are tendons, tendon sheaths, and nerves (Silverstein et al., 1986, 1987). Most reports of discomfort were found in the hand areas, specifically at the base of the thumb, suggesting that the adjustments done in the selection of the PDAT are dominated by afferent messages from the skin on the hand. However, since the hand force and muscle activity levels are both similarly effected, the result would affect loading on muscle, tendons, and nerves; tissues at risk for WMSD.

There is a time overhead associated with muscle activity that is reflected in the APDF results With the idealized on/off duty cycle for the duty cycles tested, the peak ($90^{th}$ percentile) value should be similar to the "work" portion of the cycle and the static ($10^{th}$ percentile) should be near zero (figure 6.9). As seen in Figure 6.7, the static level is low, for the most part below 1% MVC with the exception of the 83% duty cycle. The static value for the 83% duty cycle is higher, up to 3.8 % MVC, particularly for the reference level. This would suggest that at 83% duty cycle the actual muscle activity occupies more than 90% of the cycle time. While the peak and "work" portions are similar, there is a duty cycle effect in the peak not found in the mean value for the reference level (figure 6.10). The values found are well below the recommendations by Jonsson (1978) for the median and peak values and are below the 2-5% guideline for the static level for the 25 and 50% duty cycle. Aaras (1987) found that static loads as low as 1% MVC could account for chronic muscle disorders in the shoulder. In the case of the 83% duty cycle, PDAT trials, the average static load was over 1% for both ECRB and FDS. This would suggest that despite the selection of a reduced torque for the higher duty cycle, there is still the potential of long term muscle injury with the 83% duty cycle even though the torque was chosen by the participants as acceptable.

While the measured duty cycle calculation gives a sense of the overall muscle usage, it is not sensitive to the time sequence when the muscle actually turns off. The gap analysis gives a better sense of this. As mentioned, gap time per cycle is related to both "rest" time/cycle and torque. Since "rest" time is a function of both cycle time and duty cycle, both gap time/cycle and total gap time can be modeled as a function of cycle time and duty cycle (Figure 6.11). Logically, for a set duty cycle the cycle time effect is minimal at most cycle times since the total "rest" time is a set percentage of the total time (i.e. 100-duty cycle). This does not hold true for very short cycle times (less than 6 s) especially with higher force generation requirements. At this point the overhead associated with initiating and stopping the grasp takes up a significant portion of the cycle "rest" time.

The combination of wrist angle and tool movement data showed interesting changes in behaviour by the participants. With shorter cycle times and higher torque levels, the participants maintained more wrist extension. This could possibly be some form of presetting to withstand the flexion moment created by the tool. This could lead to greater loading of the tendons on the tendon sheaths. Of more interest is the role of the tool movement and wrist movement with torque. With the longer "work " time that comes with longer duty cycles, both the wrist and tool had significantly more movement with the reference level. However, with the torques chosen (PDAT), only the tool maintains this movement. This would suggest that there is a certain amount of tool slippage the subjects allow and that the torque chosen brings handgrip force down to a level they can just manage. As expected, there is more total movement with shorter cycle times. Since there was no adjustment to torque based on cycle time, this would suggest that tissues more at risk due to repetitive movement (e.g. synovial sheaths in the carpal tunnel) were not accounted for in the selection of the PDAT. It is possible that they did not feel that wrist movement could be controlled by torque. However, they did appear to maintain a fixed level through control of torque associated with duty cycle.

This study examined the effect of torque on the worker. The psychophysically determined acceptable torques chosen in this high repetition task create hand forces that would all be classed as low force. The average hand force and muscle activation levels over the whole cycle are maintained at a consistent level for different tool duty cycles through a combination of the torques chosen and the relative calculated duty cycles associated with the force and muscles. However, despite this, it is not sufficient to bring the 83% condition into an acceptable level for muscle as shown by the 1% static EMG guidelines recommended by Aaras (1987).

**Table 6.1** Comparison of hand force by duty cycle for both the reference trial (REF) and trial set at the maximum acceptable level as chosen by the participant (PDAT). "Work" is the average of the work portion of 3 cycles and Mean is the mean over an even number of cycles in a 5 minute period. Force/Torque is during the "work" portion. Results are the mean of 8 participants and 4 cycle times (* $p < 0.05$).

| Duty Cycle (%) | REF | | | PDAT | | | |
|---|---|---|---|---|---|---|---|
| | "Work" Force (N) | Mean* Hand Force (N) | Force/ Torque (N/N.m) | "Work" * Force (N) | Mean Hand Force (N) | Adjusted Force** (kg) | Force/ Torque (N/N.m) |
| 25 | 26.1 | 11.8 | 16.4 | 16.3 | 8.5 | 1.71 | 14.7 |
| 50 | 24.3 | 15.6 | 16.1 | 12.4 | 8.7 | 1.26 | 14.1 |
| 83 | 23.6 | 21.5 | 16.7 | 11.0 | 10.5 | 1.2 | 16.1 |

** Adjusted Force = mean + variance/mean hand force (Silverstein et al., 1987)

**Table 6.2** Comparison of EMG (% MVC) by duty cycle for both the reference trial (REF) and trial set at the maximum acceptable level as chosen by the participant (PDAT). "Work" is the average of the work portion of 3 cycles and Mean is the mean over an even number of cycles in a 5 minute period. Results are the mean of 8 participants and 4 cycle times (* $p < 0.05$).

| Duty Cycle (%) | Torque Level | ECRB | | FDS | | FCR | | Trapezius | |
|---|---|---|---|---|---|---|---|---|---|
| | | work | mean | work | mean | work | mean | work | mean |
| 25 | REF | 13.2 | 6.4* | 9.1 | 4.6* | 5.7 | 3.5* | .5 | .6 |
| | PDAT | 10.7* | 5.4 | 6.2* | 3.6 | 4.3* | 2.7 | .8 | .9 |
| 50 | REF | 11.9 | 8.7* | 7.9 | 6.0* | 5.8 | 4.9* | .6 | .7 |
| | PDAT | 7.9* | 5.3 | 4.7* | 3.6 | 3.6* | 3.0 | .5 | .6 |
| 83 | REF | 12.3 | 11.1* | 7.9 | 7.7* | 6.5 | 6.3* | .9 | 1.0 |
| | PDAT | 6.1* | 5.7 | 3.7* | 3.5 | 2.6* | 2.7 | .9 | .9 |

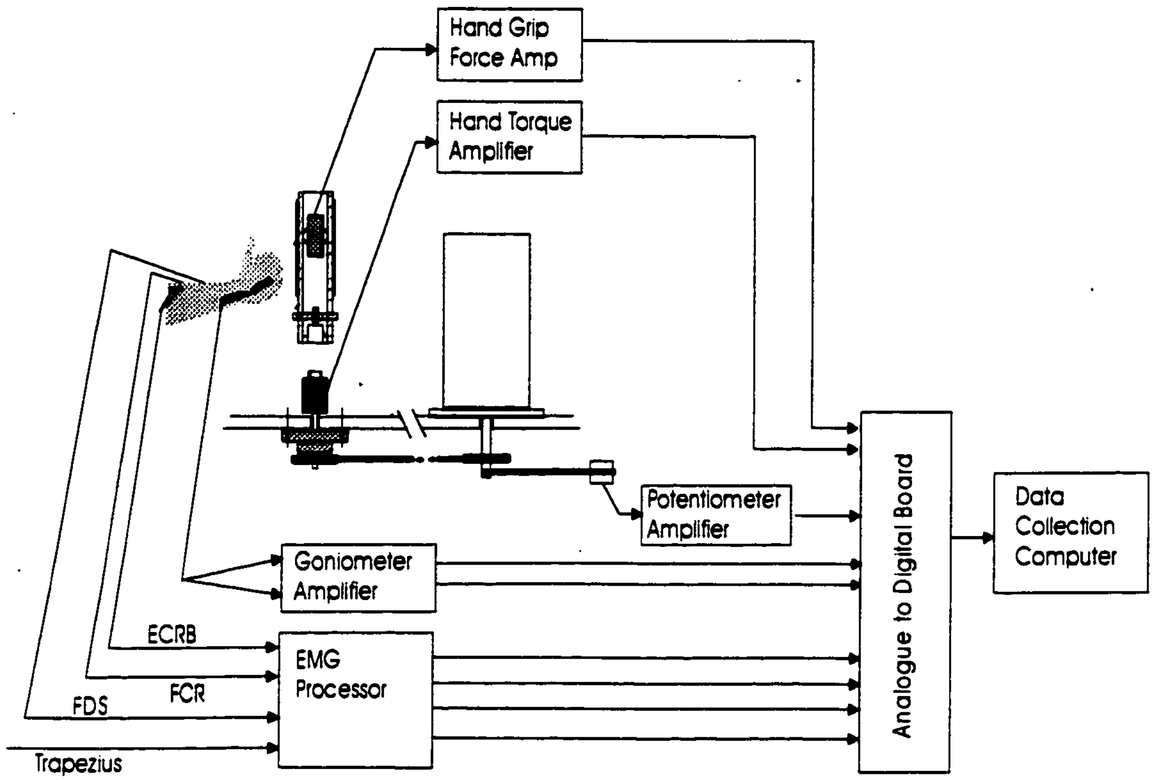



**Figure 6.1** Data collection system

A)

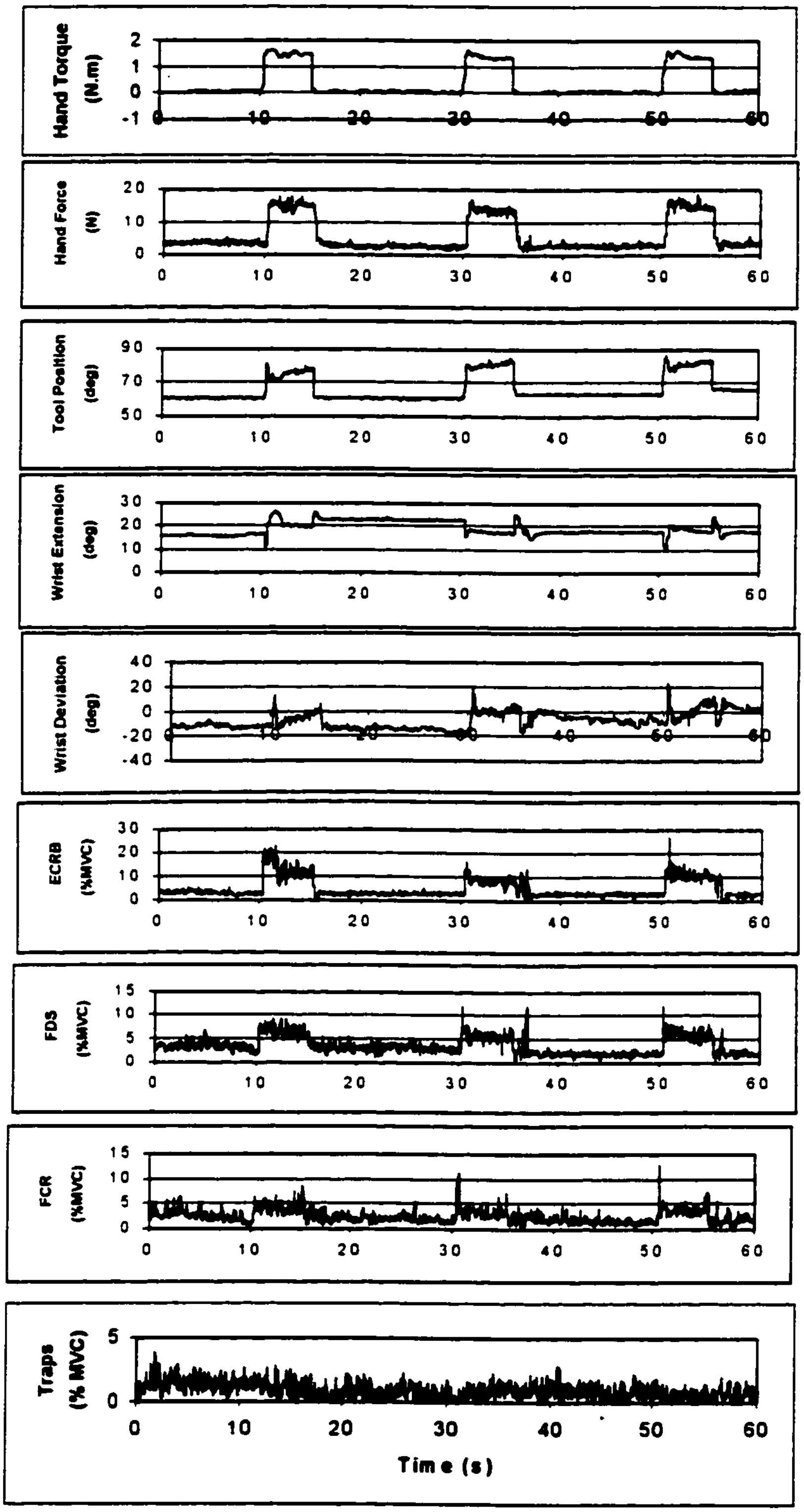
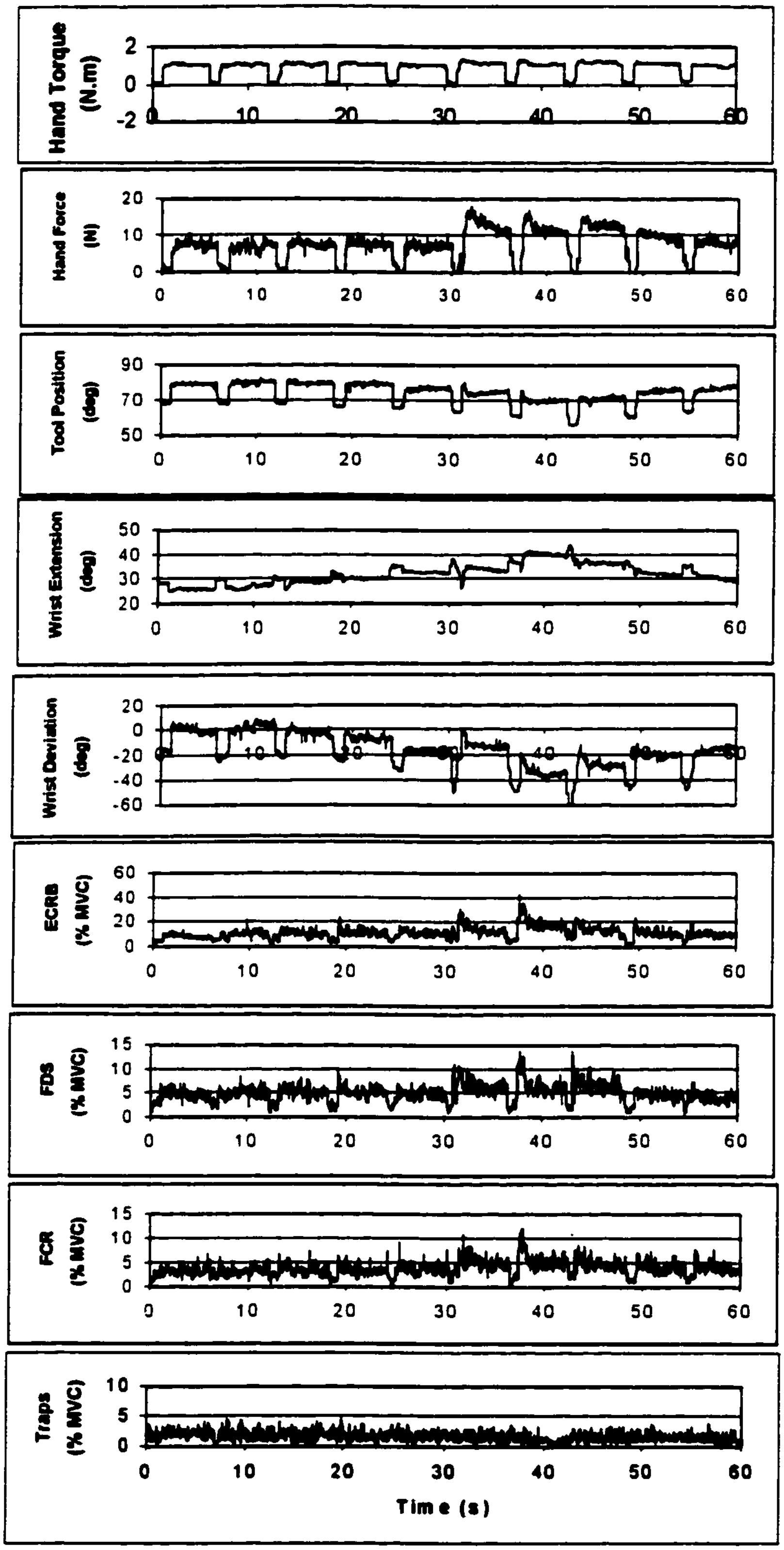



**Figure 6.2** Results over time from a typical trial. A) Reference torque trial, 20 s cycle time, 25% duty cycle B) PDAT trial, 6 s cycle time, 83 % duty cycle. Radial Deviation is positive.


Hand Torque (N.m)
Hand Force (N)
Tool Position (deg)
Wrist Extension (deg)
Wrist Deviation (deg)
ECRB (% MVC)
FDS (% MVC)
FCR (% MVC)
Traps (% MVC)
Time (s)

B)

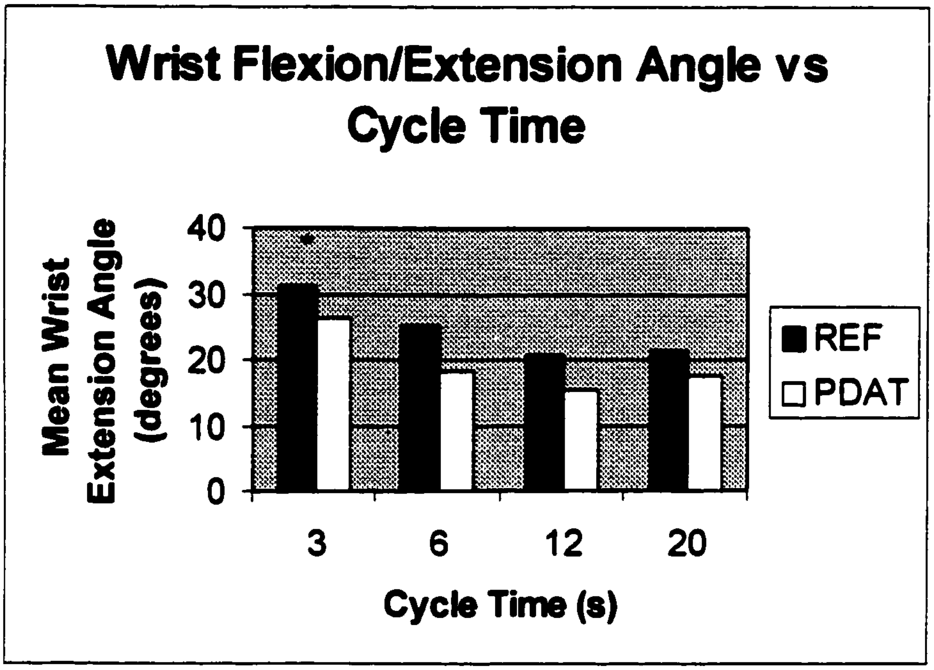
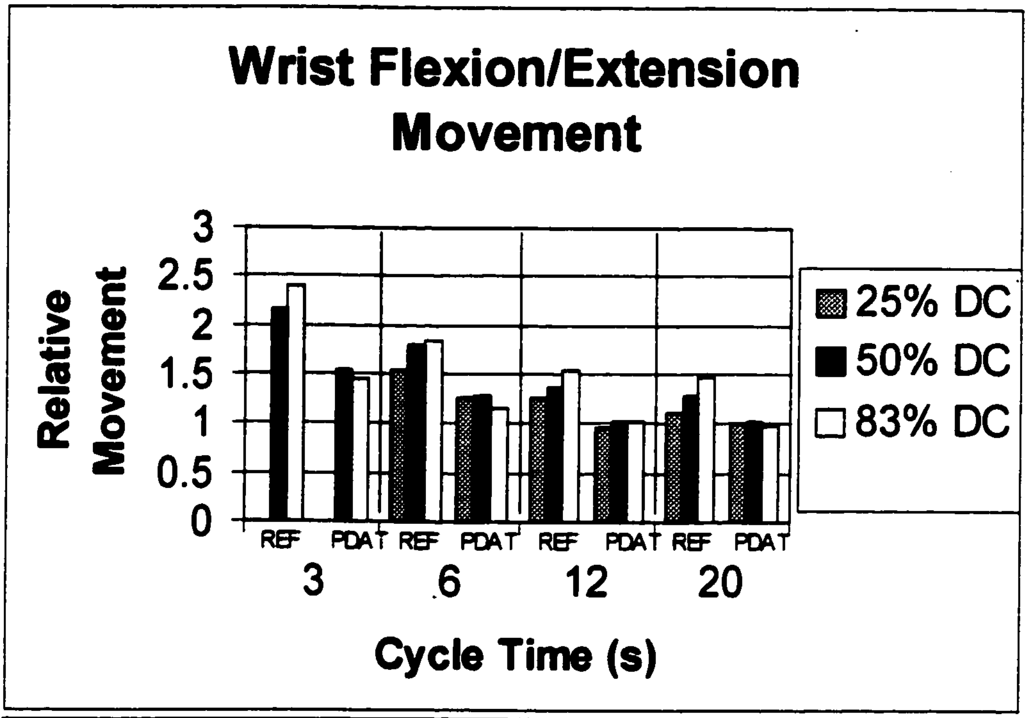



**Figure 6.3** Effect of Cycle time on the mean wrist angle in the flexion/extension axis during the "work" portion of cycle for both the reference torque (REF) and the participants chosen psychophysically determined acceptable torque (PDAT). Mean of 8 subjects, 3 duty cycles, 3 windowed portions (* $p<0.005$)

a)




b)

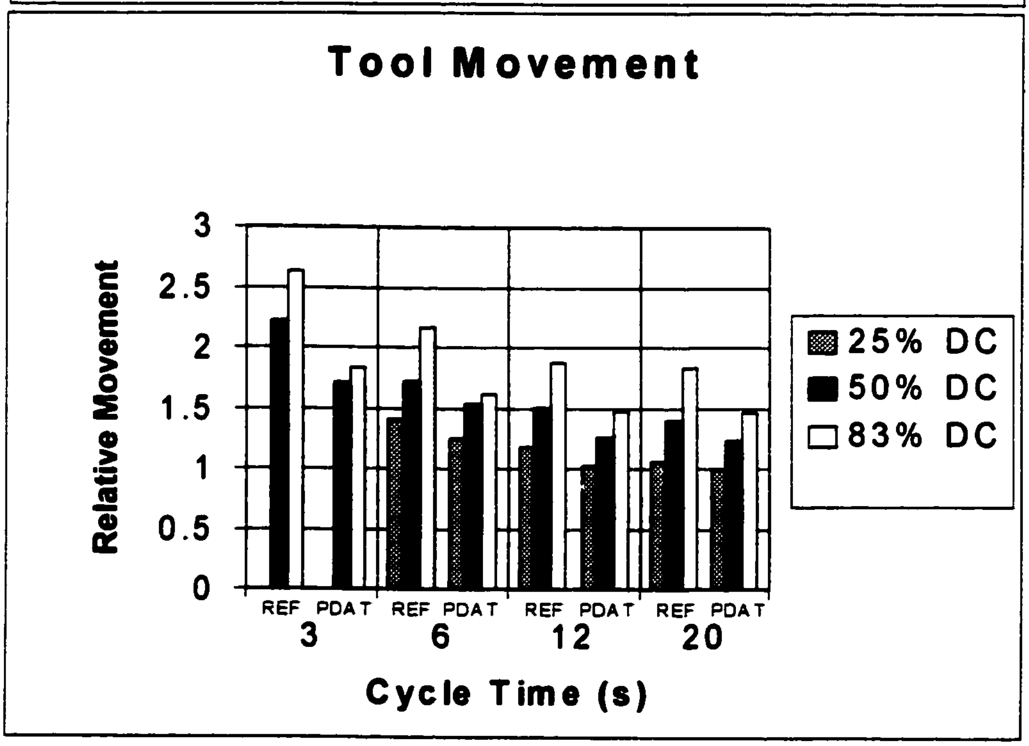
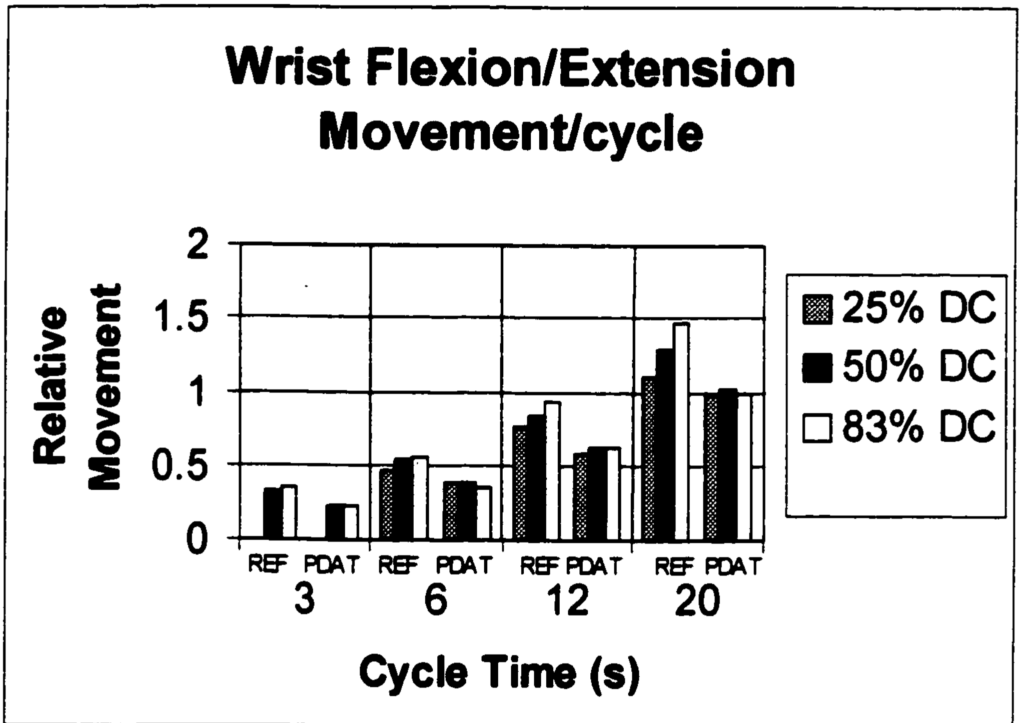



**Figure 6.4** Movement per minute for both a) the wrist flexion/extension and b) the tool over different cycle times and duty cycles for both the reference torque (REF) and the participants chosen psychophysically determined acceptable torque (PDAT). Normalized to 20 seconds cycle time, 25% duty cycle, PDAT. Mean of 8 subjects.

a)




b)

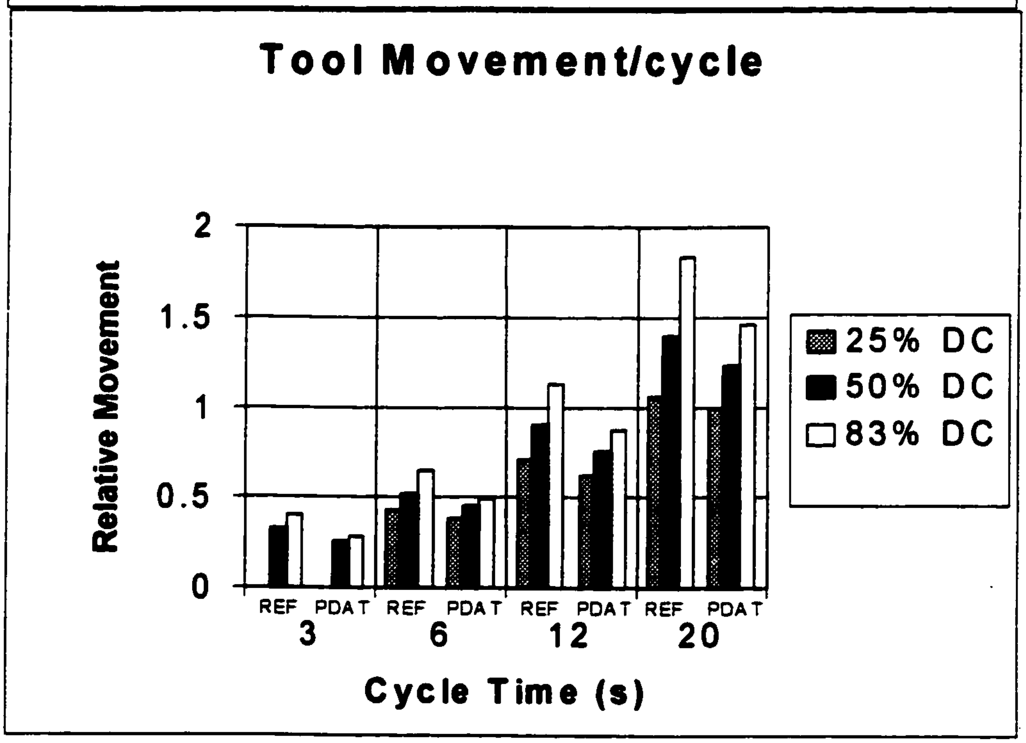
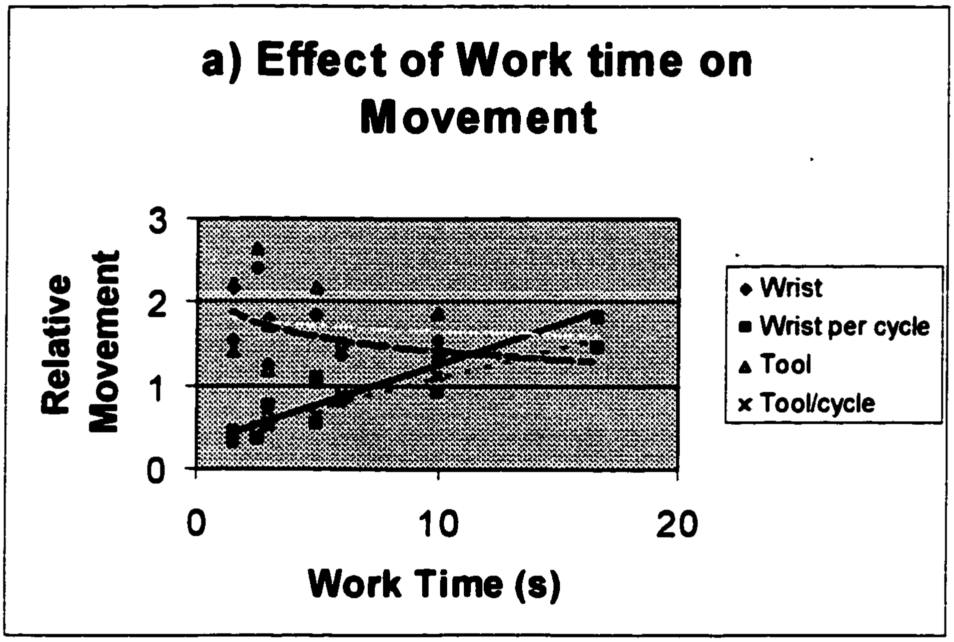



**Figure 6.5** Relative amount of movement per cycle for both a) the wrist flexion/extension and b) the tool over different cycle times and duty cycles for both the reference torque (REF) and the participants chosen psychophysically determined acceptable torque (PDAT). Normalized to 20 second cycle time, 25% duty cycle, PDAT. Mean of 8 subjects.



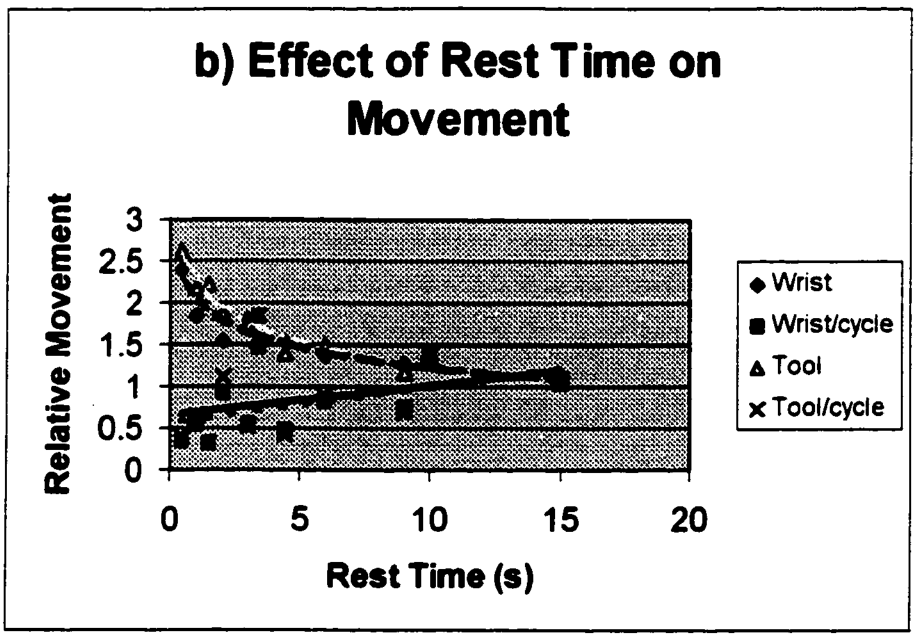




**Figure 6.6** Effect of a) work time and b) rest time on wrist flexion/extension axis movement and tool movement with the reference torque. Results for total movement per minute and movement per cycle. Mean of 8 subjects.

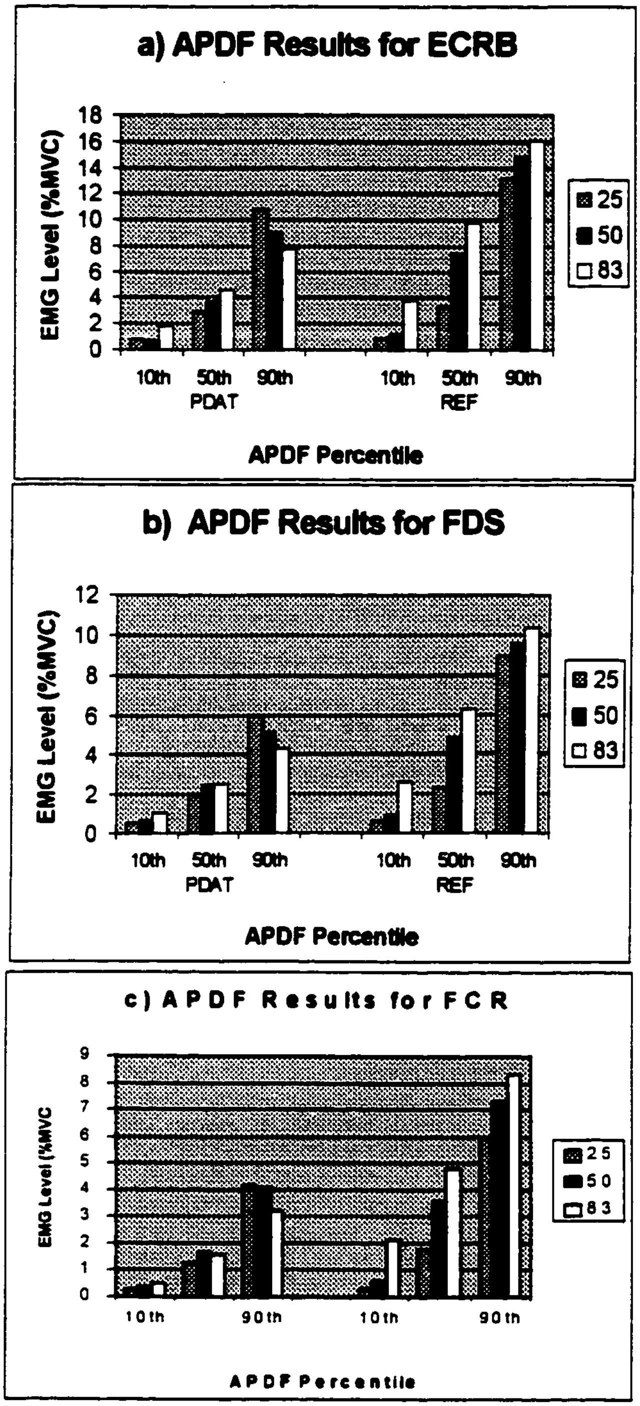



**Figure 6.7** Amplitude Probability Distribution Function Results for EMG from the three forearm muscles monitored. a) ECRB, b) FDS and c) FCR. PDAT= Psychophysically Determined Acceptable Torque, REF=Reference level torque. Mean of 8 participants and 4 cycle times.

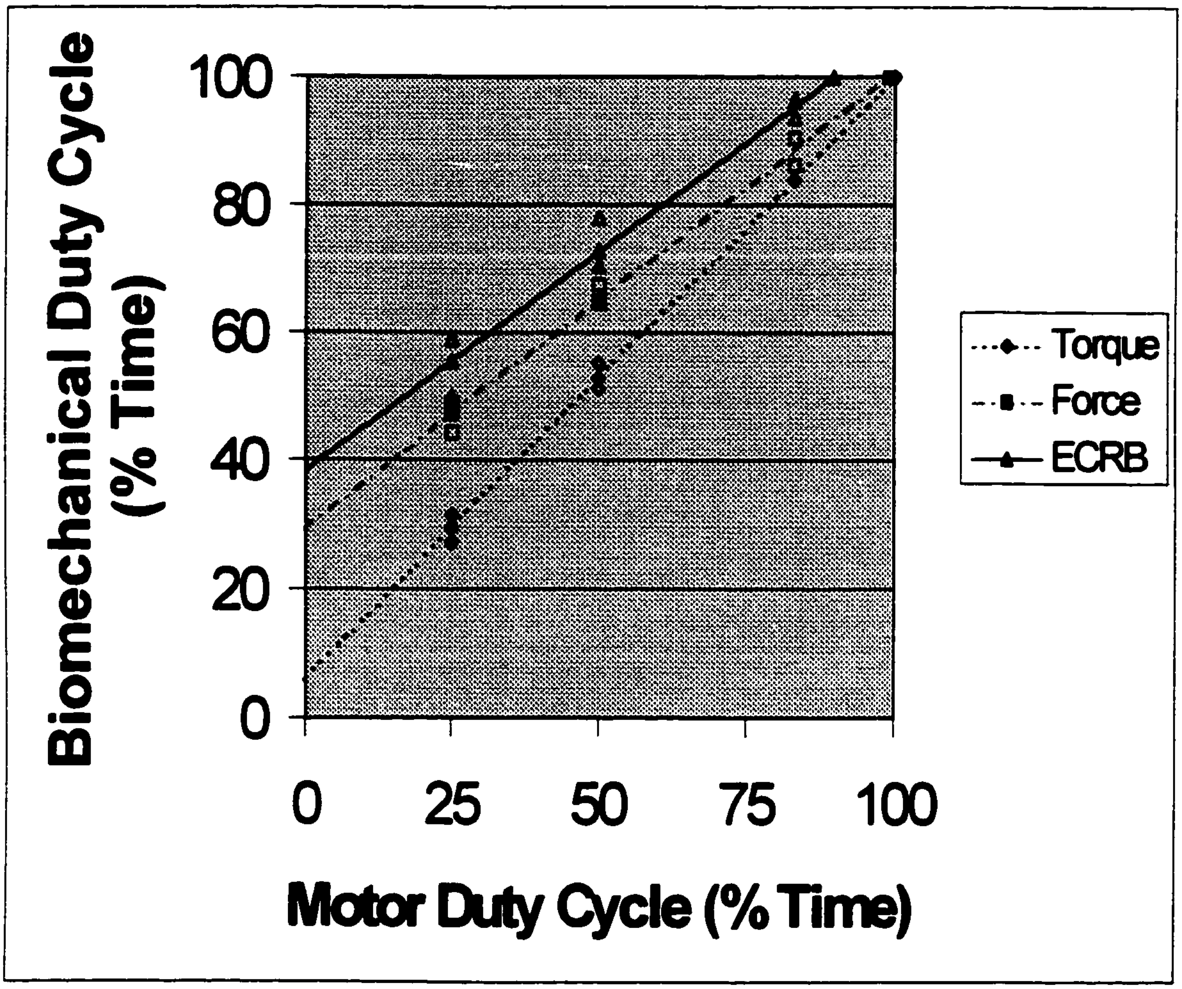



**Figure 6.8** Biomechanical Duty Cycle (mean of whole cycle/mean of work portion of cycle) for Hand Torque, Hand Force and ECRB EMG versus applied Motor Duty Cycle of the torque motor. Line and solid symbol, regression equation. Open symbols mean value of 8 subjects each torque level.

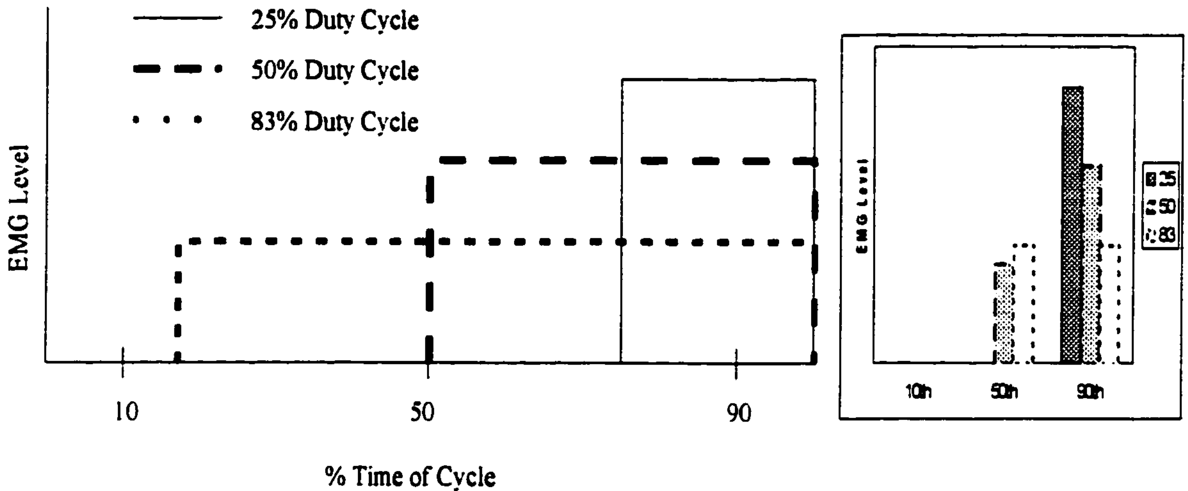
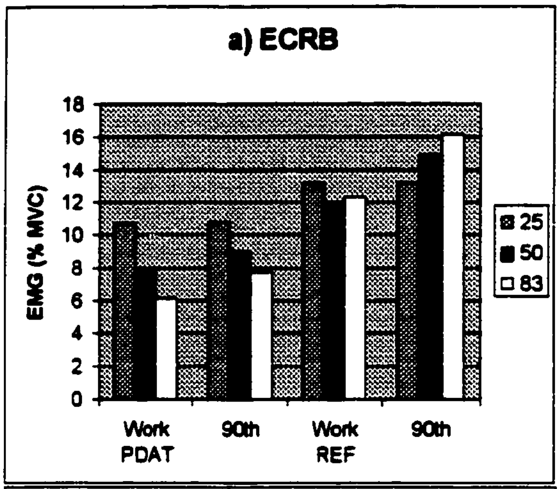
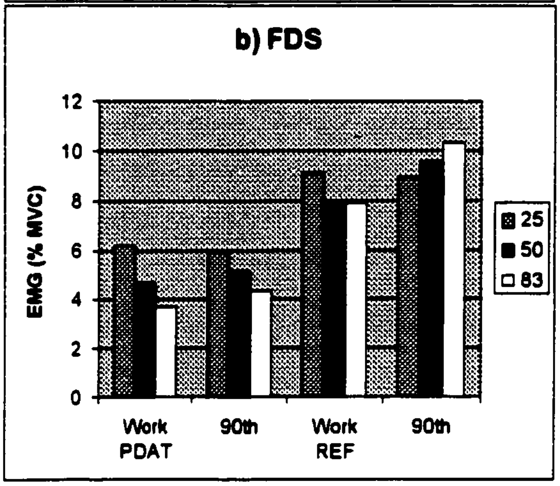



**Figure 6.9** Idealized APDF results for the different duty cycles tested at 3 different torque levels.



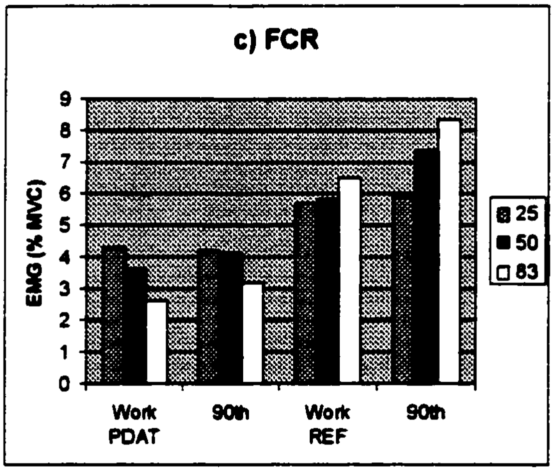




**Figure 6.10** Comparison of the EMG APDF 90th percentile value and mean value of the "work" portion of the cycle for a) ECRB, b) FDS and c) FCR by duty cycle. Mean of 8 participants, 4 cycle times

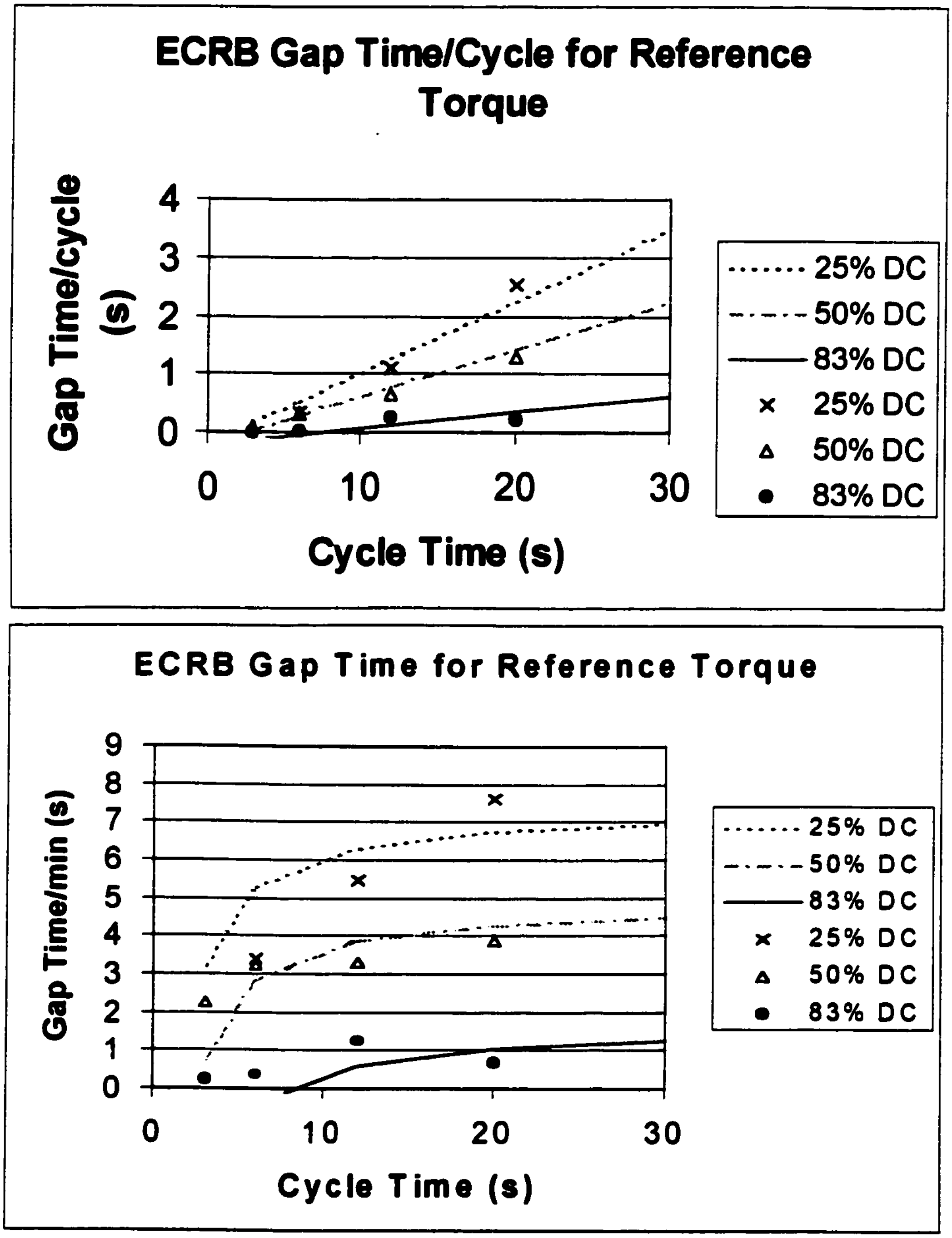



**Figure 6.11** Gap time a) per cycle and b) per minute versus cycle time by duty cycle for ECRB at the preset torque. Lines represent values calculated from the regression of gap time per cycle versus rest time per cycle. Individual points are the actual results (mean of 8 participants)

# Chapter 7

# DISCUSSION AND CONCLUSIONS

Adjustment-type psychophysical determination of acceptable loading on the upper limb is starting to be used for highly repetitive tasks. This thesis examined the use of this method when applied to a simulated repetitive hand tool task. The goals were:

1) To establish load adjust type psychophysically determined values for acceptable torque (PDAT) during in-line screw-running.
2) To examine the effect of duty cycle and cycle time on PDAT.
3) To test the psychophysical relationships between torque and perception over different conditions.
4) To examine the role of torque, duty cycle and cycle time on selected biomechanical variables representative of mechanical loading of the upper limb which may lead to WMSD

5) To examine the effect of PDAT on fatigue and discomfort over the course of a working day and over different duty cycles and cycle times.

Psychophysically determined values for acceptable torque were determined for a simulated in-line screw-running task, based on the results for 8 females with industrial experience. The values found ranged from 0.27-1.96 N.m depending on the participant and condition. These values are lower than the "up to 6 N.m" recommended by Mital and Kilbom (1992b) or the "3.2 N.m" guideline used by Ford Motor Company (AIHA, 1996). There are several possible explanations for this. First, all the tasks performed here would be classed high repetition both based on the division used by Silverstein (1985) to best differentiate injured from non-injured in her important study of the relationship between WMSD and work, and on the proposal by Sperling et al. (1991) for hand tool use. Mital and Kilbom (1992) suggest that the maximum force level would not be acceptable for high repetition tool use. Silverstein (1985) found a multiplicative effect on injury with a combination of high force and high repetition. The results here found that while the participants were forced to work in a high repetition job, they chose to work in what would be classed as low force based on the classification by Silverstein (1985). Next, the torque profile presented here represents an idealized blending of the push force, tool support, trigger activation and torque reaction force. The push force and trigger force would typically be a square wave as presented here (Cederqvist and Lindberg, 1993). The reaction torque depends on a number of factors including the type of torque shut off, and the joint characteristics (AIHA, 1996). It is possible that higher torques would be acceptable if the push force was minimal and the maximum torque was sustained only for a short period of time.

Finally, the adjustment method used will affect the level chosen. Many factors have been shown to affect the levels chosen in psychophysical adjustment studies. These include worker factors (e.g. age, gender, experience, strength, etc.), task factors (quality of simulation, frequency, posture, feature adjusted, coupling between the worker and workplace, etc.), environmental factors (heat, noise, light etc.), and study design features (presentation of the load, duration, instructions, etc.) (e.g. Ayoub, 1989; Krawczyk et al., 1992; Karwowksi, 1996). As recommended in the literature, participants here had experience working in industrial workplaces. The results of Gambarale et al. (1987) would suggest that while this is not necessary to rate relative work situations, it is important in perceiving what is a reasonable level to work at. Due to strength and anthropometric differences, genders are often tested separately. The results here are based on female participants. The instructions given in the past have been shown to bias the results (Gamberale et al., 1987). The instructions used here are presented in Appendix A. These represent a streamlined version of that used by Snook et al. (1995). All instructions were given by one researcher. The instruction sheet was read to the participants during the training days at the start of their participation. The sheet was also posted directly in front of them. Each day it was repeated to them that their goal was to "work as hard as they can without developing undue discomfort". These instructions may be such that they may bias the results one way or the other. However, since the instructions were the same for each worker, each day, internal comparisons should be consistent. The participants here worked for five hours per day, which, based on the results of Krawczyk et al. (1992) and Snook et al. (1995) is necessary to reach a level without significant differences per hour for repetitive upper limb tasks. Here, there were no significant differences over time for the levels chosen.

The effect of the presentation of the initial load found in the past (Krawczyk et al., 1992) was minimized by alternately setting the value high or low by a random amount and then averaging the results (Snook et al. 1995, Krawczyk et al., 1992). The data were collected in the same room for all participants, with two participants collected at the same time. They were allowed to talk about any topics other than the work being done. The participants were payed on an hourly basis with no incentive pay. In conclusion, all efforts were made to control known between participant and within participant effects in the collection of load adjustment type psychophysical data. However, biases based on the instructions given or workstation and psychosocial factors may have been present (Karwowski et al, 1999).

The second goal was to examine the role of both cycle time and duty cycle on PDAT. The results here showed that cycle time did not have a significant effect on PDAT but duty cycle did for the cycle times and duty cycles tested (figure 7.1). Past upper limb repetitive load adjust psychophysical studies have found an increase in load chosen with longer cycle times (Snook et al., 1995). However, in these cases there was no control for duty cycle. The results here suggest that the changes found with shorter cycle times in the past were the result of the shorter cycle times being accomplished by removing relatively more rest per cycle than an increase in the speed of the actual task. Other psychophysical adjustment studies have fixed the load and task duration and adjusted the frequency of the task (Abu-Ali et al., 1996; Dahalan and Fernandez, 1993). In those cases there is both a drop due to duty cycle as found here but also an increase associated with increased cycle time not found here. There are several possible explanations for this. First, in these other studies the tasks were done for less than an hour. As discussed, for repetitive upper limb tasks, five hours appears to be the minimum to

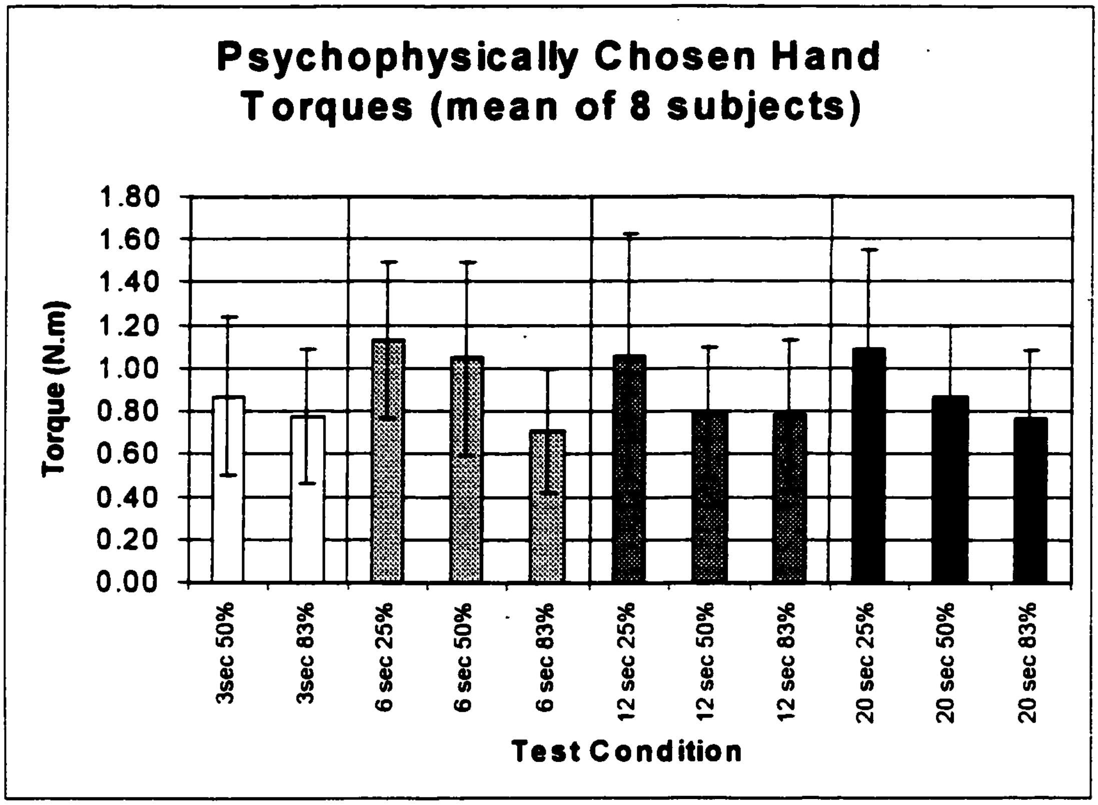



**Figure 7.1** Graph of the torques chosen by the workers (mean, standard deviation of 8) for each of the different cycle time and duty cycle conditions. Results are grouped by time (3, 6, 12 and 20 s) and within each group are the different duty cycles (25, 50 and 83%).

obtain realistic data for work over an 8 hour day. It is unclear how the frequency adjustment methodology as performed in these studies would be affected by working for a longer period of time. The difference between load adjust and frequency adjust points out another potential limiting factor of the psychophysical adjustment method. It assumes that there actually is a "safe" level for the factor adjusted for the conditions presented to the participants. The top range of workloads selected (mean of 8 subjects) here was 11.4% MVC based on ECRB muscle activity. For Snook et al. (1995) it was 17.5% based on maximum force. The top workload tested was 70% for Dahalan and Fernandez. On the other hand, the top duty cycle selected in the frequency adjust was 63% (Abu-Ali et al., 1993) compared to a maximum 83%

duty cycle tested here.

Guidelines for acceptable workload for different cycle times and duty cycles within high repetition tasks cover a wide range (Figure 7.2). The work of Rohmert (1973), can be used to express workload as a function of duty cycle and cycle time based on endurance time. It is clear that there is a large discrepancy between those results and the results presented here. The drawbacks of using endurance data for highly repetitive tasks has been expressed

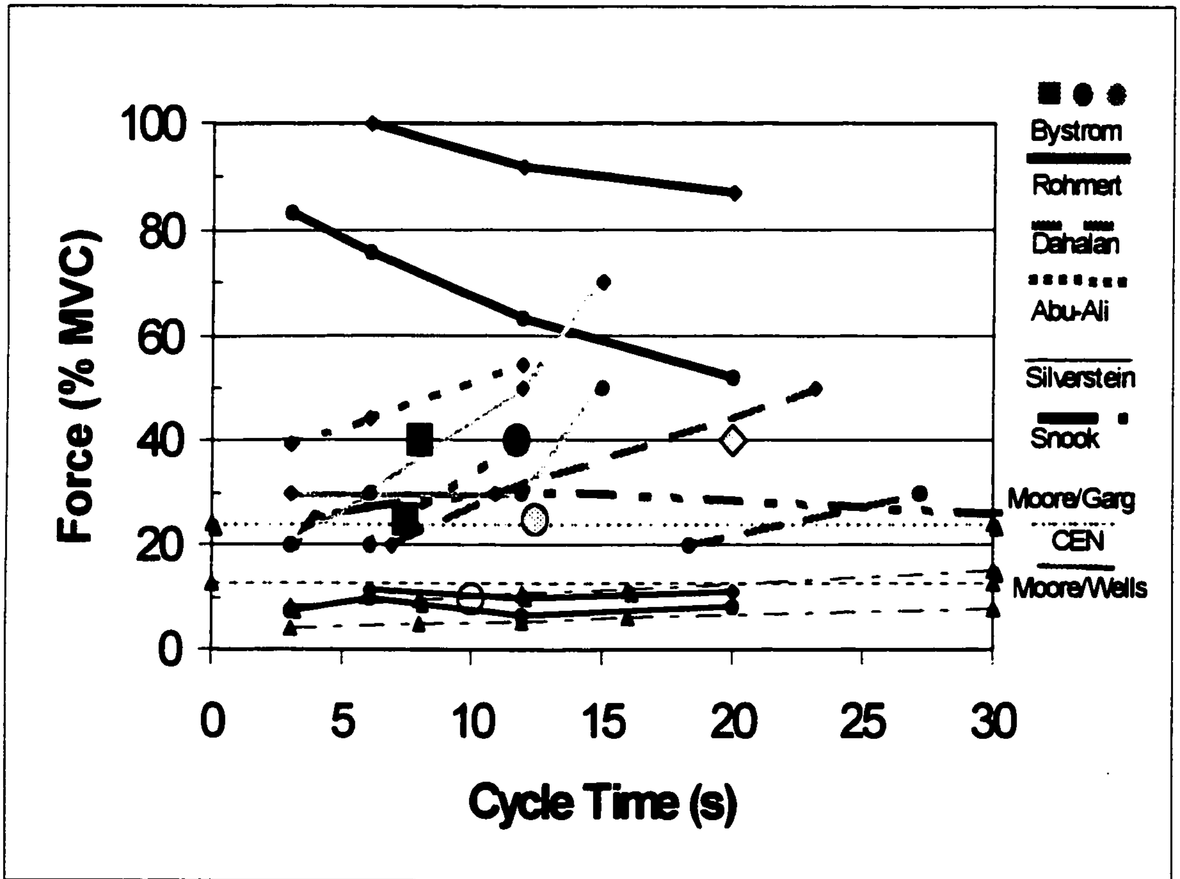



**Figure 7.2** Comparison of workload guidelines for different highly repetitive cycle times by different approaches. Psychophysical: Abu-Ali et al. (1996), Dahalan and Fernandez (1993), Snook et al. (1995), Epidemiological: Silverstein et al. (1986), Physiological: Rohmert (1973), Bystrom (1991) (Note filled marks were considered unacceptable, grey partially acceptable and empty acceptable), Developed guidelines: Moore and Garg, CEN. ●= 50% Duty Cycle ♦=25% Duty Cycle ▲= Duty Cycle not accounted for

(Mathieson and Winkel, 1992). The results here would support this and suggest that the results of Rohmert (1973) could lead to workloads that are much higher than perceived acceptable when used in highly repetitive jobs. Bystrom (1991) examined the acceptability of a number of different discreet duty cycle/cycle time/contraction intensity combinations based on a range of different physiological criteria during both exercise and recovery. His results suggest that continuous contractions are not acceptable and a mean level of 10% MVC is acceptable regardless of the duty cycle and cycle time (duty cycles tested: 25-83%, cycle times: 7.4-20 s, workloads: 10, 25, 40% MVC). Twenty-five % MVC was found to be acceptable by most criteria at 40% duty cycle/12.5 s cycle time but unacceptable at 67% duty cycle/7.4 s cycle time. Bystrom's results suggest decreased acceptable load with increased duty cycle or shorter cycle times. With his study design, it is impossible to separate the two factors. Based upon epidemiological data, the results of Silverstein (1985) do not have a gradient within high repetition tasks and is based on a 6 kg hand force for the effort portion of a cycle regardless of cycle time and duty cycle. This hand force represents, at most, 24% maximum grasp based on maximum grasp strength for women (American Medical Association, 1990). The participants here worked at what would be classed low force based on hand grasp force data (1.2-1.71 kg adjusted force). Based on both the results found here and comparisons with other studies the following conclusions are warranted: 1) Duty cycle is an important factor and needs to be included as a separate factor in psychophysical studies of highly repetitive upper limb tasks. 2) The acceptable level of work load in highly repetitive tasks with duty cycles over 50% could be 10% MVC or lower depending on the cycle time and duty cycle. This is in line with the proposed European Standard for hand forces during machine operation. It has a maximum duty cycle of 67% and forces that equate to 8.3% - 12.6% MVC for cycle times from 3-20 s for females.

The third goal was to test the psychophysical relationships between torque and perception over different conditions. The results found here showed that the participants were able to perceive the torques presented to them consistent with Steven's Law ($S=KI^n$, where S is the sensation, K is a constant, I is the stimulus intensity and n is the exponent specific to a certain situation). For low torques (below approximately 1.25 N.m), participants tended to underestimate the torque magnitude particularly for short cycle times and short duty cycles The exponents found here were significantly affected by cycle time and the scaling factor by duty cycle. The perceived torques associated with the PDAT chosen by the 8 participants who continued on into the adjustment study were determined from the actual torques for each condition and the results for their particular regression equation for that condition. No significant difference was found for perceived torque for either cycle time or duty cycle, despite the duty cycle effect on actual torque. These findings could suggest that differences in the relationship between perceived and actual torque help account for the torques chosen, such that the participant may perceive the levels as the same, although they differed. This, in reality is what we asked of them, although the rating was to be based on feelings of discomfort due to torque not actual level of torque. However, if discomfort is either a sign of injury or a precursor to injury, which is a function of biomechanical loading of tissues, then a analogous relationship may exist between perceived discomfort and torque. When trying to test a more complex sensation using "difficulty to perform all day" versus actual torque on a subset of participants, the relationship was still strong. However, fewer regression coefficients were significant and there were no significant differences between duty cycle or cycle time conditions for exponent, although again duty cycle did affect the scaling factor.

A selection of biomechanical variables were examined here. These included wrist posture, wrist and tool movement, hand grip force and torque, and an amplitude probability distribution and gaps analysis of the EMG from four muscle sites on the right upper limb. The purpose was to examine the combined effects of the cycle time, duty cycle and torque chosen on variables that can affect loading on the tissues at risk of WMSD. Hand force has been linked to injury (Silverstein et al., 1986, 1987). Silverstein used a technique (adjusted force=mean hand force + variance/mean) that when modeling work as a cyclical square wave would be equivalent to measuring the work portion of a task regardless of cycle time and duty cycle. The adjusted hand force found here (1.2-1.71 kg depending on duty cycle) was below the 6 kg used by Silverstein to show a large odds ratio between injured and non-injured workers. Through the torques tested here, the ratio between torque and hand force was not significantly affected by torque. Based on this ratio, one would predict a torque of 3.8 N.m in order to have an adjusted hand grip force of 6 kg regardless of cycle time or duty cycle. For the participants here, this would represent over 30% MVC for the ECRB. Based on the results of Bystrom (1991), this would not give adequate recovery for muscle with high repetition (cycle times less then 30 seconds) and duty cycles above 50%. The mean muscle activity of 5.7% MVC for the PDAT condition ECRB is below the recommendation of 17% MVC based on post exercise physiological response (Bystrom, 1991). Based on a combination of both work response and recovery response, it appears that this value shifts to below 10% MVC. Therefore, it appears the levels the participants in this study chose, would be considered acceptable for muscle tissue based on Bystrom's work.

The amplitude probability distribution function of the EMG is another way of looking at a job and studying its acceptability in terms of muscle. In this case, the values for the static (10$^{th}$ percentile), dynamic (50$^{th}$ percentile) and peak (90$^{th}$ percentile), were below the values recommended by Jonsson (1978) for all muscles for the PDAT conditions. However, the guidelines proposed by Jonsson, similar to Rohmert, are based on endurance data and may not be appropriate for highly repetitive work. Aaras (1987) suggested that the static component recommended by Jonsson (2-5% MVC) was too high and that levels as low as 1% could lead to chronic muscle disorders. In the 83% duty cycle condition, even though the participants chose the lowest torques, they were not able to bring the static component below 1% MVC for the ECRB and just barely for the FDS. This is consistent with the biomechanical duty cycle data found here. To achieve a static level near zero, the muscle duty cycle should be less than 90% of the time. Based on the results here, that would occur with an applied motor duty cycle of 75% of the time.

The peak levels suggested by Jonsson (50-70% MVC) are much higher than the levels at or below 10% found here. When work is impulsive in nature with varying frequencies and duty cycles as modeled here, the peak level will represent the work load of the work portion of the cycle for any duty cycles greater than 10%. That was supported here. If the mean EMG was controlled for by the participants and accounting for the biomechanical duty cycle, and ensuring a static EMG near zero, the maximum possible work portion (peak EMG) based on the data here would occur with a biomechanical duty cycle of 10% of the time. However the minimum biomechanical duty cycle for the ECRB found here was actually 38% of the time.

Based on this and with the mean extensor EMG during the PDAT trials of roughly 5.5% MVC found here, the maximum peak level likely to be chosen by the participants would have been 14.5% MVC. The results here suggest that it is important to account for the biomechanical duty cycle when examining the amount of work done.

Overall, the participants selected a greater average workload (mean torque over complete cycle) for higher duty cycles, yet the mean hand force and mean EMG were not significantly different. This result can be accounted for by the difference between the biomechanical duty cycle and the nominal work duty cycle (figure 7.3). The hand grasps the tool longer than the actual torque producing time of the motor plus there will be muscle activity during pause periods. It has been suggested that the first muscle fibres on are the last off (Hägg, 1991; Sjøgaard et al., 1992). This would imply that muscle must completely turn off to shut off the final fibres. With very short cycle times, particularly for higher duty cycles, this time is limited, reducing the number of gaps (Veiersted et al., 1990) in muscle activity (figure 7.4). The location of the cut off for the reduction in gap time was found to be sensitive to torque, however the relationship was difficult to define with the data here as there was only a full range of duty cycle/cycle time data at the 1.4 N.m torque level. It does suggest, however, that the opportunity existed for the participants to have adjusted for this effect to a certain extent by adjusting the torque. The relationship between muscle activity level, cycle time and duty cycle on gap time needs further study. In conclusion, for muscle, the EMG results here would suggest that a) at a 83% applied duty cycle, despite reducing the torque level, participants could not reduce muscle activity into acceptable levels based on static EMG guidelines from Aaras (1987), and b) at very short cycle times it may not be possible to achieve sufficient rest time for the active fibres.

A number of injury mechanisms are proposed for compression of the median nerve in the Carpal Tunnel. These include pressure in the carpal tunnel and mechanical compression of the median nerve by the flexor tendons (Keir, 1995). The nerve is at greatest risk of mechanical compression of the nerve when the wrist is in flexion and the extrinsic finger flexor

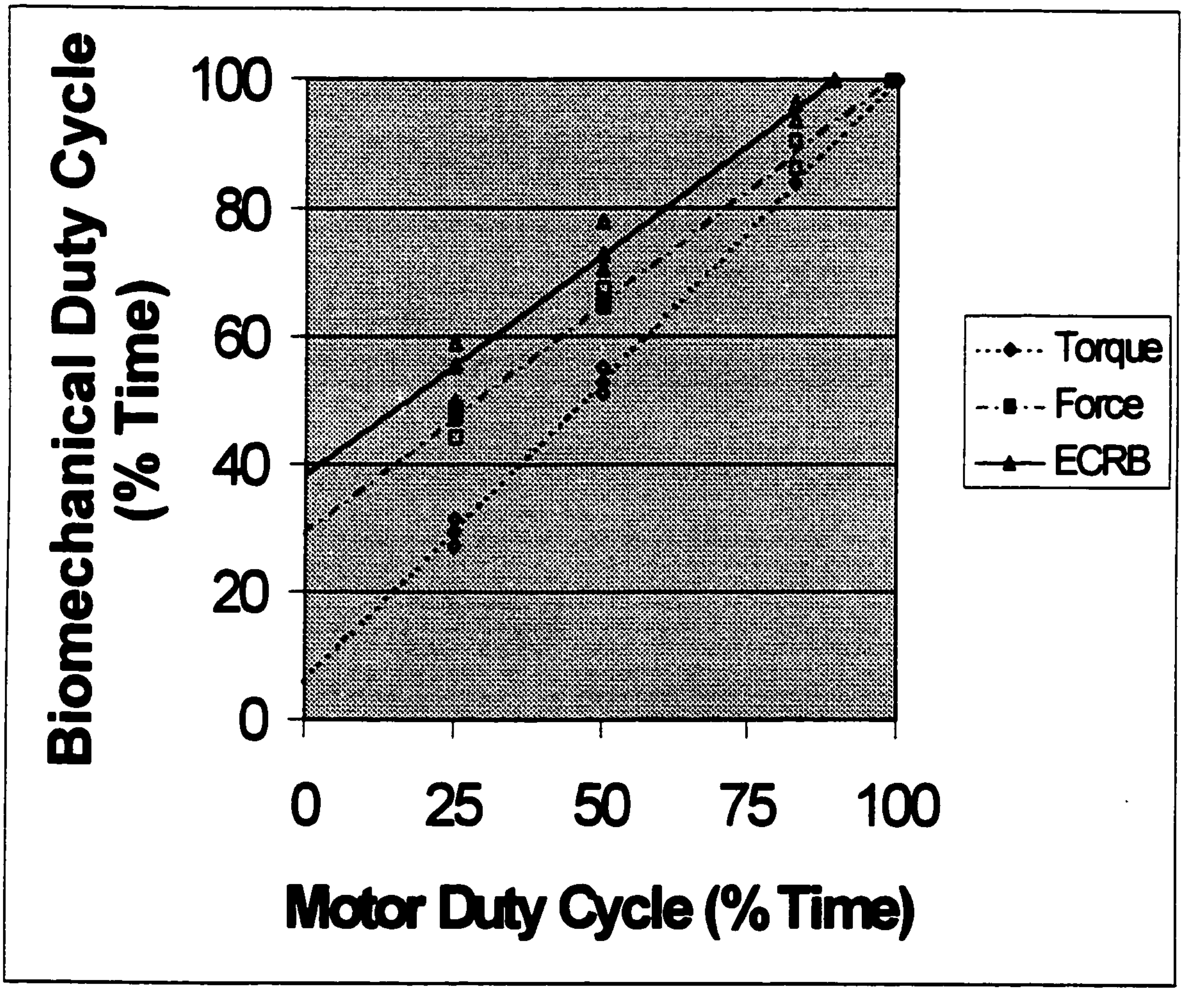



**Figure 7.3** Biomechanical Duty Cycle (mean of whole cycle/mean of work portion of cycle) for Hand Torque, Hand Force and ECRB EMG versus applied Motor Duty Cycle of the torque motor. Line and solid symbol, regression equation. Open symbols mean value of 8 subjects each torque level.

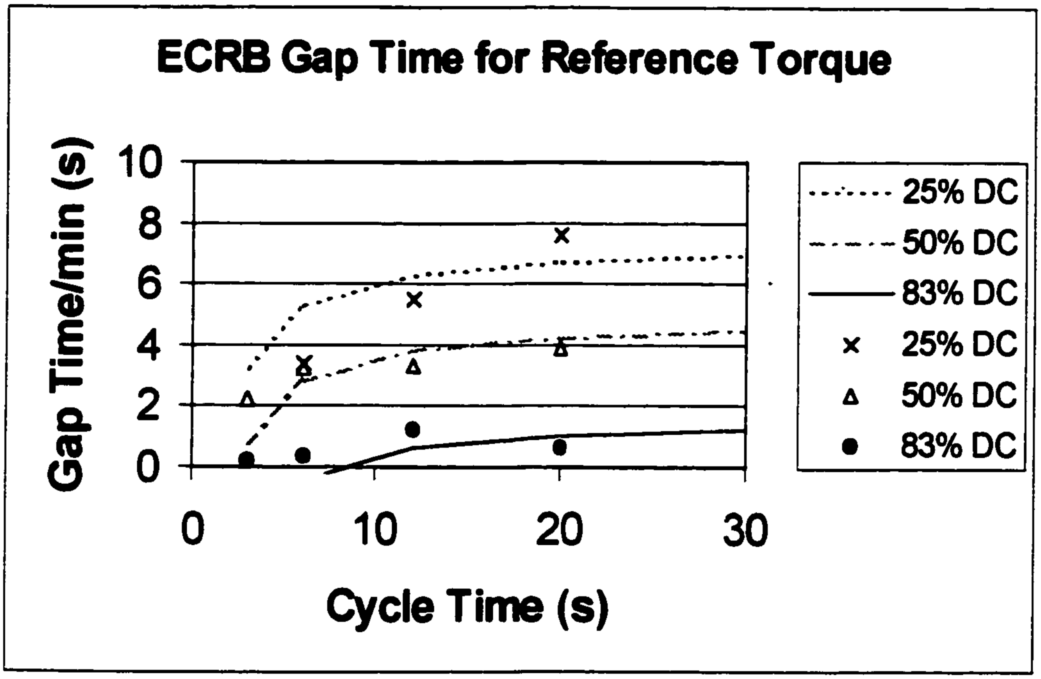



**Figure 7.4** Gap time per minute versus cycle time by duty cycle for ECRB EMG at the preset torque. Lines represent values calculated from the regression of gap time per cycle versus rest time per cycle. Individual points are the actual results (mean of 8 participants)

tendons that lie next to the nerve and are loaded due to muscular activity (Keir, 1995). Pressure in the carpal tunnel has been shown to be related to both force in the tendons and wrist posture, particularly extension. It has been shown that certain normal work tasks can lead to pressures above 30 mm Hg, therefore disruption of local blood supply would be expected (Armstrong et al., 1991; Rempel et al., 1992). For the task presented here, during force production, the wrist was in extension. The amount of extension was greatest with short cycle times (figure 7.5). However, wrist extension with the shortest cycle time was near 25 degrees. With a hand grasp of 16 N, the estimated force in the tendons for FDS and FDP to the index and long fingers would range from 7.4 to 17.4 N (mean 12.1 N) based on the division of forces

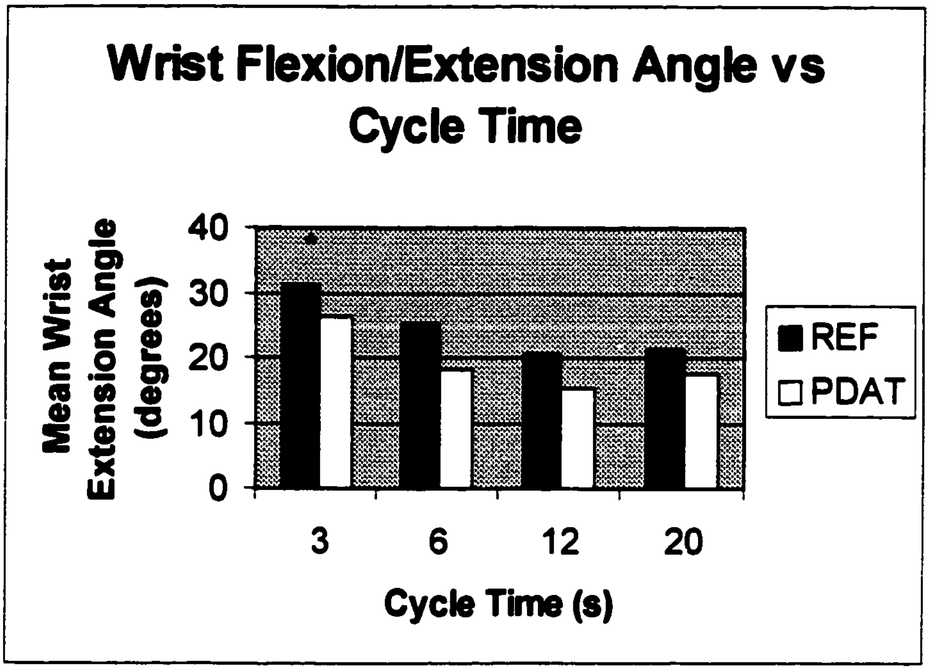



**Figure 7.5** Effect of Cycle time on the mean wrist angle in the flexion/extension axis during the "work" portion of cycle for both the reference torque (REF) and the participants chosen psychophysically determined acceptable torque (PDAT). Mean of 8 subjects, 3 duty cycles, 3 windowed portions (* $p<0.005$)

per finger of Hazelton et al. (1975) and the optimization finger model of An et al. (1985). Keir (1995) loaded these four tendons with 9.8 N and measured the pressure through a range of postures. At 25 degrees extension with loading similar to found here, the pressures in the carpal tunnel were below 30 mm Hg. One might expect, therefore, that for the posture adopted and the load levels chosen, the median nerve is not at risk of injury in the carpal tunnel for this particular injury mechanism.

Proposed injury mechanisms for tendons and tendon sheaths include acute tension, creep, and fraying due to sliding friction (Goldstein et al., 1987). Moore et al. (1991) suggested that excursion of the tendons in the carpal tunnel may be important in the risk of developing injury. In this case, there is more movement with shorter cycle times, but not as much as would be expected because this is offset by less movement per cycle with shorter cycle times. This is likely because the relative movement per cycle is dependent on both the time of the work portion of the cycle (which is both duty cycle and cycle time dependent on the limit of the cycle time) and torque level. At higher torques, as in the reference torque, it appears that the participants move both their wrist and tool the same relative amount. At the PDAT, however, the work time has more effect on the tool movement than the wrist movement. The results may suggest that the participants chose levels where they could control the amount of movement of their wrist.

Finally, this thesis examined the effect of PDAT on fatigue and discomfort over the course of a working day and over different duty cycles and cycle times. The participants were asked to adjust their load level to "go home without any unusual discomfort in your hands, wrist or forearms". Typically, the participants did show a higher level of discomfort at the end of the day based on the visual analogue scale rated discomfort. However they did not show a significant effect over time based on measures from the EMG test contraction. Neither the discomfort VAS nor the 7 point overall discomfort scale showed any significant effect of cycle time or duty cycle. This would suggest that there was a level of discomfort that they would tolerate and that they adjusted the torque values to achieve it. The sources of perceived discomfort which may have acted as the limiting factor included mechanical pressure on the hands, sustained loading of the joints and tendons, or muscular fatigue. The discomfort they did report was located in the fingers and hand, not in the wrist or in the forearm where one might expect pain due to muscle or tendon injury. Fransson-Hall and Kilbom (1993) noted that the thumb/thenar portion of the hand was the most sensitive to external pressure. The discomfort we observed at the base of the thumb could be the result of stretching of the skin between the thumb and index fingers or due to possible intrinsic muscle pain (thenars or first dorsal interosseus). If pressure alone was responsible for the discomfort in the hand and fingers, it would be expected that there would be more discomfort on the palmar side than the dorsal side, particularly in the middle phalanx of the middle finger since this was found to be the location of most pressure while grasping a 50 mm cyclinder (Hall, 1995). This was not the case. For the fingers, the greatest reports of discomfort were reported as stiffness in the back of the fingers. Sensitivity to pain in the hand has been found to increase with both repetition and duration of pressure (Fransson-Hall and Kilbom, 1993). Therefore, both cycle time and duty cycle could have affected any threshold levels for discomfort.

With shorter cycle times, participants did not choose significantly different torque levels. Yet, there was evidence of increased muscle fatigue, particularly in the FDS. This leads to two main questions, what causes the increased fatigue and why was it not adjusted for? The EMG gap results while performing the task suggested that at short cycle times, there was limited time for the muscle to shut off. This could be the source of the increased fatigue. The participants did not adjust the load to account for the increased fatigue, and therefore, presumably did not detect it. This could be due to either the magnitude not being sufficiently large enough to have a significant effect or the increased number of rest pauses decreasing the perception of fatigue. The addition of small pauses has been shown to increase the endurance time in submaximal contractions (Bystrom et al., 1991) and decrease discomfort (Sundelin, 1993). This may suggest that adding more frequent pauses gives the perception of greater comfort despite increased fatigue. This could limit workers ability to guard against overload.

*Conclusions*

This thesis gives psychophysically developed guidelines for a workplace specific task requiring response to an externally generated force typical of powered hand tools. It is concluded that:

1. Duty cycle is an important factor in psychophysical adjustment studies of highly repetitive upper limb tasks and needs to be included to generalize results,
2. Participants appear to choose the load based on time weighted hand grip force or muscle activity,
3. Participants are able to estimate the load being adjusted according to Steven's Law in such a way that they under estimate low loads and over estimate high loads,
4. The PDAT didn't appear to be based on muscle fatigue, which may limit its use in preventing muscle pain
5. Duty cycle of muscle activity is longer than that implied by the task
6. A task duty cycle of 83% with the cycle times used may lead to static muscle loads of greater than 1% MVC.
7. Based on psychophysical data collection methods, for the monotask of highly repetitive in-line screwrunning, it is recommended that the tool torque not exceed 1.06 N.m with 25% duty cycle or 0.79 N.m with a 50% duty cycle. Acceptable level of work load in highly repetitive tasks with duty cycles over 50% could be 10% MVC or lower depending on cycle time and duty cycle, consistent with European Standards recommendations.

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# Appendix A

## PARTICIPANT INSTRUCTION SHEET

**Job Instructions:**

1. Grab Handle on hearing beep.

2. Resist handle from turning in your hands

3. If necessary, adjust work load according to instructions below.

4. Release handle when workload drops off.

**Instructions for Adjusting Work Load:**

1. Imagine you:
   a) Are on piece work, getting paid for the amount of work you do
   b) Are working an 8 hour shift
   c) Must go home without any unusual discomfort in your hands, wrist or forearms

We want you to work as hard as you can without straining your hand, wrist or forearm.

2. Workload is defined as how hard the handle twists within your hand.

3. If you feel you are working too hard:
   Push the *right* (-) mouse button to *decrease* the workload

4. If you feel you can work harder:
   Push the *left* (+) mouse button to *increase* the workload

**Don't Be Afraid To Make Adjustments:** You can never make too many

**This is not a contest:** We want your judgement on how hard you can work without developing unusual discomfort in the hands wrists or forearms. Only you know how you feel.

We strongly encourage you complete all movements during the day. We depend upon you for successful results, and greatly appreciate your participation!!

# Appendix B

## PRELIMINARY QUESTIONNAIRE

## Participant Screening Questionnaire

Description of Self

6. Today's Date: Day________Month_________Year_________

7. Date of Birth: Day________Month_________Year_________

8. Gender: Female________Male_______

9. Weight: __________lbs or ________Kg

10. Height: ________ft______in or __________cm

11. Are you:
    i) a) Right-handed__________b) Left-Handed___________ c)Both______

    ii) a) Non-smoker__________ b) smoker__________

Employment History

12. Are you currently employed? Yes________ No_________

    If Yes, what do you do (job classification)?____________

    If No, a) When did you finish your most recent job?

    Month:____________ Year____________

    b) what did you do (job classification)?______________

Questions 8-14 apply to your current or most recent job.

13. How long have you worked at your present or most recent job?

    __________________Years __________________Months

14. If you have worked at your present or most recent job for one year or less, did your previous job involve similar repetitive movement of your hands and arms?

    Yes_______ No__________

15. List the main work activities you perform(ed) at your present or most recent job and the approximate percentages of time spent during an average day.

| Work Activity | % of Time |
| --- | --- |
| ______________________________ | _______________ |
| ______________________________ | _______________ |
| ______________________________ | _______________ |

16. How many hours did you work your most recent week including overtime?
_______________hours

Over the past 6 months approximately how many hours have you averaged?

Per Week __________ hours

Per Day ___________hours

17. How frequent are/were your breaks typically? Please list each break below.

| Break duration (min) | Start Time | a.m. or p.m. |
| --- | --- | --- |
| ____________________ | __________ | _______ |
| ____________________ | __________ | _______ |
| ____________________ | __________ | _______ |
| ____________________ | __________ | _______ |

18. Do/did you have another job at the same time as your present or most recent

job? _______ Yes _________No

19. In your present/most recent job did/do use any torque producing hand tools (eg.

Screwdrivers, screwrunners, drills, grinders) _______Yes _________No

If Yes: a) Were any of these hand tools powered (air or electrical)

_______Yes __________ No

b) What percentage of your work time do you use hand tools? ____%Time

Health

20. Do you have frequent:

| | | | | | |
|---|---|---|---|---|---|
| a) | Headaches | _____ | No | _____ | Yes |
| b) | Backache | _____ | No | _____ | Yes |
| c) | Generalized achiness | _____ | No | _____ | Yes |
| d) | Joint Stiffness | _____ | No | _____ | Yes |

| | | | | |
|---|---|---|---|---|
| 21. | Have you ever sought medical advice for pain in any of these parts of the body (eg. From a doctor, physiotherapist, chiropracter, etc ... ) in the past year. Please check all that apply. | a) Neck | No | Yes |
| | | b) Shoulder | No | Yes |
| | | c) Upper Arm | No | Yes |
| | | d) Elbow | No | Yes |
| | | e) Lower Arm | No | Yes |
| | | f) Wrist | No | Yes |
| | | g) Hand | No | Yes |
| | | h) Upper back | No | Yes |
| | | i) Lower back | No | Yes |

| | | | | |
|---|---|---|---|---|
| 22. | Have you ever had any medical treatment for pain in any of these parts of the body (eg. From a doctor, physiotherapist, chiropracter, etc ... ) in the past year. Please check all that apply. | a) Neck | No | Yes |
| | | b) Shoulder | No | Yes |
| | | c) Upper Arm | No | Yes |
| | | d) Elbow | No | Yes |
| | | e) Lower Arm | No | Yes |
| | | f) Wrist | No | Yes |
| | | g) Hand | No | Yes |
| | | h) Upper back | No | Yes |
| | | i) Lower back | No | Yes |

23. If you have answered Yes to any part of question 21 or 22 please provide us with the following information:

| Diagnosis | Year | Area Affected | Cause | Days Sick Leave |
|---|---|---|---|---|
| __________ | _____ | ______________ | _________ | ____________ |
| __________ | _____ | ______________ | _________ | ____________ |
| __________ | _____ | ______________ | _________ | ____________ |
| __________ | _____ | ______________ | _________ | ____________ |

24. Have you ever been diagnosed by a health care professional as suffering from any of the

of the following? If Yes please indicate when this condition was first diagnosed in the space provided.

| | | | |
|---|---|---|---|
| a) Diabetes Mellitus | NO | YES | Year 19 |
| b) Kidney Failure | NO | YES | Year 19 |
| c) Carpal Tunnel Syndrome | NO | YES | Year 19 |
| d) Thoracic Outlet Syndrome | NO | YES | Year 19 |
| e) Amyloidosis | NO | YES | Year 19 |
| f) Acromegaly | NO | YES | Year 19 |
| g) Hypothyroidism | NO | YES | Year 19 |
| h) High blood pressure | NO | YES | Year 19 |
| i) Hyperparathyroidism | NO | YES | Year 19 |

25. Have you ever broken any bones?

_________No _________ Yes

If Yes, which bone __________ and when?__________

__________ __________

26. Have you ever sought medical advice for a sprain or dislocation?

_________No _________ Yes

If Yes, which joint __________ and when?__________

__________ __________

27. Have you ever been diagnosed by your health care professional as having arthritis, rheumatism or "wear or tear"?

_________No _________ Yes

If Yes, which joint __________ and when?__________

__________ __________

28. Are you pregnant or have you been pregnant in the past 12 months?

___________No __________ Yes

Hobbies

29. Do you have have any hobbies that require use of hand tools?

___________No __________ Yes

If yes, how many hours per week on average ________________hours

# Appendix C

## SYMPTOM SURVEY

Participant:________________ Date:__________________ Day:________________

## RIGHT ARM EVALUATION — Back

Circle the appropriate numbers below for each column.

### Fingers and Thumb

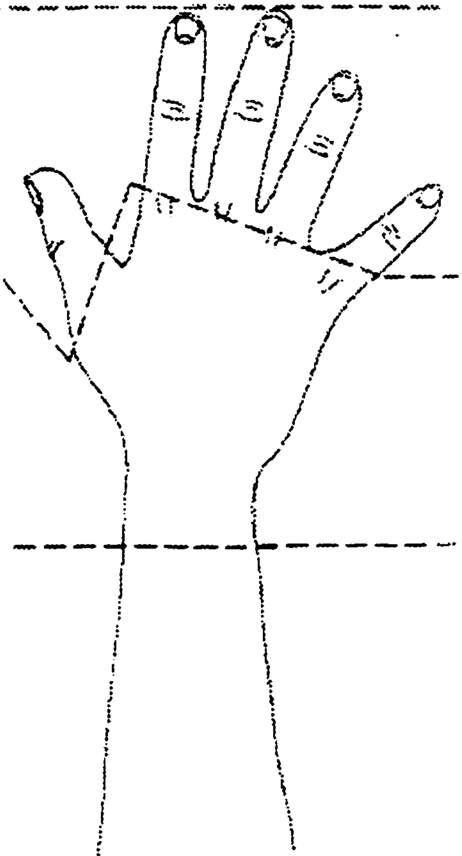
| Soreness (Pain) | Stiffness | Numbness (Tingling) |
|---|---|---|
| 0 = No soreness | 0 = No stiffness | 0 = No numbness |
| 1 = A little sore | 1 = A little stiff | 1 = A little numb |
| 2 = Somewhat sore | 2 = Somewhat stiff | 2 = Somewhat numb |
| 3 = Very sore | 3 = Very stiff | 3 = Very numb |

### Hand and Wrist

| Soreness (Pain) | Stiffness | Numbness (Tingling) |
|---|---|---|
| 0 = No soreness | 0 = No stiffness | 0 = No numbness |
| 1 = A little sore. | 1 = A little stiff | 1 = A little numb |
| 2 = Somewhat sore | 2 = Somewhat stiff | 2 = Somewhat numb |
| 3 = Very sore | 3 = Very stiff | 3 = Very numb |

### Forearm

| Soreness (Pain) | Stiffness | Numbness (Tingling) |
|---|---|---|
| 0 = No soreness | 0 = No stiffness | 0 = No numbness |
| 1 = A little sore | 1 = A little stiff | 1 = A little numb |
| 2 = Somewhat sore | 2 = Somewhat stiff | 2 = Somewhat numb |
| 3 = Very sore | 3 = Very stiff | 3 = Very numb |



Back

Now indicate the location on the drawing. Use:
So for Soreness
St for Stiffness
N for Numbness

### Overall Discomfort

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| No Discomfort | Very Little | A Little | Some Discomfort | Much | Very Much | Extreme Discomfort |

Participant:_____________ Date:_______________ Day:_______________

## RIGHT ARM EVALUATION — Front

Circle the appropriate numbers below for each column.

### Fingers and Thumb

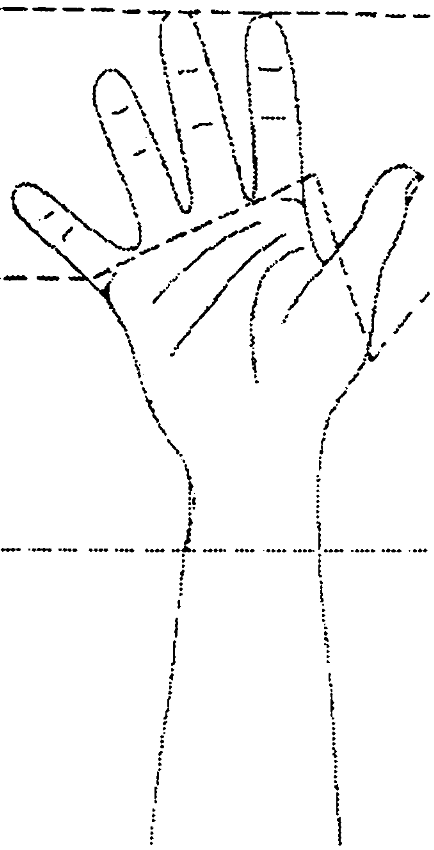
| Soreness (Pain) | Stiffness | Numbness (Tingling) |
|---|---|---|
| 0 = No soreness | 0 = No stiffness | 0 = No numbness |
| 1 = A little sore | 1 = A little stiff | 1 = A little numb |
| 2 = Somewhat sore | 2 = Somewhat stiff | 2 = Somewhat numb |
| 3 = Very sore | 3 = Very stiff | 3 = Very numb |

### Hand and Wrist

| Soreness (Pain) | Stiffness | Numbness (Tingling) |
|---|---|---|
| 0 = No soreness | 0 = No stiffness | 0 = No numbness |
| 1 = A little sore | 1 = A little stiff | 1 = A little numb |
| 2 = Somewhat sore | 2 = Somewhat stiff | 2 = Somewhat numb |
| 3 = Very sore | 3 = Very stiff | 3 = Very numb |

### Forearm

| Soreness (Pain) | Stiffness | Numbness (Tingling) |
|---|---|---|
| 0 = No soreness | 0 = No stiffness | 0 = No numbness |
| 1 = A little sore | 1 = A little stiff | 1 = A little numb |
| 2 = Somewhat sore | 2 = Somewhat stiff | 2 = Somewhat numb |
| 3 = Very sore | 3 = Very stiff | 3 = Very numb |



**Front**

Now indicate the location on the drawing. Use:
- So for Soreness
- St for Stiffness
- N for Numbness

### Overall Discomfort

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| No Discomfort | Very Little | A Little | Some Discomfort | Much | Very Much | Extreme Discomfort |