Modeling Human Perception of Postural Stress

by

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Abstract

Static posture holding (SPH) tasks refer to a variety of manual work tasks that require workers to statically maintain working postures over certain time periods. SPH tasks are common across various industrial sectors including agriculture, manufacturing, chemical and construction. Time durations of SPH tasks, i.e., posture holding times (PHT), vary greatly, ranging from a few seconds to a few tens of minutes per single execution.

Inadequately designed SPH tasks can impose large physical stresses on the human musculoskeletal system. Excessive physical stress is known to be a risk factor of work-related musculoskeletal disorders (WMSDs). It also compromises worker's job satisfaction and work productivity. Therefore, the physical stresses of SPH tasks must be accurately evaluated, and if necessary, be controlled through ergonomic interventions so as to enhance workers' occupational health and general well-being.

Discomfort-time sequences of SPH tasks were investigated in an effort to determine the existing relationship between perceived discomfort and posture holding time. Previous research studies suggested that an increase in PHT results in increased perceived discomfort and the discomfort-PHT relationship may be described using a simple mathematical function form with a small set of parameters. However, the existing studies do not seem to have fully elucidated the mathematical characteristics of the discomfort-PHT relationship. Multiple studies suggested that a simple linear time function form can represent the relationship. On the other hand, Reneman et al. (2001) reported that a negatively accelerated logarithmic

time function form depicts the relationship. This study proposed the power function as an adequate representation of the discomfort-PHT relationship of SPH tasks. This function form is capable of representing three distinct monotonically increasing time patterns, that is, linear, negatively accelerated and positively accelerated time increase patterns, depending on the choice of the exponent parameter value.

An investigation was conducted on the inter-individual variation in perceived discomfort of static posture holding. The level of discomfort experienced by a worker conducting a SPH task is assumed to be affected by among other parameters, the worker's physical and psychological characteristics. Thus, even when performing identical tasks different individuals with different physical and psychological characteristics would experience different levels of discomfort. Therefore, for a given SPH task, a group or a population of individuals gives rise to a probability distribution of perceived discomfort, which describes the inter-individual variation in discomfort perception. Such mathematical depiction of the inter-individual variation can greatly help determine the proportion of the workforce that would experience excessive (or manageable) discomfort from an SPH task and further assist in deciding the acceptability of the task from a population accommodation point of view.

Determining which SPH tasks are acceptable or unacceptable or whether current SPH tasks need to be redesigned or not requires a certain index/metric that operationalizes the construct of discomfort level of an SPH task in a manner that guides designers decision making. This research work presents a new quantitative index for characterizing discomfort levels of SPH tasks. This new index is named the population accommodation level estimate (PALE) and estimates the proportion of the target worker population that experiences less than excessive discomfort. This new index is predicated upon the use of empirical discomfort distributions. The probabilistic approach employed in this study may allow for a more direct determination of accommodation levels for various manual work tasks. Using this approach, effective intervention strategy can be made based on desired accommodation performance.

In conclusion, the main findings from this dissertation work were as follows: (1) three distinct time increase patterns, namely, the linear, negatively accelerated and positively accelerated time increase patterns, characterize discomfort-time sequences of prolonged SPH trials (2) the relationship between PHT and perceived discomfort in SPH can be adequately described by the power function form (3) different individuals can experience significantly different postural stresses even in identical manual work tasks. A consequence of the inter-individual differences in work performance is that simple descriptive statistics become limited in describing such tasks, and (4) psychophysical perception of discomfort can be expressed in probabilistic terms. Re-design recommendations may now be based on the probability distribution of discomfort ratings. Discomfort levels os SPH tasks can be quantified by a metric/index predicated on the use of empirical discomfort distributions. Such index may be useful for decision making involved in ergonomics design interventions.

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Chapter 1

Introduction

The term Musculoskeletal disorder (MSD) refers to the type of disorder charcterized by a disturbance of structure or function or both due to a genetic or embryological failure in development or as the result of exogenous factors such as certain chemical substances, injury or disease. In the workplace, these type of disorders could be the result of prolonged muscular effort, repeated actions or non-natural postures. Awkward, stressful working postures are known to be associated with increased risks of work-related musculoskeletal disorders (WMSD) (David et al., 2008, Kee and Lee, 2005). The U.S Department of Labor reported that Musculoskeletal disorders (MSDs) cases accounted for 33% of all injury and illness cases in 2011 (BLS, 2011). A total of 387,820 MSDs were recorded in 2011 yielding a rate of 39 cases per 10,000 full-time workers (BLS, 2011). According to research published by the National Institute of Occupational Safety and Health (NIOSH), there is strong evidence for a relationship between physical exertion and work-related musculoskeletal disorders (WMSD) (Benard et al., 1997,). A literature survey of published sources have shown a strong causal relationship between awkward postures and MSDs (Baron et. al., 1991, Hignett, 1996, Myers et. al., 1999, Ngan et al., 2010, Cook et al., 2001, Trinkoff et al., 2003, Janowitz et al., 2011). Thus, to reduce WMSD risks and promote workers health, postural stresses from manual work tasks must be accurately evaluated, and if necessary, be controlled through effective interventions (Putz-Anderson, 1988; Burdorf, et al., 1991; Armstrong et al., 1993, Hignett 2003, Silverstein and Clark 2004, Denis, et. al., 2008).

Two main constructs are discussed in this dissertation: (1) Static Posture Holding (SPH) tasks, which require workers to maintain fixed working postures for certain time durations and (2) Time durations of posture maintenance reffered to as, Posture Holding Time (PHT). The literature shows several studies investigating the relationship between perceived discomfort of SPH and PHT (Kirk and Sayodama 1973, Corlett and Manenica 1980, Miedema et al. 1997, Reneman et. al. 2001 and Kee 2004). In these studies, human subjects performed fixed duration SPH tasks and then subjectively rated the corresponding levels of perceived discomfort. The Borg CR-10 and the magnitude estimation method, were employed for the self-assessment of perceived discomfort.

This dissertation discusses some of the theories and studies on discomfort-time relationships for static maintenance tasks and evaluation of work-related postural stresses. We also introduces a novel probability-based method for characterizing postural stresses of manual work tasks. The first part of this work addresses the lack of agreement among researchers in the field of ergonomics concerning choice of an adequate mathematical function form for representing the discomfort-time relationship of SPH tasks. The second part of this dissertation discusses some of the limitations of the existing posture evaluation tools - inability to describe the individual differences in the perception of work-related postural stresses. Finally, this work introduces a new probability-based technique for characterizing discomfort levels of SPH tasks that is yet to be found in literature.

Corlett and Manenica (1980) postulated that the two main parameters influencing discomfort were the PHT and muscular force and that their mathematical relationship was a logarithmic one, which could be expressed in a linear form. Manenica (1986) showed that estimated discomfort for static posture maintenance tasks increased linearly as a function of time. Kee (2004) investigated the relationship between, external load, upper limb postures and PHT on perceived discomfort. Discomfort was found to increase linearly as PHT increases. On the other end of the spectrum, Reneman et al.(2001) investigated the discomfort-time relationship and contended that a negatively accelerated logarithmic time function form depicts the relationship. These and several other studies showed that there is lack of agreement in characterizing discomfort-time relationships. An additional observation was that in some of the studies the researchers aggregated discomfort-time sequences obtained from multiple SPH trials and performed statistical analyses on the combined time-series dataset or on the mean response.

1.1 Research Objectives

The review of literature on discomfort perception of manual work tasks revealed a gap in the characterization of discomfort-time relationship and a relatively simple characterization of postural stress that may be insufficient for describing which postures are generally regarded as stressful and which are not. A few studies have attempted to charaterize mathematical characteristics of the discomfort-time relationship by examining individual discomfort-time sequences of prolonged SPH trials. Consequently, the discomfort-time relationship at individual trial level is not clearly understood. Also, past research studies seemed to have investigated task parameters that affect the mean of perceived discomfort across different individuals without shedding much light on the variation between individuals. The lack of ability to describe inter-individual differences means that it is impossible to accurately estimate the percentage of workers who can perform a manual work task with minimum postural discomfort. Thus, the objectives of this study were : (1) Elucidate the nature of the relationship between perceived discomfort of SPH and PHT, with a specific focus on identifying time-increase patterns of individual-time sequences, and (2) Address some of the research gaps in the field of ergonomics with regard to SPH task evaluation, one of which is lack of ability to account for the individual differences in the perception of postural stresses. Addressing these research questions will enhance our understanding of the discomfort-time relationship in SPH. Also, addressing the lack of inter-individual variability of the existing assessment tools will be a step foward in advancing the way working postures are evaluated and subsequent intervention strategies designed.

1.2 Research and Dissertation Organization

This dissertation is comprised of six chapters, organized as follows: Chapter one is a brief introduction to the two phases of this research work and chapter six will present the conclusion, study limitations and proposed future studies. In chapter two, a review of literature is presented covering the two phases of this study. The literature review largely covers static posture holding tasks and the perception of discomfort in manual work tasks. Further review ofthe relevant literature is presented in each of the main manuscripts. Chapter three explores the relationship between perceived discomfort of static posture holding and posture holding time. Chapter four demonstrates the inter-individual variability in perceived postural stresses associated with static working postures. Chapter five introduces a novel probability-based method for quantifying discomfort levels of SPH tasks.

The limitations of the study, recommendations for future studies and conclusions are discussed in chapter six. The appendices outlines the specific experimental protocols, details on subject recruitment, summaries of collected data and other relevant information pertaining to this dissertation.

Chapter 2

A Review of the literature on discomfort perception during static posture holding tasks

2.1 Introduction

Static posture holding (SPH) tasks refer to manual work tasks that require workers to statically maintain postures for a few seconds to tens of minutes. These tasks are common across many different occupations and work groups and can be found in most industrial sectors, including the manufacturing, service, agriculture, mining and construction industries (Chung et al. 2003a, Chung et al. 2005). Time durations of SPH tasks, referred to as posture holding times (PHTs), vary greatly ranging from several seconds to a few tens of minutes depending on the muscle group involved.

SPH tasks can impose significant biomechanical and physiological stresses on the musculoskeletal system, and thereby, cause physical strains to performers - maintaining certain postures, especially with external loads, requires forceful isometric muscle contractions. When performing such SPH tasks, workers would experience rapid increase in muscle fatigue and perceived discomfort/pain. Even postures that require low-level muscular exertions may eventually lead to these undesirable consequences when sustained for long periods of time (Rohmert 1960). Static posture holding is also known to hamper blood circulation and perfusion, which may lead to ischemia at local body regions (Buckle and Devereux 2002).

In combination with biomechanical and physiological stresses, such responses may result in degenerative changes to soft tissues and contribute to chronic pain and functional impairments. Multiple research studies suggest that static work is indeed a risk factor for work-related musculoskeletal disorders (WMSDs) (Westgaard and Aaras 1984, Keyserling et al. 1988, Genaidy and Karwowski 1993, Putz-Anderson and Galinsky, 1993, Miedema et al. 1997, Hgg 1998) although the exposure-effect relationships have not been fully elucidated. All things considered, stresses/strains of SPH tasks must be accurately evaluated, and if necessary, be controlled through adequate interventions so as to enhance the occupational health, productivity and general well-being of those who perform SPH tasks.

One approach widely adopted to assess stresses/strains of manual work tasks is to use workers' self-assessment of task-related discomfort/pain; in this empirical, psychophysical approach, individuals rate the discomfort/pain associated with a task of interest while or after performing a trial of the task. A psychophysical discomfort/pain scale or rating method is utilized for subjective ratings. The use of perceived discomfort/pain in the evaluation of manual work tasks seems to be justified on the following grounds: first, perceived discomfort/pain has been shown to be correlated with physical stress and strain measures, such as muscle fatigue (Noble et al. 1981, Putz-Anderson and Galinsky 1993) and static body joint moments (Boussenna and Corlett, 1982, Jung and Choe, 1994). Discomfort and WMSDs are both related to the exposure of the musculoskeletal system to biomechanical loads (Milner 1985, Nag 1991, Putz-Anderson and Galinsky 1993, Dul et al. 1994, Miedema et al. 1997). Researchers in the field generally view discomfort/pain as a precursor of work-related injuries (Corlett and Bishop 1976, Kee and Lee 2012). Minimization of discomfort will presumably contribute to reduction of the WMSD risks (Dul et al., 1994). Second, discomfort is by definition undesirable and brings about negative consequences, such as productivity loss and low job satisfaction and, therefore, an important evaluation criterion for manual tasks, independently of the question if it can be used as an estimator of the risk of WMSDs (Dul et al. 1994, Miedema et al. 1997).

Multiple previous studies have employed the "self-assessment of perceived discomfort (pain)" approach in investigating the stresses/strains of SPH tasks. Also, multiple studies investigated perceived exertion, perceived postural stresses and perceived physical strain during static postural tasks using the psychophysical approach. These constructs seem to be similar to the notion of perceived discomfort in that they all aim to measure physical strain during work tasks. In studying these constructs, these research studies have generally looked into the three main task parameters that specify a SPH task including: posture, posture holding time and external load. Summarized reviews of some such studies are presented in the paragraphs that follow:

Olendorf and Drury (2001) evaluated postural discomfort and perceived exertion associated with 20-seconds long SPH tasks. One hundred and sixty eight postures representing the postures in the Ovako Working-posture Analysing System (OWAS) were considered. The postures comprised combinations of three arm postures, four back postures, seven leg postures and two load levels. The two force categories used- 1.1 kg and 10.1 kg- represented the lower ends of the OWAS force categories.The Borg CR10 scale and five-point body part discomfort scale were used as rating methods. Twelve male subjects participated in their study. The task required the study participants to statically hold the box for 20 seconds in a posture and self-report their perceived exertion at the end of the 20 seconds. A large poster of the Borg CR-10 scale was positioned in the line of view of the subjects. The results of their study did indicate that external load was a major driving factor in body part discomfort. Specifically, they reported that increasing the load level resulted in higher discomfort scores. Additionally, their study also did report increased discomfort and fatigue for tasks that had arm postures above the shoulder level and leg postures that required the subject to perform the static posture holding task with both knees in flexion and one knbee in flexion.

A number of studies have utilized the method of magnitude estimation to evaluate postural discomfort. In this method, the subject is presented with stimuli and asked to assign a value to the perceived magnitude of stimulus. This is analogous to the respondent setting his/her own standard for measuring their discomfort. In this regard, magnitude estimation methods are different from the Borg CR-10 method which provides the respondent with verbal anchors by which to rate their perception of discmfort. In their study, Chung et al. (2003b) examined time changes of perceived discomfort of 16 minutes long squatting tasks with four different stool heights. The subjects rated whole-body and body part discomfort levels using the free modulus magnitude estimation method every 2 minutes while holding the postures for 16 minutes. The results of their study reported a linear relationship between discomfort and posture holding time. Chung et al. (2003a) evaluated 31 leg postures based on a subjective discomfort rating. Subjects maintained each posture for 1 minute. The free modulus magnitude estimation method was used. The task involved the subjects adopting a specific posture and upon completion, reporting their numeric estimates for nine verbal descriptors representing level of discomfort. The first descriptor was 2.2 (extremely comfortable) and the last, 100.0 (extremely uncomfortable). The numeric estimates were self-selected by each subject and averaged across the subjects. The main finding of this study was that leg postures had significant effects on discomfort perception. Chung et al.

(2005) performed a series of experiments to collect perceived discomfort data associated with various postures. In their experiments, subjects maintained each posture for 1 minute. The free modulus magnitude estimation method was used.

In their study, Genaidy et al. (1995) developed a ranking system for the stressfulness of the non-neutral static postures around body joints. This was based on the ratings of perceived discomfort. The subjects rated the joint discomfort ratings following a 60- second period of static posture holding. A linear scale of 0-10 perceived discomfort ratings was used to assess the level of joint discomfort. Overall, they did report that the highest discomfort ratings were found in the shoulder joints, followed by the wrist, elbow, lower back and neck region. Kee and Karwowski (2003) developed a similar ranking system but one based on joint motions. Sitting and standing joint motions were considered in this study. Subjects rated their perceived discomfort using the magnitude estimation method. Their study showed that the discomfort ratings for neutral postures were different depending on the joint involved. In particular, hip and lower back motions were reported to exhibit higher discomfort ratings, while elbow joint motions had lower discomfort ratings.

Park et al. (2009) examined the effects of obesity on perceived postural stress associated with a 20 seconds long static box holding task. A total of 84 postures were considered in their study. The Borg CR10 scale of perceived exertion was used as an index of discomfort. The task involved statically holding a 5 kg box for 20 seconds. The study identified non-straight back, elevated arms and flexed knees as SPH task parameters that increases stress for both obese and non-obese groups. This study went further and examined the relationship between the RPE data and the four OWAS action codes. It was demonstrated in this study that the obese and non-obese groups perceived the level of postural stress (RPE) corresponding to each OWAS code differently. The study therefore raised concerns with the use of the OWAS action codes for both the obese and non-obese workers. Their findings concluded that OWAS action codes could not be effectively used to quantify WMSD risks for obese workers.

In investigating the maximum holding times (MHTs) of SPH tasks, Reneman et al. (2001) considered two static postural tasks: forward bending and overhead work. This study examined the relationship between perceived exertion and maximum holding times. Subjects performed maximal capacity static holding task and reported their perceived discomfort every 30 seconds until task termination. The Borg CR-10 scale was used to evaluate postural discomfort. They reported a logarithmic relationship between average CR-10 scores and posture holding times.

Jung et al. (2010) examined a 15- minute long static-sustaining task. Subjective discomfort, heart rate and EMG median frequency were measured every 3 minutes. A total of 13 postures were considered. The subjects were required to self-report their subjective rating of discomfort every 3 minutes while maintaining a randomly selected lower limb posture. Borg's RPE (range: 6-20) and Borg's CR-10 (range: 0-10), were used as subjective measures for evaluating discomfort. They reported that discomfort was significantly affected by posture. Specifically, Knee flexion postures and kneeling postures had the highest discomfort scores over time.

The study conducted by Manenica (1986) examined maximum duration posture holding tasks for seven different postures. The goal was to find a technique for quick and reliable postural load assessment. Fifteen female subjects participated in a tapping task in each of the seven differrent postures. The subjects reported their perceived discomfort every 30 seconds until each posture was terminated. At the termination of each postural task, the subject reported the body part with the highest discomfort. Discomfort perception was assessed on the 20-point RPE scale proposed by Borg (1973). Based on the results of this study, discomfort was found to increase linearly as a function of time. Overall, the study concluded that subjective ratings could be reliable in measuring postural load discomfort.

Eperiments were conducted by Kirk and Sadoyama (1973) to investigate the discomfort-time relationship during SPH tasks. Discomfort was measured for a static pull task and a two-handed static torque production task. Eighteen subjects took part in this study. Six load levels were used and the task involved the subjects holding the load using a handle in the two modes for maximum duration, while reporting their discomfort every 30 seconds. They used a five-point rating scale to report their perceived exertion. A rating of 1 was defined as just noticeable discomfort while a rating of 5 was defined as extremely uncomfortable. The relationship between holding time and percentage of maximum holding force was found to be linear.

Kee (2004) empirically investigated the effects of external load, upper limb postures and PHT on perceived discomfort. The subjects held given postures for 60s and rated their subjective discomfort scores at 5, 20, 40 and 60 seconds using the free modulus method of magnitude estimation. The effects of external load and holding time were much larger than those of upper limb postures. Mean discomfort was found to increase linearly as posture holding time increases. A literature was conducted by Kee and Lee (2001) to investigate the relationship between discomfort and several other measures for postural assessment including posture holding time, maximum holding time, torque and joints and lifting index.

Their survey of literature reported a number of findings including; a linear relationship between discomfort and posture holding time and an inverse relationship between whole body discomfort and maximum holding time.

As has been stated earlier, all the preceding studies used either the Borg scales or the magnitude estimation methods to assess perceived discomfort of SPH tasks. The magnitude estimation method and the Borg CR-10 scale both yield ratio-scale measurements, and therefore, support a variety of statistical analyses.

2.2 Posture Evaluation Methods

Researchers in the field of ergonomics have extensively studied the evaluation of posture and static loads (Corlet et. al., 1986). Postural evaluation of manual work tasks is achieved by use of : (1) direct observation methods, (2) indirect observation methods, and (3) subjective methods. Some of the direct observation methods utilized by analysts include: The Ovako Working Posture Analysing System (OWAS), Rapid Upper Limb Assessment (RULA), and Rapid Entire Body Assessment (REBA). Direct observation methods include instrumentation techniques, such as: Goniometers, Motion capture (Vicon) and Electromyography (EMG). Subjective evaluation of postures is done based on the subjective strain experienced by individuals in various postural load tasks. Various subjective methods are used in evaluation of static work tasks inlcuding: Borg's CR-10 scale and the magnitude estimation ratio-scale.

2.2.1 Ovako Working Posture Analysing System(OWAS)

This study used various working postures based on the OWAS posture classification system. OWAS is a work sampling-based method for identifying poor working postures (Karhu et. al., 1977). The system predefines four postures of the back, three of the upper limb and seven for the lower limbs. These three body parts provide a total of 84 whole body posture categories. The OWAS technique also employs three levels of hand-held load (three categories): handload<10kg, 10 - 20kg, handload>20kg. OWAS therefore utilizes a total of 252 posture-load combinations to represent various industrial working postures. These 252 posture -load combinations are then classified into predetermined stress levels and expressed in terms of a 4-level OWAS action codes. The four action codes represent different stress levels indicating varying needs for ergonomic interventions. The four action levels are defined as follows:

Action level 1: no corrective measures (normal postures).

Action level 2: corrective measures in the near future (stressful postures).

Action level 3: corrective measures as soon as possible (stressfull postures).

Action level 4: corrective measures immidiately (awkward postures).

2.2.2 Rapid Upper Limb Assessment(RULA)

The RULA technique was developed by McAtamney and Corlett (1993) as an assessment to disorders of the upper limb. The technique observes postures of the upper limbs, back and legs classifies them into four action levels. The RULA technique uses predefined body postures and three scoring tables to obtain a posture score representing stress level. The system divides the body parts into two posture scores: A (trunk, neck and legs) and B (upper arm, lower arm and wrists). These scores are obtained from scoring tables and added together to determine a grand score. The grand scores are divided into four action levels defined as follows:

Table 2.1: Action levels for RULA

Action level	**RULA score**	**Recommended action**
1	1-2	Posture acceptable
2	3-4	Changes may be required
3	5-6	Investigation and changes needed soon
4	7	Changes required immidiately

The RULA technique has been validated as an assessment tool for upper limb musculoskeletal risks by McAtamney and Corlett (1993). The scoring system provides an indication of the level of stress/discomfort by individual body parts and serves as a basis for ergonomic interventions.

2.2.3 Rapid Entire Body Assessment(REBA)

The REBA technique was developed by Hignett and McAtamney (2000) to address working postures in the healthcare industry. The tool addresses additional loading musculoskeletal risks that are mostly encountered by healthcare practioners. REBA is based on the same format as OWAS and RULA in that the body is divided into groups. The first group comprises of the trunk, neck and leg postures, while the second group comprises of the upper arm, lower arm and wrist postures. Posture scores are assigned to each body part. Two scoring tables allow postures and loads to be combined to give a score for each group.

REBA provides five action codes representing stress levels. The five action levels are defined as follows:

Table 2.2: Action levels for REBA

Action level	**REBA score**	**Risk level**	**Recommended action**
0	1	Negligible	None necessary
1	2-3	Low	May be necessary
2	4-7	Medium	Necessary
3	8-10	High	Necessary soon
4	11-15	Very High	Necessary NOW

2.2.4 The Borg (CR-10) scale

The Borg scale (1982) is an overall intergrated configuration of the signals, perceptions, and experiences of the body while enduring physical strain. It is essentially a category-ratio scale that relates physical workload and subjectively experienced strain. The Borg's CR-10 (Figure 2.1) is therefore capable of highlighting inter-individual differences in the perception of experienced strain (Noble and Robertson, 1996). The scale has ratings from 0 to 10 with verbal explanations of each rating. A detailed definItion of the ratings and the comprable verbal anchors are explained to the subject before administering the test. The verbal anchors provide the test subject with a simpler way of interpretaing the subjective ratings. A large print of the scale is then placed in the line of sight of the test subject at the begining of the task and he or she is asked to rate the percived exertion immidiately the task is completed.

0 -	Nothing at all
0.5 -	Extremely weak (just noticeable)
1 -	Very weak
2 -	Weak (light)
3 -	Moderate
4 -	Somewhat strong
5 -	Strong (heavy)
6 -	-
7 -	Very strong
8 -	-
9 -	-
10 -	Extremely strong (almost max)
.	Maximal

Figure 2.1: Borg's new category-ratio (CR-10) scale. Reprinted from Borg 1982.

Chapter 3

The relationship between perceived discomfort of static posture holding and posture holding time

3.1 Introduction

Static posture holding (SPH) tasks, which require workers to maintain fixed working postures for certain time durations, are common across occupations and can be found in most industrial sectors, including the manufacturing, agriculture and service industries (Miedema et al. 1997, Olendorf and Drury 2001, Chung et al. 2003a, Chung et al. 2005). Time durations of posture maintenance, often referred to as posture holding times (PHTs), vary greatly among SPH tasks. Some SPH tasks may last up to a few tens of minutes.

As in the cases of other manual work tasks, SPH tasks can impose large biomechanical and physiological stresses on the musculoskeletal system and cause significant discomfort to workers if designed without consideration of human characteristics, capabilities and limitations. It is important to control such discomfort via ergonomic design as it can seriously compromise workers productivity and job satisfaction level (Corlett and Bishop 1976). Also, controlling discomfort may contribute towards the reduction of work-related musculoskeletal disorders (WMSDs) risks (Dul et al. 1994). Past research studies suggested association between discomfort and WMSDs on the grounds that they are both related to exposure to biomechanical load on the musculoskeletal system (Milner 1985, Nag 1991, Putz-Anderson and Galinsky 1993, Dul et al. 1994, Miedema et al. 1997, Fathallah et. al., 2004, Meyers, et. al., 1997, Kemmlert and Kilbom 1987). Some researchers indeed view work-related discomfort/pain as a precursor of WMSDs (Corlett and Bishop 1976, Kee and Lee 2012).

Three task parameters, that is, posture, external loads and PHT, seem to specify the level of discomfort that a worker experiences from conducting an SPH task; of course, the workers personal physical and psychological characteristics also contribute as was demonstrated in Park et al. (2009). Multiple studies investigated how the task parameters affect discomfort levels of SPH tasks as its understanding is crucial for controlling discomfort through ergonomic design/redesign. Genaidy et al. (1995), Kee and Karwowski (2001), Olendorf and Drury (2001), Chung et al. (2002, 2005) and Park et al. (2009) empirically examined the effects of posture and external loads. In these studies, human subjects performed fixed duration ($usually \leq 1 minute$) SPH trials that vary in posture and external loads, and then, subjectively rated the corresponding levels of perceived discomfort. Psychophysical discomfort scales and rating methods, such as the Borg CR-10 scale and the magnitude estimation method, were employed for the self-assessment of perceived discomfort. The Borg CR-10 scale and the magnitude estimation method yield ratio-scale measurements, and therefore, support a variety of statistical analyses (Kee 2004).

Several studies investigated the relationship between PHT and perceived discomfort in SPH (Kirk and Sadoyama 1973, Corlett and Manenica 1980, Manenica 1986, Miedema et al. 1997, Reneman et al. 2001, Chung et al. 2003b and Kee 2004). These studies adopted an approach of empirically examining time changes of perceived discomfort during prolonged (often maximum duration) SPH trials - in these studies, subjects reported perceived discomfort ratings at predetermined time intervals while performing prolonged SPH trials. The resulting discomfort-time sequences were analysed to understand the discomfort-PHT relationship (hereafter, simply "the discomfort-time relationship" for the sake of brevity).

The existing studies on the discomfort-PHT relationship generally suggest that: for static maintenance of any working posture, 1) an increase in PHT results in increased perceived discomfort and 2) the discomfort-PHT relationship may be described using a simple mathematical function form with a small set of parameters. However, the existing studies do not seem to have fully elucidated mathematical characteristics of the discomfort-PHT relationship. First of all, they are not in agreement as to the choice of an adequate mathematical function form for representing the relationship. Multiple studies suggested that a simple linear time function form, that is, $Discomfort = C_1 PHT + C_2$, can represent the relationship (Corlett and Manenica 1980, Manenica 1986, Dul et al. 1994, Meijst et al. 1995, Kee 2004). On the other hand, Reneman et al. (2001) reported that a negatively accelerating logarithmic time function form expressed as $Discomfort = C_1 lnPHT + C_2$ depict the relationship.

Aside from the lack of agreement, the existing studies also have a limitation that in characterizing the discomfort-PHT relationship, they aggregated discomfort-time sequences obtained from multiple SPH task trials and performed statistical analyses on the combined time-series dataset or the mean response. Therefore, the relationships identified do not necessarily represent what is actually observed in each individual discomfort-time sequences but rather some average trend at group level. It appears that very few studies have attempted to characterize mathematical characteristics of the discomfort-PHT relationship by examining individual discomfort-time sequences of SPH task trials the authors are not aware of any such studies. Consequently, the discomfort-PHT relationship at the level of actual individual observations is not well understood. Related to this lack of understanding, some research questions arise:

- What time increase patterns do individual discomfort-time sequences of prolonged SPH task trials exhibit? Does a single pattern (e.g., linear increase over time) universally describe various discomfort-time sequences or do multiple distinct patterns coexist?
- Is there a simple mathematical function form with a small set of parameters that can robustly represent various individual discomfort-time profiles of SPH task trials?

Addressing the above research questions will enhance our understanding of the discomfort-PHT relationship in SPH, and thereby, may further contribute to the ergonomic design of SPH tasks. Especially, identifying an adequate parametric function form has practical applications: it provides a basis for converting discrete discomfort-time sequences of prolonged SPH trials into continuous time functions. Also, it allows representing discomfort-time profiles parsimoniously using a small set of parameters. These applications in turn will facilitate various quantitative analyses and modelling based on discomfort-time sequences data empirically obtained from SPH trials. Therefore, the objective of this study was to empirically address the two research questions posed above.

Fifteen males and fifteen females participated in the experiment. Each participant performed maximum duration SPH task trials employing 12 different working postures. A discomfort-time sequence describing time change of perceived discomfort was obtained from each SPH task trial. The discomfort-time sequences were visually examined to characterize the discomfort-PHT relationship at the individual task trial level. Also, curve-fitting analyses were conducted on each discomfort-time sequence using three simple mathematical function forms: the linear($Discomfort = C_1PHT + C_2$), logarithmic($Discomfort = C_1lnPHT + C_2$) and power function forms ($Discomfort = C_1PHT^{C_2} + C_3$). This was for determining an adequate mathematical function form for representing individual discomfort-time profiles of SPH task trials. The linear and logarithmic function forms have been suggested as possible models of the discomfort-PHT relationship (Corlett and Manenica 1980, Manenica 1986, Dul et al. 1994, Meijst et al. 1995, Reneman et al. 2001, Kee 2004). The power function form was considered as it is capable of representing three distinct monotonically increasing time patterns, that is, linear, negatively accelerating and positively accelerating time increase patterns, depending on the choice of the exponent parameter value.

3.2 Methods

3.2.1 Participants

Fifteen males and fifteen females participated in this study as paid volunteers. The age, height, body mass and body mass index (BMI) data of the two participant groups are summarised in Table 3.1. The participants were free of obvious neurological and musculoskeletal disorders. Prior to participation, the participants had an introductory session during which the nature and protocol of the study were explained and all questions were answered. The participants also familiarized themselves with the use of the Borg CR-10 scale during the introductory session. Each participant signed a written informed consent before participation. The Auburn University Institutional Review Board approved the experimental protocol.

Table 3.1: Summary of the age, height, body mass and the BMI data for the two participant groups.

Dimensions	Mean and Standard Dev. Male	Female
Age(years)	28.80 ± 8.46	29.40 ± 6.60
Height(years)	180.89 ± 7.13	162.76 ± 5.37
Body Mass(kg)	86.20 ±11.70	63.26 ± 9.30
BMI(kg/m^2)	26.39 ± 3.48	23.86 ± 3.26

3.2.2 Experiment

The participants performed maximum duration SPH trials employing 12 different static postures. Each trial involved statically holding a box until the point of maximal discomfort, which corresponds to the rating of 10 on the Borg CR-10 scale. The "box" was a generic representation of hand-held loads handled during manual work tasks. It weighed 2 kg, had dimensions of $180mm \times 180mm \times 200mm$ and had no handles. The 12 postures are described in Figure 3.1.; they were selected to represent various possible ways of static box holding and include both standing and seated postures. An analysis based on the Ovako Working Posture Analysing System (OWAS) (Karhu et al., 1977) indicated that they cover all four postural stress levels of the OWAS: Action Codes 1 4. Each participant conducted a single trial for each of the 12 postures. Thus, a total of 360 trials were performed in this study: 360 trials $= 12 postures \times 30$ participants.

Each SPH trial was preceded by a preparatory "posture marking" session - in the posture marking session, the participant posed to correctly attain the posture specified for the ensuing SPH trial. Then, while the participant was in the posture, the experimenter adjusted two fixtures (moveable vertical posts with adjustable arms) to mark the positions of the following

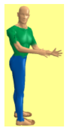
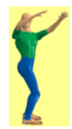
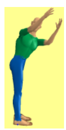
Posture Number	Posture	Description	Posture Number	Posture	Description
1		Straight back. Both arms above the shoulders. Elbow joints fully extended. Standing on both feet with the legs straight.	**7**		Back bent forward by approximately 25°, no twisting. Both arms out and below the shoulders. Elbow joints fully extended. Standing on both legs with the knees flexed. The included angle between the upper and lower legs is approximately 150°.
2		Back twisted by approximately 25°, no bending. Both arms out and below the shoulders. Elbow joints fully extended. Standing on both feet with the legs straight.	**8**		Back twisted by approximately 25°, no bending. Both arms out and below the shoulders. Elbow joints fully extended. Standing on both legs with the knees flexed. The included angle between the upper and lower legs is approximately 150°.
3		Straight back. Both arms out and below the shoulders. Elbow joints fully extended. Sitting down on a stool with the legs hanging free.	**9**		Back bent forward by approximately 25°, no twisting. Both arms above the shoulders. Elbow joints fully extended. Sitting down on a stool with the legs hanging free.
4		Back bent forward by approximately 25°, no twisting. Both arms out and below the shoulders. Elbow joints fully extended. Standing on both feet with the legs straight.	**10**		Back twisted by approximately 25°, no bending. Both arms above the shoulders. Elbow joints fully extended. Standing on both legs with the knees flexed. The included angle between the upper and lower legs is approximately 150°.
5		Back bent forward by approximately 25° and twisted by 25°. Both arms above the shoulders. Elbow joints fully extended. Standing on both feet with the legs straight.	**11**		Back bent forward by approximately 25° and twisted by 25°. Both arms above the shoulders. Elbow joints fully extended. Standing on both legs with the knees flexed. The included angle between the upper and lower legs is approximately 150°.
6		Back bent forward by approximately 25°, no twisting. Both arms out and below the shoulders. Elbow joints fully extended. Sitting down on a stool with the legs hanging free. No backrest is provided.	**12**		Back bent forward by approximately 25° and twisted by 25°. Both arms above the shoulders. Elbow joints fully extended. Sitting down on a stool with the legs hanging free. No backrest is provided.

Figure 3.1: The 12 box holding postures

body landmarks: the right shoulder acromion process, the centre of the back of the left hand and the right kneecap (patella) centre (Figure3.2). The adjustable arms of the vertical posts slide vertically along the post, rotate around the post and slide back and forth along their long axes; thus, their tips are able to mark different positions in the 3-D space. In addition to the three body landmarks, the feet positions on the floor were also marked, with chalk (Figure 3.2). The markings were for assisting the participant to correctly adopt and maintain the specified box holding posture during the ensuing SPH trial. At the completion of the posture marking, the participant was given a rest period so that he/she could fully recover from possible fatigue due to the posture marking.

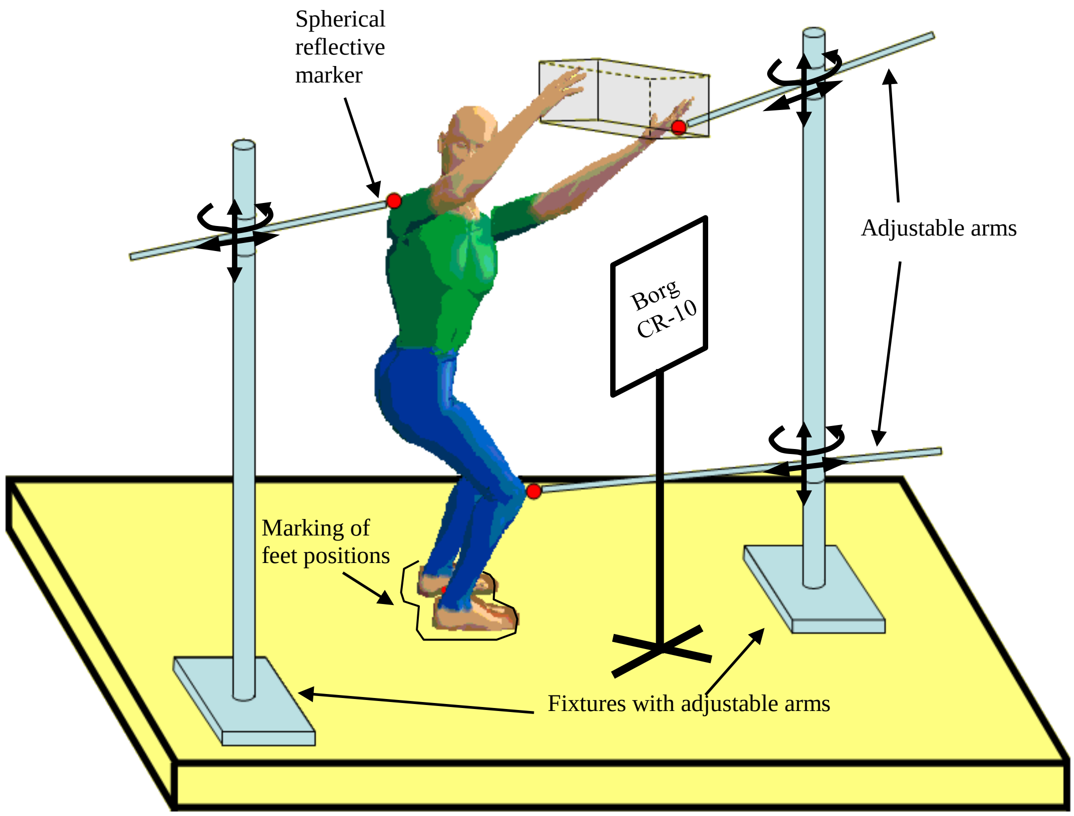


Figure 3.2: The experimental set-up

After the posture marking session, the SPH trial proceeded as follows: the participant quickly attained the specified posture using the previously obtained posture markings as visual references. Then, the experimenter brought the box to the participant. The participant grabbed the box without actually bearing the box weight while the experimenter holding the box. A camcorder started audio and video-recording the participant. At a beeping sound signalling the onset of the SPH task trial (time zero), the experimenter let go of the box and the participant started bearing the load. The participant maintained the posture until the point of maximum discomfort. While maintaining the posture, the participant shouted the numbers in the Borg CR-10 scale, that is, 0, 0.5, 1, 2, , 10, at the time instants when he/she started perceiving the corresponding discomfort levels. In other words, the time instants were self-determined. This is different from the method of verbally reporting discomfort levels at predetermined time intervals, which was employed by some previous studies, such as Reneman et al. (2001), Chung et al. (2003b) and Kee (2004). Despite the difference, however, both methods are predicated upon the assumption that humans can accurately report discomfort level perceived at a certain time point during prolonged exertion. Putz-Anderson and Galinksy (1993) employed a method similar to ours in which subjects terminated a simulated work task when the perceived discomfort reached a pre-specified level on the Borg CR-10 scale.

During each SPH trial, the participant was shielded from time cues. A large print of the Borg CR-10 scale was placed to be seen by the participant; it intended to help the participant self-select the time instants of the discomfort levels . In each SPH trial, the first number shouted could be any of the eleven numbers (0, 0.5, 1, 2, , 10) on the Borg CR-10 scale; after that, the number increased monotonically. Again, the participant finished the SPH trial at the point of maximum discomfort (the rating of 10 on the Borg CR-10 scale). In each SPH trial, the occurrence times of different discomfort levels were determined from the camcorder recordings; the sequence of the discomfort rating-occurrence time pairs represented the discomfort-time profile of the trial.

During each SPH trial, the tips of the adjustable arms helped the participant maintain the correct posture. When any of the body landmarks moved away from its correct position indicated by an adjustable arms tip, the experimenter instructed the participant to rectify the posture.

Each participant was allowed to have a sufficient rest time between consecutive SPH trials to eliminate any cumulative fatigue effects; the next trial was not started until the participant was fully recovered from the preceding trial. The order of the presentation of the 12 postures was randomised for each participant. Each participant performed the 12 SPH task trials over 4 sessions of three postures.

3.2.3 Data Analyses

The discomfort-time sequences obtained from the 360 SPH trials were individually displayed in lined scatter plots. Then, each lined scatter plot was visually examined so as to characterize the discomfort-time relationship at individual SPH trial level. Curve-fitting analyses were conducted to further ascertain the nature of the discomfort-time relationship. Three simple mathematical function forms were fitted to each discomfort-time sequence: the linear ($Discomfort = C_1PHT + C_2$), logarithmic ($Discomfort = C_1lnPHT + C_2$) and power ($Discomfort = C_1PHT^{C_2} + C_3$) function forms. Note that all three function forms have an additive constant term. The least square approach was adopted for the curve fitting analyses. Microsoft Excels built-in curve-fitting functions and Solver were utilized.

Two error measures, time-averaged absolute deviation (TAD) and maximum absolute deviation (MAD), were employed to quantify the fitting performance of the three function forms. For a given discomfort-time sequence, $(t_i,\ D_i\ ),i = 1, ..., N$, where i is the index of numbers shouted by the performer, N is the total number of numbers shouted, and t_i and D_i represent the time and discomfort level (on the Borg CR-10 scale) of the i^{th} number shouted, respectively, the TAD value of a best fit function $f(t)$ is computed as follows:

$$TAD = \frac{\sum_{i=1}^{N} |(D_i - ft_i)|}{N} \tag{3.1}$$

The MAD value is computed by:

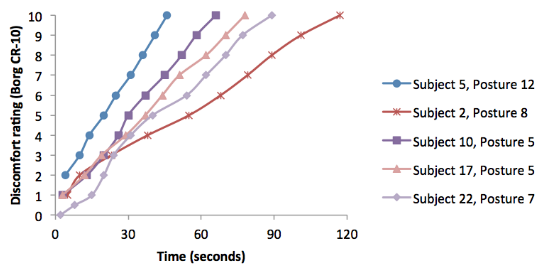
$$MAD = max(|D_1 - f(t_1)|, ..., |D_N - f(t_N)|) \tag{3.2}$$

A two-way analysis of variance (ANOVA) was conducted to test the effects of function form, posture and function formposture interaction on each error measure. The function form factor had three levels: logarithmic, linear and power. The posture factor had 12 levels as described in Table 2. The main "null" hypothesis was that the three function forms do not significantly differ from one another in the mean values of TAD and MAD, irrespective of posture. Post-hoc Tukey analyses were performed to compare the fitting performance of the three function forms for each of the 12 postures. The α-level was set to be 0.05 for all the statistical analyses. The Minitab software program was used to perform all the statistical analyses (Minitab® 16 Statistical Software).

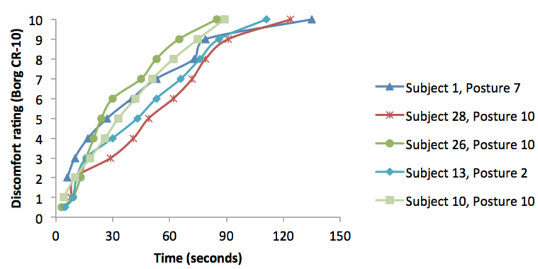
In addition to comparing the fitting performance of the three function forms via ANOVAs and post-hoc analyses, each function form was evaluated on an absolute basis in terms of the proportion of the discomfort-time sequences that it can adequately fit. The adequateness criterion employed was as follows: a function form is considered to adequately represent a discomfort-time sequence if TAD<0.5 and MAD<1; otherwise, it is considered inadequate. Although rather arbitrary, this criterion of TAD<0.5 and MAD<1 is thought to be a strict one considering the 0-10 range of the Borg CR-10 scale.

3.3 Results

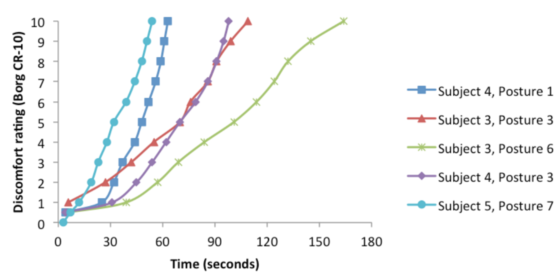
Visual examinations of the lined scatter plots individually displaying the 360 discomfort-time sequences indicated that three distinct time increase patterns describe most of the discomfort-time sequences. The three distinct patterns were: the negatively accelerated, linear and positively accelerated time patterns. Figures 3.3a-c provide some example discomfort-time sequences for each of the three time increase patterns.



(a)



(b)



(c)

Figure 3.3: Some discomfort-time sequences exhibiting each of the three distinct time increase patterns: (a) linear, (b) negatively accelerating and (c) positively accelerating. For each time increase pattern, five randomly selected discomfort-time sequences are presented

The ANOVAs results are summarized in Table 3.2. The function form, posture and function form X posture interaction effects were found to be significant for TAD. For MAD, the function form and posture effects were found to be significant; the function form X posture interaction effect was approaching statistical significance (p=0.066). The significance level was set at $\alpha = 0.5$.

Table 3.2: The ANOVA results for the Time-Averaged Deviations(TAD) and Maximum Absolute Deviation(MAD)

	TAD			MAD		
	DF	SS	P	DF	SS	P
Function form	2.00	134.56	0	2.00	544.7	0
Posture	11.00	10.46	0	11.00	12.00	0.001
Function form x Posture	22.00	13.86	0	22.00	8.20	0.066
Error	1044	71.00	0	1044	259	0
Total	1079	230.31	0	1079	824	0

The multiple bar graph in Figure 3.4a provide the mean TAD values of the three function forms for each of the twelve postures. Post-hoc Tukey tests indicated that for each posture, the mean TAD value of the power function form was significantly smaller than those of the linear and logarithmic functions forms. A similar multiple bar graph for MAD is provided in Figure 3.4b. Again, for each posture, the mean MAD value of the power function form was found to be significantly smaller than those of the others.

The proportions of the discomfort-time sequences that the three functions form adequately represent (TAD<0.5 and MAD<1) were as follows: 78.8% (284 out of 360) for linear, 5.8% (21 out of 360) for logarithmic and 96.4% (347 out of 360) for power.Figure 3.5 provides a graphical summary of the fitting performance. Additionally, Figure 3.6a-3.6c provide some examples of discomfort-time sequences adequately represented by the three function forms.

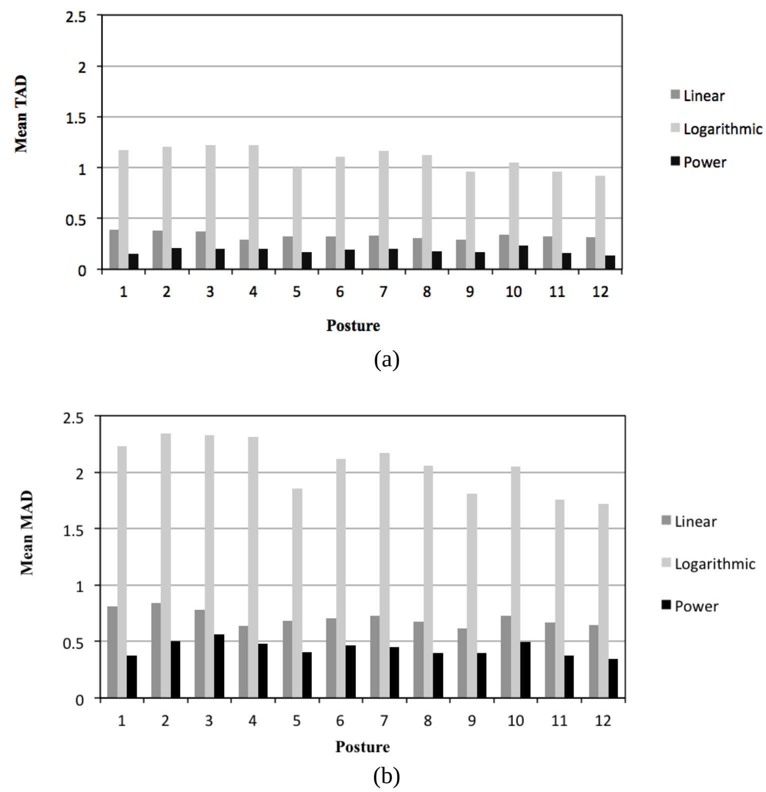


Figure 3.4: The mean TAD and MAD values of the three function forms computed for each of the twelve postures: (a) TAD and (b) MAD

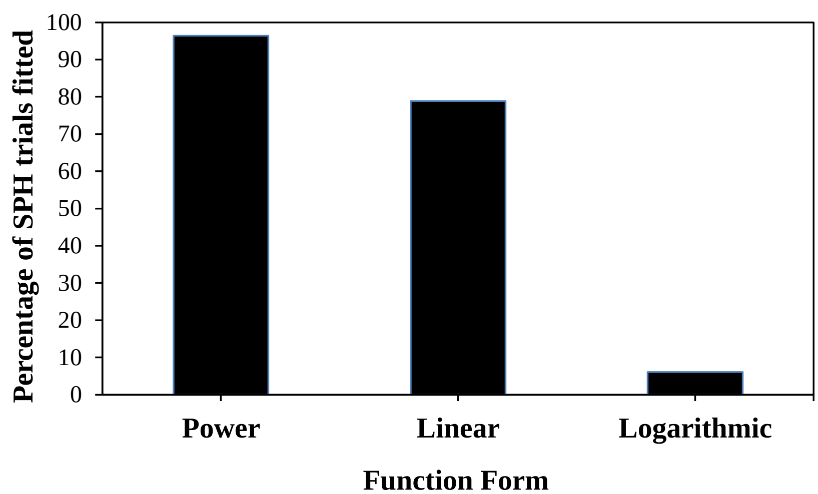
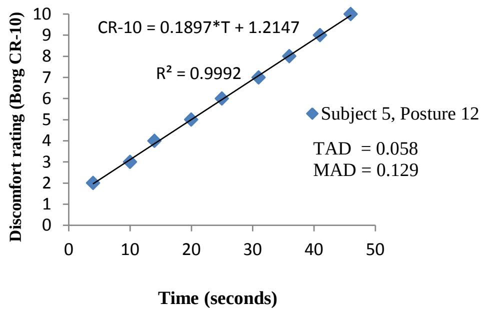
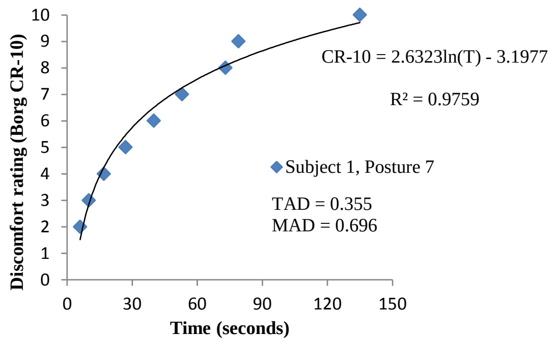


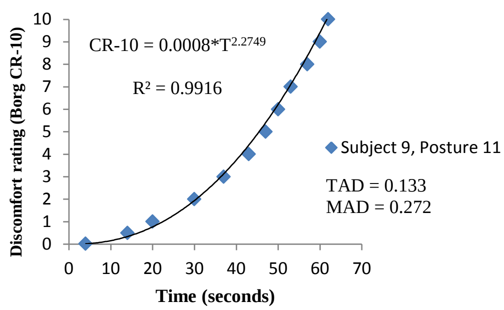
Figure 3.5: Summary of the fitting performance measure for the three function forms.



(a)



(b)



(c)

Figure 3.6: Examples of adequate functional representation of discomfort-time sequence data (TAD<0.5 and MAD<1): (a) linear, (b) logarithmic and (c) power.

For the 347 discomfort-time sequences adequately represented as power functions, the distributions of the three parameters of the power function form, that is, C_1, C_2, and C_3 in $(Discomfort = C_1 PHT^{C_2} + C_3)$, are graphically illustrated in Figures 3.6a-3.6c.

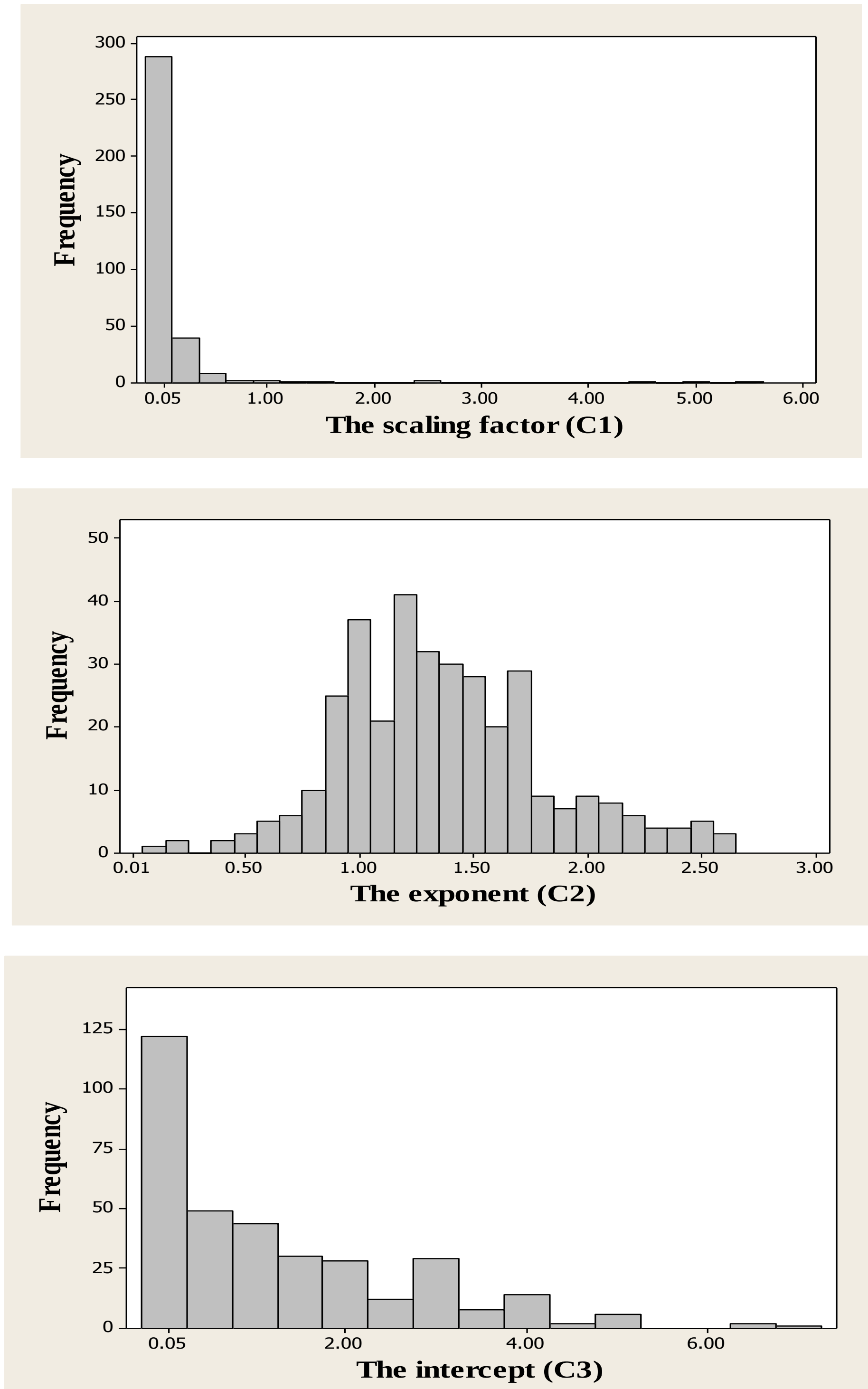


Figure 3.7: The distributions of the power function parameters for the 347 discomfort-time sequences represented as power functions with TAD<0.5 and MAD<1: (a) the scaling factor C1, (b) the exponent C2 and (c) the intercept C3 .

3.4 Discussion

The objective of the current study was to elucidate the nature of the relationship between perceived discomfort of SPH and PHT. To accomplish the research goal, this study examined a total of 360 discomfort-time sequences empirically obtained from maximum duration SPH trials. The focus was specifically on addressing the following research questions:

- What time increase patterns do individual discomfort-time sequences exhibit? Does a single pattern, for example, linear increase over time, prevail across different discomfort-time sequences or do multiple distinct patterns coexist?
- Is there a simple mathematical function form that can adequately represent various discomfort-time sequences? In other words, what is the mathematical representation of the relationship between PHT and perceived discomfort?

Visual examinations of lined scatter plots that depict the 360 discomfort-time sequences addressed the first question (Figure 3.3). The discomfort-time sequences did not exhibit a single universal pattern of time increase; but, instead, three different patterns appeared to co-exist. They were: the linear, negatively accelerating and positively accelerating time increase patterns (Figure 3.3). The three patterns seemed to characterize most of the observed discomfort-time sequences. The co-existence of multiple distinct time increase patterns was further supported by the ANOVAs (Table 3.2) and the comparisons of the three function forms in the mean TAD and MAD values (Figure 3.4). Across the 12 postures considered in this study, the power function form, which can represent all of the three time increase patterns mentioned above, resulted in significantly smaller mean TAD and MAD values than the linear and logarithmic function forms, each of which is capable of representing only one type of time increase pattern. The linear function form represents only the linear time increase pattern; the logarithmic function form, only the negatively accelerated time increase pattern.

As for the second research question, the power function form was found to be able to fit most of the individual discomfort-time sequences examined in this study with small fitting errors - it was able to fit 347 out of the 360 (96.4%) discomfort-time sequences satisfying the adequateness criterion of TAD<0.5 and MAD<1. Once again, although rather arbitrary, the criterion of TAD<0.5 and MAD<1 can be considered as a strict one considering the 0-10 range of the Borg CR-10 scale. When evaluated with the same adequateness criterion, the logarithmic function form was found to adequately fit only 21 out of 360 (5.8%). The linear function form was found to perform significantly better than the logarithmic adequately fitting 284 out of the 360 (78.8%) discomfort-time sequences; however, the power function form still outperformed the linear by a large margin (17.6%=96.4%-78.8%). Based on these results and also the co-existence of the three distinct time increase patterns visually observed (Figure 3.3), this study reccomends that the power function form, $Discomfort = C_1 PHT^{C_2} + C_3$, be used to mathematically describe the relationship between perceived discomfort of SPH and PHT.

The power function form $Discomfort = C_1 PHT^{C_2} + C_3$, provides a mathematical basis for converting empirically obatined discomfort-time sequences of SPH trials to continuous time functions. This model realizes parsimony of representation as it uses only three parameters. The three parameters quantitatively characterize different aspects of a discomfort-time profile. The parameter C_1, is a scaling factor. The exponent C_2 determines the appearance of a profile's time increase pattern: the negatively accelerated ($0<C_2<1$), positively accelerated ($C_2>1$) or linear ($C_2=1$) time increase patterns. C_1 and C_2 together determine the growth rate of a discomfort-time profile. The parameter C_3 is the intercept and represents the starting point of perceived discomfort during an SPH trial, that is, the level of discomfort perceived immediately after the onset of an SPH trial. The three parameters can be used in combination to compute other meaningful quantities. For example, the PHT to reach a particular discomfort level D' can be computed by:

$$PHT_{\mathrm{D'}} = ((D' - C_3)/C_1)^{1/C_2} \tag{3.3}$$

The three parameters and interpretable quantities derived from them would facilitate statistically analysing empirically obtained discomfort-time sequences data, and thereby, support various hypothesis testing and modelling studies. For example, multivariate statistical analyses could be performed on the vector consisting of the three parameters to understand the effects of certain task-related or personal variables on entire discomfort-time profile of SPH. Also, the problem of predicting an entire discomfort-time profile based on a certain set of predictor variables could be formulated as that of predicting the three parameter values.

For the 347 discomfort-time sequences represented by the power function form with TAD<0.5 and MAD<1, the distributions of the three parameters C_1, C_2 and C_3 are depicted in Figures 3.7a-3.7c, respectively. Some observations from Figures 3.7a-c included the following: 1) the scaling factor C_1 appeared to follow an exponential distribution, 2) the exponent C_2 appeared to be normally distributed; the mean was 1.36 and the range was from 0.14 to 2.94, and 3) the intercept C_3 seemed to be exponentially distributed. Concerning the variability observed in the distributions of the three parameters, some questions arise naturally: what gives rise to such variability? Can certain personal or task-related variables account for the variability, and if so, how much of the variability can they account for? Is it possible to predict the parameter values, and therefore, an entire discomfort-time profile based on a certain set of predictor variables? Currently, an investigation is being carried out in search of the answers to these questions.

It is perhaps worth pointing out that the power function form representation $Discomfort = C_1 PHT^{C_2} + C_3$ bears a resemblance to the Steven's power law in that it relates the magnitude of a physical stimulus (PHT) to a psychological response (discomfort) using the power relationship - the Steven's power law describes the relationship between the magnitude of a physical stimulus and its perceived intensity and is mathematically described as $\Psi(I) = kI^a$ where I denotes the magnitude of a physical stimulus and $\Psi(I)$, its perceived intensity (Gescheider, 1985). Despite the similarity, however, it is thought that the power function representation of the discomfort-time relationship cannot be considered as an instance of the Stevens power law. This is because perceived discomfort is not the same as perceived intensity of PHT, that is, perceived time duration. As the relationship $Discomfort = C_1 PHT^{C_2} + C_3$ indicates, an increase in PHT results in increased discomfort. However, some intermediate variables, biomechanical or physiological, would be required to explain how that occurs. Further investigations are needed to identify the intermediate variables and the mechanism through which increased PHT leads to an increase in perceived discomfort.

The two main findings of this study can be summarized as follows: 1) three different monotonically increasing time patterns (negatively accelerated, linear and positively accelerated) co-exist in discomfort-time profiles of SPH trials and 2) the power function form can serve as a general representation of the discomfort-time relationship. These results are not identical to those of past research studies. Previously, multiple studies suggested that the relationship between perceived discomfort of SPH and PHT is linear in its nature, and thus, be represented using the linear time function form (Corlett and Manenica 1980, Manenica 1986, Dul et al. 1994, Meijst et al. 1995, Kee 2004). Reneman et al. (2001) on the other hand contended that the negatively accelerated logarithmic time function form depict the discomfort-time relationship. Regarding the differences between the current and previous research results, it should be noted that the current study does not contradict the past research studies. This study reports that the positively accelerated time increase pattern is found in some discomfort-time sequences of prolonged SPH trials in addition to the linear and negatively accelerated time increase patterns, which were observed in previous studies. It is thought that this study was able to find a wider range of time increase patterns than the previous studies because it had an opportunity to examine a larger number of discomfort-time sequences. Also, the fact that multiple previous studies (Corlett and Manenica 1980, Manenica 1986, Dul et al. 1994, Meijst et al. 1995, Kee 2004) suggested the linear time function form representation of the discomfort-time relationship could be understood in light of the current results. As mentioned earlier, the linear function form was found to be able to fit 284 out of the 360 (78.8%) discomfort-time sequences with TAD<0.5 and MAD<1. This indicates that the linear function form is indeed useful in representing many discomfort-time profiles. Reneman et al. (2001) only examined two postures in investigating discomfort-time profiles of SPH trials. This may explain why they observed only the negatively accelerated time increase pattern in their study.

The current research findings are expected to contribute to the efforts to control discomfort and WMSD risks associated with SPH through ergonomic design interventions. Especially, they may serve a basis for developing new posture analysis tools for analysing stresses of SPH tasks. The existing posture analysis tools, including the Ovaco Working Posture Analysing System (OWAS) (Karhu et al. 1977, Karhu et al. 1981) and the Rapid Upper Limb Assessment (RULA) method (McAtamney and Corlett 1993), do not allow considering PHT in evaluating postural stresses of working postures. The new knowledge on the nature of the discomfort-time relationship in SPH and the power function form representation found in this study may guide the development of future posture analysis tools aimed at estimating the population distribution of discomfort for a given SPH task described in terms of working posture and PHT. Of course, to realize such posture analysis tools, a large database of discomfort-time sequences will also need to be established. The current study provided an initial set of data for building such database.

Some limitations of the current study are acknowledged along with future research directions: first, this study considered only two-handed static box holding tasks and one hand-load weight level (2kg). Although this study examined a large set of discomforttime sequences, collecting and analysing more data in various task conditions would be beneficial especially for confirming the validity of the research findings over a wider range of conditions and also developing useful posture analysis tools. Related to this, a discomfort-time sequence database for one-handed SPH tasks is currently under development. Second, most of the study participants in this study were young and of the normal weight category. Future studies will need to examine discomfort-time profiles of older and/or obese individuals to understand the effects of age and obesity level and also confirm the validity of the study findings within those segments of the population. Third, this study examined only subjective ratings of perceived discomfort without employing other stress/strain measures. Collecting and analysing physical and physiological response data along with perceived discomfort ratings would further enhance our understanding of the discomfort-time relationship in SPH.

Chapter 4

An investigation on inter-individual variation in perceived discomfort of static posture holding.

4.1 Introduction

Static posture holding (SPH) tasks, which require workers to statically maintain working postures for certain time durations, can be found in most industrial sectors, including the manufacturing, agriculture and service industries (Miedema et al. 1997, Olendorf and Drury 2001, Chung et al. 2003a, Chung et al. 2005). SPH tasks can lead to overloads on the musculoskeletal system and cause significant discomfort to workers if they are designed without consideration of human capabilities and limitations. Stressful SPH tasks may increase the incidences of work-related musculoskeletal disorders (WMSD). The association between perceived discomfort and WMSD has been reported in a number of studies (Corlett and Bishop 1976, Genaidy and Karwowski, 1993, Genaidy et al, 1995, Kee and Lee 2012). Research suggests that controlling work-related discomfort through ergonomics interventions may contribute towards the reduction of WMSD risks (Dul et al. 1994, Putz-Anderson and Galinsky, 1993, Miedema et al., 1997). It would also improve the quality of work life for many workers.

In general, an SPH task can be specified by three parameters, that is, posture, external load and task duration. These parameters affect the level of discomfort that a worker experiences from conducting the task. In addition, the workers physical and psychological characteristics also contribute as was demonstrated in Park et al. (2009). Thus, even when performing identical SPH tasks, that is, identical in terms of the three parameters, different individuals with different physical and psychological characteristics would experience different levels of perceived discomfort. Therefore, for a given SPH task, a group or a population of individuals gives rise to a probability distribution of perceived discomfort, which describes the inter-individual variation in discomfort perception. Such mathematical depiction of the inter-individual variation can greatly help determine the proportion of the workforce that would experience excessive (or manageable) discomfort from an SPH task and further assist in deciding the acceptability of the task from a population accommodation point of view.

In ergonomics and related research areas, numerous studies have examined discomfort resulting from SPH. Many of these studies aimed to understand the effects of posture and external load on perceived discomfort (Genaidy et al., 1995, Kee and Karwowski, 2001, Olendorf and Drury, 2001, Chung et al., 2005, Drury et al. 2006, and Park et al., 2009, Kee and Lee, 2010). In these studies, the participants were asked to perform SPH task trials for short time duration, and then, subjectively rate the corresponding levels of perceived discomfort. The SPH trials varied in posture and/or external load. In many of these studies, it was reported that certain body part postures, such as non-straight back, elevated arms and bent legs, increase postural stresses from SPH (Park et al. 2009, Olendorf and Drury, 2001, Genaidy et al., 1995 and Chung et al. 2002). Also, external loadings were identified as the major driving factor of bodily discomfort (Boussenna et al. 1982, Manenica 1986, Reneman et al. 2001, Dickerson et al. 2006, Dickerson et al. 2007, Kee 2004, and Kee and Lee, 2010). Some studies investigated the effect of task duration (posture holding time) on discomfort of SPH (Corlett and Manenica 1980, Boussenna et. al 1982, Meijst et. al. 1995, Miedema et. al. 1996, Reneman et. al. 2001, Chung et al. 2003, Kee and Lee 2010). In these studies, for a set of working postures, human subjects were asked to perform SPH as long as they could, and while holding each posture, rate their perceived discomfort at predetermined time intervals. The trials were terminated when the maximum discomfort level was reached. The results of these studies indicated that posture significantly affects perceived discomfort along with posture holding time and external load. Also, these studies reported that perceived discomfort monotonically increases over time during a prolonged SPH task trial (Reneman et al. 2001, Chung et al. 2003, Corlett et al. 1980). Reneman et al. (2001) proposed using a negatively accelerated, modified logarithmic function to describe the discomfort-time relationship. Other studies have suggested using a linear function to describe the discomfort-time relationship (Corlett and Manenica 1980, Meijst et. al. 1995, Kee 2004). The previous studies on perceived discomfort of SPH typically employed psychophysical discomfort scales and rating methods, such as the Borg CR-10 scale (Borg, 1982) and the magnitude estimation method (Gescheider, 1985) for human subjects self-assessment of perceived discomfort.

The previous research efforts described above have greatly advanced our understanding of perceived discomfort from SPH. Nonetheless, however, some significant knowledge gaps seem to exist, which hamper adequately representing and evaluating discomfort associated with SPH. The past research studies mostly focused on testing and characterizing the effects of SPH task parameters on perceived discomfort. In doing so, they investigated if the task parameters significantly affect the mean of perceived discomfort computed across different individuals. Statistical analysis methods, such as the analysis of variance and/or linear regression techniques, were employed in accordance with this approach. Whilst this approach is suitable for understanding the effects of SPH task parameters, it does not shed light upon discomfort responses of individuals and the variation in them. The authors are unaware of any research studies that seem to have examined SPH-associated discomfort with a focus on the inter-individual variation. As a consequence, little is known about the nature and magnitude of such variation. This lack of knowledge is problematic as it hinders considering SPH task design and evaluation from the population accommodation point of view. Population accommodation has been one of the fundamental principles of ergonomics design.

As an initial effort towards alleviating the current dearth of research mentioned above, this study aimed to empirically address the following questions:

- What probability distributions are suitable for modeling the inter-individual variation in perceived discomfort from SPH? Can a well-known, single family of probability distributions, such as the normal family, be utilized across different SPH tasks, or do different SPH tasks require different types of probability distributions?

- When quantified in terms of the common measures of dispersion, such as standard deviation and range, how large is the inter-individual variability in SPH-associated perceived discomfort? Do different SPH tasks vary significantly in the amount of inter-individual variability? If yes, do the SPH task parameters, such as posture and external load, affect the inter-individual variability? What are the characteristics of SPH tasks that exhibit large (or small) inter-individual variability?

A large set of perceived discomfort ratings data obtained from an SPH experiment was utilized to accomplish the research goal. In the experiment, 10 male and 10 female participants conducted SPH for a set of 180 predetermined SPH tasks. The 180 SPH tasks were combinations of 60 postures and 3 hand load levels. The posture holding time was fixed at 20 seconds for all of the SPH tasks. For each SPH task, the participants performed subjective rating of perceived discomfort using the Borg CR-10 discomfort scale. For each SPH task, the perceived discomfort values obtained from the 20 participants were used to ascertain the nature of the underlying probability distribution. Also, the measures of spread as well as centre were computed from them. Statistical analyses were conducted to address the research questions posed.

4.2 Methods

4.2.1 Participants

Ten males and ten females participated in this study as paid volunteers. All participants were free of obvious neurological and musculoskeletal disorders. Prior to participation, the participants had a training session during which the nature and protocol of the study were explained and all questions were answered. During the training session, the participants also familiarized themselves with the use of the Borg CR-10 scale. Each participant signed a written informed consent before participation. The Auburn University Institutional Review Board approved the experimental protocol. Table 4.1 summarizes the age, height, body mass and body mass index (BMI) data of the study participants for each gender.

Table 4.1: Summary of the age, height, body mass and body mass index (BMI) data for the male and female participant groups.

	Male	Female
Dimensions	**Mean (SD)**	**Mean (SD)**
Age (Years)	27.00 (4.75)	28.00 (4.32)
Height (cm)	181.86 (7.61)	165.25 (6.64)
Body Mass (kg)	86.10 (15.89)	68.14 (12.58)
BMI (kg/m^2)	25.90 (3.93)	25.02 (4.89)

4.2.2 Experiment

The participants performed short-period (20 seconds) one-handed static object holding tasks for 180 posture-hand load conditions: 180 posture-hand load conditions = 60 postures x 3 hand load levels. The 60 postures represent various one-handed static object holding postures that can be found in workplaces and were generated by combining four back, three arm and five lower body postures. Figure 4.1 describes the body part postures used to generate the 60 whole-body postures. Leg posture 5 was specifically included in this study due to its prevalence in many postural work tasks including, assembly line jobs, construction and painting. Three hand load conditions were utilized: 0 kg (no hand load), 2.2 kg and 3.6 kg (cylindrical objects were used as the hand loads). For each of the 180 posture-hand load combinations, each participant performed a single object holding trial the order of presentation of the 180 trials was randomized for each subject. Therefore, a total of 3600 object holding trials were performed: 3600 trials = 180 posture-hand load combinations x 20 participants.

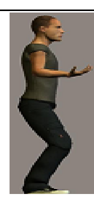
Part	Body posture categories				
Arm	Arm Posture 1 Arm below shoulder level	Arm Posture 2 Arm at 90 degrees	Arm Posture 3 Arm elevated above shoulder		
					
Back	Back Posture 1 Straight	Back Posture 2 Bent approximately 25^0	Back Posture 3 Twisted approximately 25^0	Back Posture 4 Bent approximately 250 & twisted approximately 25^0	
					
Leg	Leg Posture 1 Both legs straight	Leg Posture 2 Both legs bent approximately 150^0	Leg Posture 3 Both legs bent approximately 150^0, body moved forward by both limbs	Leg Posture 4 Straight, body moved forward by one limb	Leg Posture 5 One leg bent at approximately 150^0, on a raised support
					

Figure 4.1: Body part postures used to generate the 180 whole-body posture categories used in the current study.

During each experimental trial, human figure illustration depicting the posture for the given trial was shown to the participant to help him/her adopt the posture. Once the posture was adopted, the object was brought to the participants dominant hand by the experimenter and the participant commenced the 20-seconds one-handed static holding task. Immediately after the completion of each experimental trial, the participant reported his/her perceived postural stress using the Borg CR-10 scale (Figure 4.2). A large print of the Borg CR-10 was located in the line of sight of the participant to help him/her self-select his/her discomfort rating.

0 -	Nothing at all
0.5 -	Extremely weak (just noticeable)
1 -	Very weak
2 -	Weak (light)
3 -	Moderate
4 -	Somewhat strong
5 -	Strong (heavy)
6 -	-
7 -	Very strong
8 -	-
9 -	-
10 -	Extremely strong (almost max)
.	Maximal

Figure 4.2: Borg's new category-ratio (CR-10) scale. Reprinted from Borg 1982.

Prior to a box holding trial, a participant changed into a tight outfit (tight short and short sleeves). Also, spherical reflective markers were attached on body landmarks so that the body postures can be accurately recorded by the VICON motion capture system during the experiment trial. After this initial preparatory set up, the participant adopted the posture and performed the one-handed static object holding task the object was be brought to the participants dominant hand by the experimenter immediately after the participant adopted the posture. In each trial the VICON system kept track of the positions of the attached reflective markers over time and display the distances between their current and correct positions in real-time. When a body attached marker is farther away from its correct position the experimenter instructed the participant to correct the posture. For each SPH task, Subjects were asked to rate their level of discomfort at the completion of each 20-seconds long SPH task trial.

The 180 SPH trials were performed over three sessions by each participant. The three sessions were conducted on three separate days to prevent fatigue effects. The participants were given sufficient rest period between consecutive trials. Even when the participated reported no fatigue, at least 1 minute rest period was provided before the next trial. Also, and after 9 experimental trials, the participant was given an extra 5 minute rest period before he/she could start the next trial. The subjects were also allowed to have additional rest periods as they wanted. Similar rest patterns were reported by Olendorf and Drury (2001) who also had the participants in their study perform a 20 s long SPH task. In their study, participants were allowed 45 s breaks between consecutive trials.

4.3 Data analyses

This study aimed to address two sets of research questions. The first set pertained to identifying mathematical probability distributions suitable for modelling the inter-individual variation in perceived discomfort of SPH. Of particular interest was to determine if a well-known, single family of probability distributions, such as the normal family, be utilized across different SPH tasks or different SPH tasks require different types of probability distributions. The second set of research questions concerned the magnitude of the inter-individual variability in perceived discomfort of SPH, and especially, whether or not it is affected by SPH task parameters.

To address the first set of research questions, for each of the 180 SPH tasks that vary in posture and hand load, a probability histogram was generated using the corresponding perceived discomfort dataset. Then, each probability histogram was visually examined. In addition, Minitabs Individual Distribution Identification Tool (Minitab® 16 Statistical Software) was used to identify a mathematical probability distribution that adequately fits each dataset. The Individual Distribution Identification Tool allows for evaluating up to 14 different distribution families: the normal, lognormal, 3-parameter lognormal, exponential, 2-parameter exponential, Weibull, 3-parameter Weibull, largest extreme value, smallest extreme value, gamma, 3-parameter gamma, logistic, loglogistic and 3-parameter loglogistic types. These distribution families are commonly used in probability modeling and statistical analyses and cover a wide range of distribution shapes. For each dataset, the Individual Distribution Identification Tool performed the goodness of fit test using each of the 14 distribution types. In addition, it identified the distribution type that best fits each dataset. The best-fitting distributions found for the 180 SPH tasks were examined to determine if a single, well-known distribution type can model the inter-individual variation in perceived discomfort across various SPH tasks.

To address the second set of research questions, two dispersion measures, that is, the standard deviation and range, were computed for each of the 180 SPH task using the corresponding dataset. Then, frequency histograms were plotted for each dispersion measure.

To test the effect of SPH task parameters (body part posture and hand load) on each dispersion measure, four-factor ANOVAs were conducted. The analyses evaluated the effects of hand load level, arm posture, back posture, leg posture and their interactions. The hand load factor had three levels. The arm, back and leg postures had three, four and five levels respectively. In performing the ANOVAs, the highest order interaction (the four-way hand load level x arm posture x back posture x leg posture interaction) was used as the error term since only one experimental unit was available for each combination of the factor levels. Anderson and McLean (1974) supported using the higher order interactions as the error term in experiments with only one experimental unit per factor level combination.

In addition to the two dispersion measures mentioned above, two measures of centre, that is, the mean and median, were computed for each SPH task using the corresponding dataset. A frequency histogram was plotted for each centre measure. Scatter plots were used to examine possible relationships between the measures of centre and those of dispersion.

The Minitab software program was used to perform the statistical analyses (Minitab® 16 Statistical Software). The α-level for the statistical analyses was set at 0.05. All tests of significance were performed at $= 0.05$. Graphical outputs were provided by MS excel (Microsoft 2010).

4.4 Results

4.4.1 Probability distributions for modeling the inter-individual variation in perceived discomfort

The results for distribution identification for each of the 180 SPH tasks are summarized in Figure 4.3. In one-third of all the 180 datasets none of the 14 distributions in Minitab could adequately fit the dataset ($p<0.05$). The results of the distribution identification showed that there is no single well-known distribution family that can be used to robustly fit different SPH tasks.

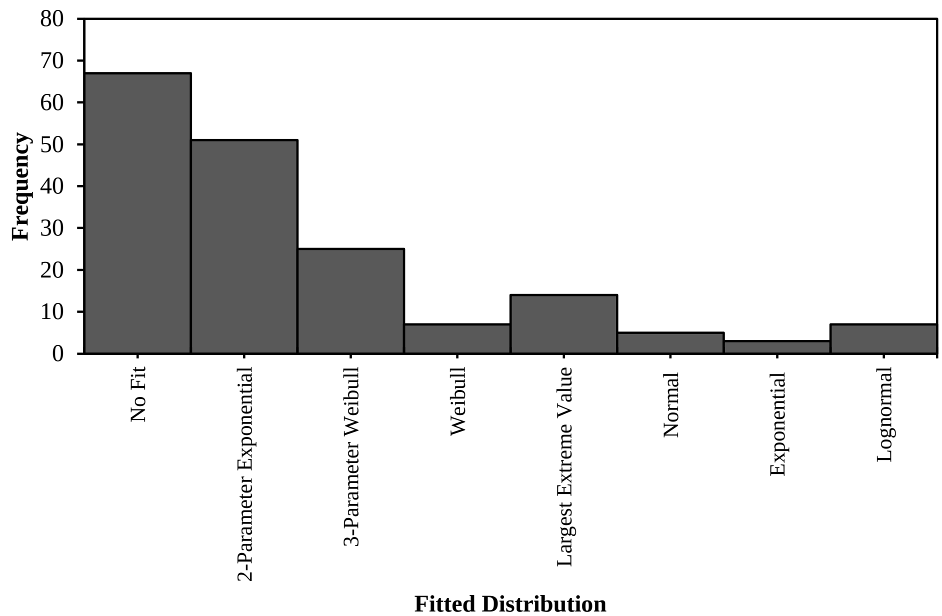
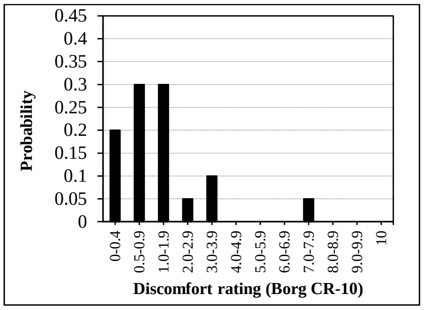
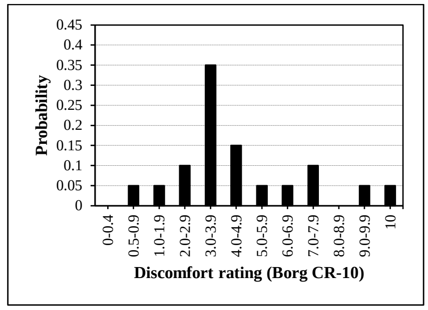


Figure 4.3: Histogram showing the fitted distributions for the 180 SPH tasks. A total of 14 distributions available in Minitab were used to fit the data.

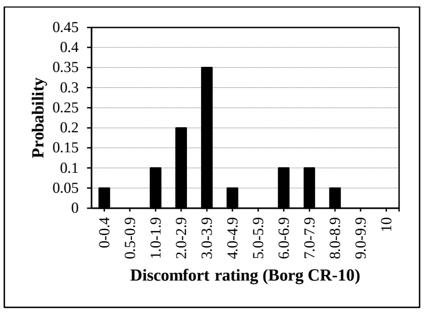
A few example datasets were selected and their frequency histograms were generated as shown in Figures 4.4 (a) to (f) and Figures. 4.5 (g) to (j). These histograms clearly indicate the lack of a common distribution or family of distribution to characterize the SPH tasks.



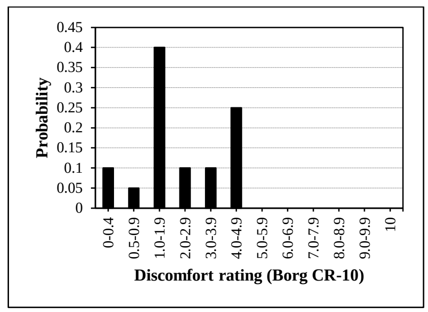
(a) Posture 3



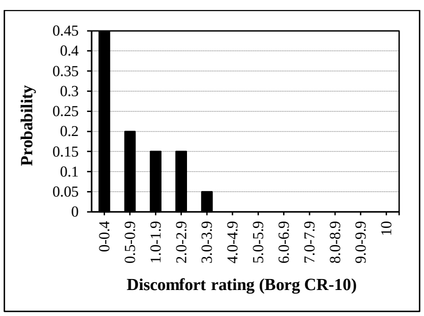
(b) Posture 107



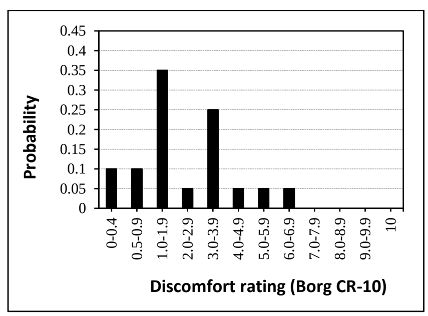
(c.) Posture 17



(d) Posture 150

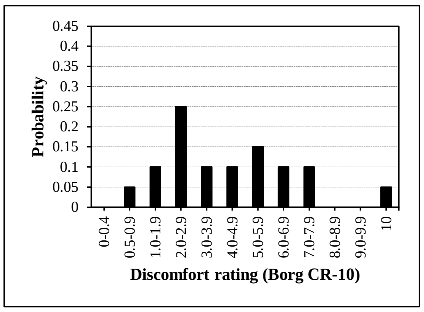


(e) Posture 2

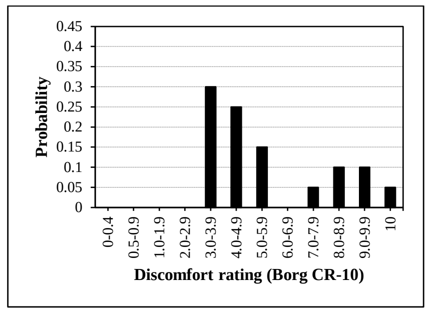


(f) Posture 47

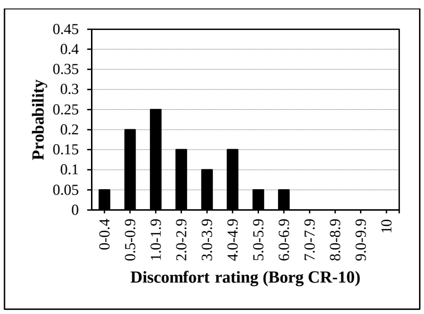
Figure 4.4: (a) Both legs straight, Arm below the shoulder level, Straight back and holding a 3.6 kg hand-load. (b) Both legs straight, body moved forward by the limbs, back bent and twisted, arm raised above the shoulder level and holding a 2.2 kg load. (c) Both legs straight, arm above the shoulder level, Back bent by approximately 25 degrees and holding a 2.2 kg load (d) One leg bent at approximately 150 degrees, and on a raised support, Arm at 90 degrees , Straight back and holding a 3.6 kg hand-load.(e) Both legs straight, arm below the shoulder level, Straight back and holding a 2.2 kg hand-load. (f) Both legs bent approximately 150 degrees , arm below the shoulder level, Straight back and holding a 2.2 kg hand-load. .



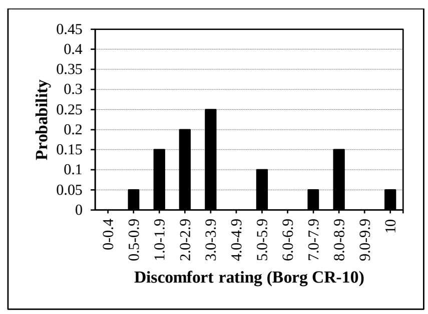
(g) Posture 9



(h) Posture 18



(i.). Posture 6



(j) Posture 81

Figure 4.5: (g) Both legs straight, arm above the shoulder level, Straight back and holding a 3.6 kg load (h) Both legs straight, arm above the shoulder level, Back bent by approximately 25 degrees and holding a 3.6 kg load. (i) Both legs straight, Arm at 90 degrees , Straight back and holding a 3.6 kg hand-load (j) Both legs bent approximately 150 degrees, body moved forward by both limbs, Straight back, arm raised above the shoulder level and holding a 3.6 kg load.

4.4.2 Statistical analyses on the magnitude of inter-individual variation in perceived discomfort.

As described earlier in Section 4.3, for each of the 180 SPH task conditions, two measures of dispersion, that is, sample standard deviation and range, were computed using the corresponding perceived discomfort dataset to quantify the magnitude of the inter-individual variation in perceived discomfort. The frequency histograms shown in Figure 4.6 describe the distributions of the dispersion measures, respectively.

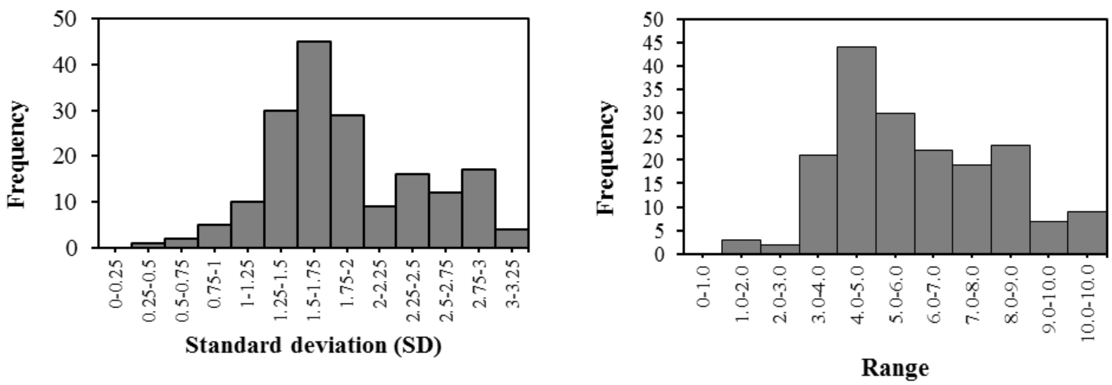


Figure 4.6: Histograms showing the distribution of standard deviation and range for 180 SPH tasks.

Additionally, frequency histograms were constructed for the measures of center (mean and median), figure 4.7. These histograms show the distribution of mean and median discomfort for different SPH tasks.

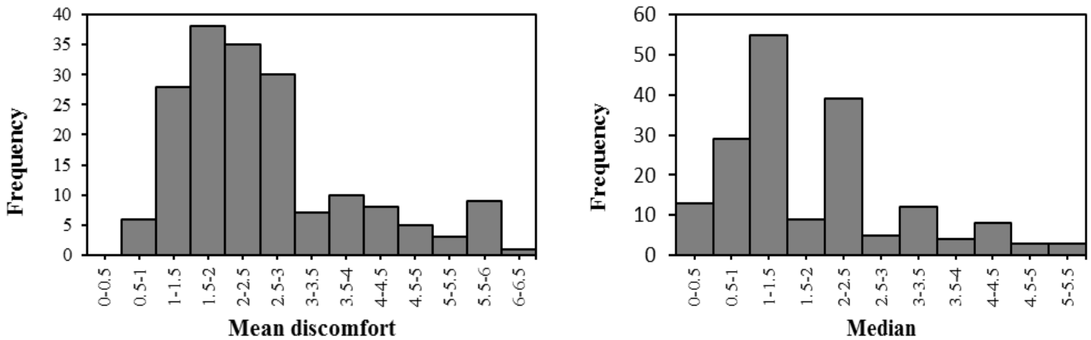


Figure 4.7: Histograms showing the distribution of Mean and Median for 180 SPH tasks.

The results from the ANOVAs that tested the effects of body part posture (arm, back, and leg) and hand load level on the two measures of dispersion (SD and range) are provided in Table 4.2, for each dispersion measure. The ANOVA results showed statistical significance for some of the main effects and interaction effects. The following observations can be made from them: for standard deviation, arm posture, leg posture and load level were found to be significant. For range, only two main effects, leg posture and load level, were significant. For both standard deviation and range, the load level main effect accounted for the largest percentage of the total variation. Of the ten possible interaction effects in each case, the (back x leg) and (back x leg x load) interaction effects seemed to be the major contributors to the total variation.

Table 4.2: The ANOVA results for the two measures of spread: standard deviation and range

	St. dev.			**Range**		
Source	**DF**	**SS**	**P**	**DF**	**SS**	**P**
Arm	2	0.61	**0.0170***	2	7.02	0.065
Back	3	0.09	0.7	3	1.61	0.725
Leg	4	6.95	**0.0000***	4	72.17	**0.0000***
Load	2	21.24	**0.0000***	2	281.05	**0.0000***
Arm x Back	6	0.21	0.797	6	3.4	0.829
Arm x Leg	8	1.11	0.065	8	21.18	0.046
Arm x Load	4	0.44	0.186	4	9.01	0.133
Back x Leg	12	13.6	**0.0000***	12	122.64	**0.0000***
Back x Load	6	0.36	0.524	6	4.54	0.711
Leg x Load	8	0.8	0.196	8	13.35	0.232
Arm x Back x Leg	24	3.31	**0.0200***	24	49.68	0.058
Arm x Back x Load	12	0.26	0.983	12	2.53	0.999
Arm x Leg x Load	16	0.94	0.625	16	22.08	0.351
Back x Leg x Load	24	5.35	**0.0000***	24	64.84	**0.0009***
Error	48	3.3		48	58.26	
Total	179	58.59		179	733.36	

Additional ANOVA analyses were conducted for the measures of center (mean and median). In addition to the main effects of arm, leg and load being significant, the 2-way back- leg and leg-load interactions were significant. Two 3-way interactions also found to be significant: Arm x Back x Leg and Back x Leg x Load. The results are summarized in table 4.3.

Table 4.3: The ANOVA results for the two measures of center: mean and median.

	Mean			Median		
Source	**DF**	**SS**	**P**	**DF**	**SS**	**P**
Arm	2	5.59	**0.000***	2	6.43	**0.000***
Back	3	0.59	0.243	3	0.88	0.171
Leg	4	24.96	**0.000***	4	18.06	**0.000***
Load	2	124.65	**0.000***	2	120.86	**0.000***
Arm x Back	6	0.61	0.627	6	0.99	0.453
Arm x Leg	8	2.375	0.048	8	1.47	0.388
Arm x Load	4	0.96	0.158	4	1.75	0.049
Back x Leg	12	68.45	**0.000***	12	45.35	**0.000***
Back x Load	6	0.22	0.949	6	0.88	0.529
Leg x Load	8	3.74	**0.004***	8	2.58	0.081
Arm x Back x Leg	24	17.28	**0.000***	24	16.87	**0.000***
Arm x Back x Load	12	0.57	0.976	12	1.24	0.822
Arm x Leg x Load	16	1.33	0.865	16	3.47	0.246
Back x Leg x Load	24	29.82	**0.000***	24	19.3	**0.000***
Error	48	6.62		48	8.13	
Total	179	287.77		179	248.28	

The main aim of this study was to show how the SPH task parameters affect the amount of inter-individual variability in perceived discomfort. The ANOVA results showed significant three-way interactions for some of the measures of spread and center. For SD, the 3-way interactions between the arm, back, leg and Back, leg, and load were found to be significant. Only the 3-way interaction between the back, leg and load was found to be significant for the range. The interaction plots for SD are shown in figures 4.8 and 4.9 Figure 4.10 shows the interaction plot for range. Visual observation of Figures 4.8, 4.9 and 4.10 reveal the complex nature of these higher order interactions.

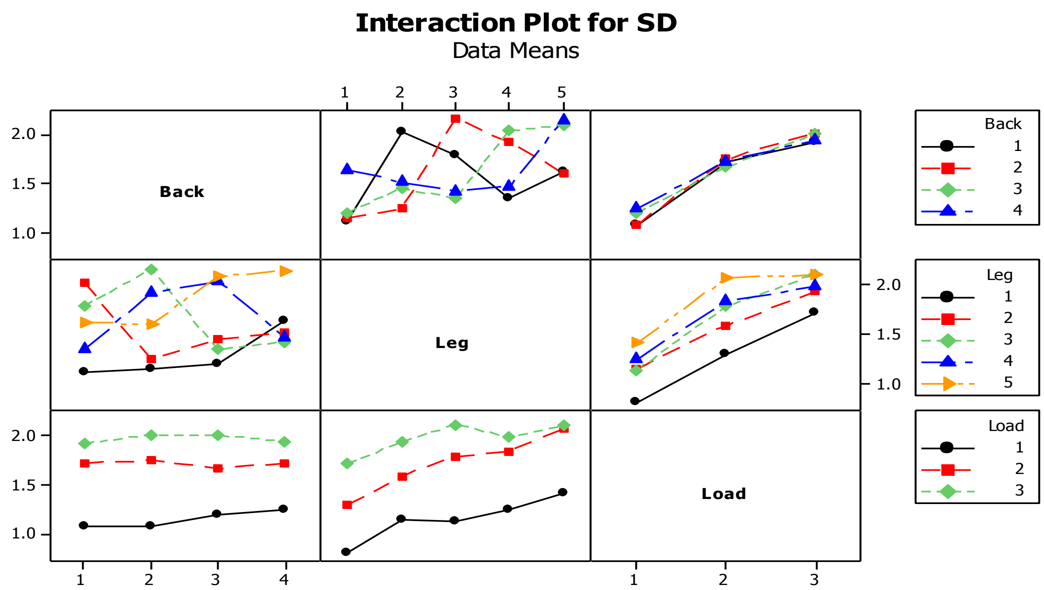


Figure 4.8: Three-way interaction plot for the back, leg and load interaction.

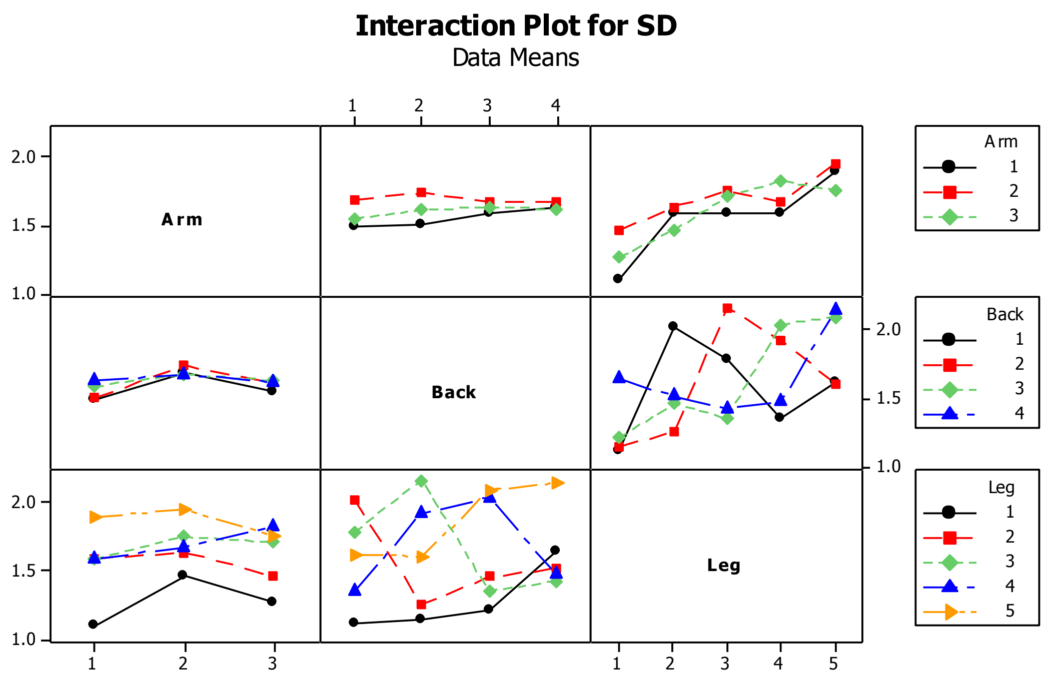


Figure 4.9: Three-way interaction plot for the arm, back and leg interaction.

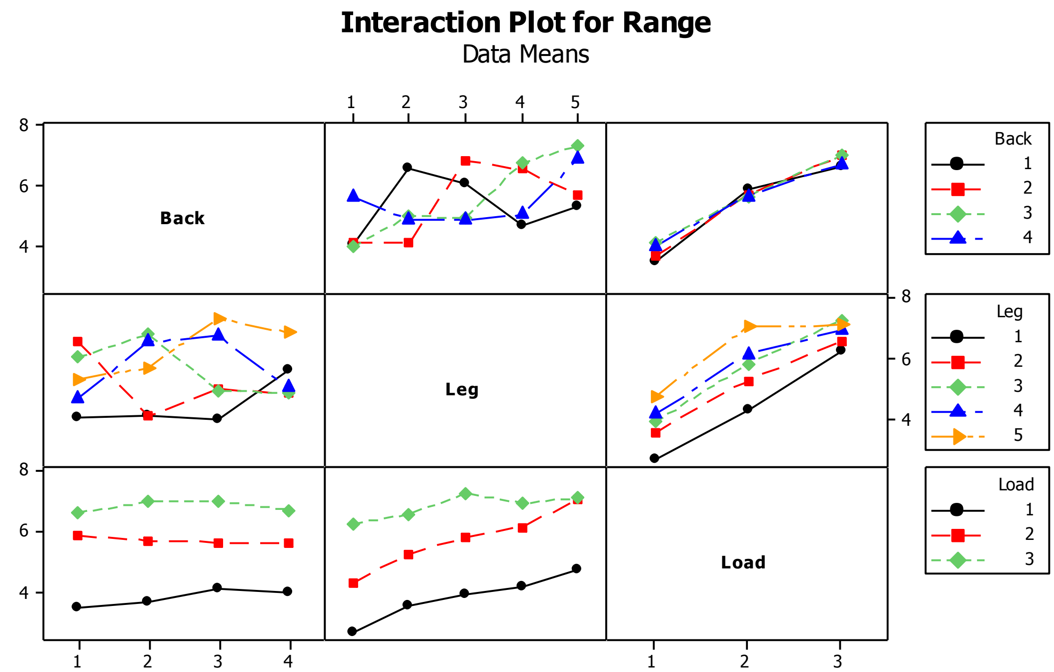


Figure 4.10: Three-way interaction plot for the back, leg and load interaction for the range.

The three-way interactions were very complex (Tables 4.8 - 4.10); nonetheless, an attempt was made to find some interesting patterns from the tables. The highest inter-individual variations were found in load level three (holding a 3.6 kg load). The load level thus affected variability significantly. It is apparent that leg posture 1(straight legs) exhibit the smallest variability, while leg posture 5 (right foot in a flexed position, on a raised support) exhibit the largest variability. In most cases, although not all, the interaction of non-straight back postures and non-straight leg postures were associated with higher inter-individual variability.

Legs	1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
	Load 1	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**
1 	**0.7**	**1.2**	**1.5**	**0.7**	**1.0**	**1.7**	**0.9**	**1.3**	**1.5**	**1.0**	**1.8**	**2.2**
2 	**1.1**	**2.2**	**2.7**	**0.9**	**1.3**	**1.6**	**1.2**	**1.5**	**1.7**	**1.4**	**1.4**	**1.7**
3 	**1.1**	**2.0**	**2.2**	**1.3**	**2.5**	**2.7**	**1.1**	**1.2**	**1.7**	**1.1**	**1.4**	**1.9**
4 	**1.2**	**1.5**	**1.4**	**1.3**	**2.1**	**2.4**	**1.3**	**2.2**	**2.7**	**1.3**	**1.6**	**1.5**
5 	**1.3**	**1.8**	**1.7**	**1.3**	**1.8**	**1.8**	**1.6**	**2.3**	**2.4**	**1.4**	**2.5**	**2.6**

0.7 – 1.0	**1.1 – 1.4**	**1.5 – 1.8**	**1.9 – 2.2**	**2.3 – 2.6**	**2.7 – 3.0**
Lowest	Low	Medium		High	Highest

SD

Figure 4.11: Three-way interaction plot for the back, leg and load interaction for standard deviation.

Leg	1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 
1 	**0.9**	**1.4**	**1.1**	**1.0**	**1.4**	**1.0**	**1.3**	**1.2**	**1.1**	**1.2**	**1.9**	**1.9**
2 	**2.0**	**2.1**	**2.0**	**1.0**	**1.6**	**1.2**	**1.6**	**1.5**	**1.3**	**1.8**	**1.4**	**1.4**
3 	**1.5**	**1.8**	**2.0**	**2.1**	**2.2**	**2.2**	**1.2**	**1.4**	**1.5**	**1.6**	**1.6**	**1.1**
4 	**1.2**	**1.4**	**1.5**	**1.7**	**1.9**	**2.1**	**2.0**	**2.0**	**2.1**	**1.4**	**1.4**	**1.6**
5 	**1.9**	**1.8**	**1.2**	**1.7**	**1.6**	**1.6**	**1.8**	**2.4**	**2.1**	**2.3**	**2.1**	**2.1**

0.9 – 1.1	1.2 -1.4	1.5 – 1.7	1.8 – 2.0	2.1 – 2.3	2.4 – 2.6
Lowest	Low	Medium		High	Highest

SD

Figure 4.12: Three-way interaction plot for the arm, back and leg interaction for standard deviation.

Legs	1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
	Load 1	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**
1 	**2.2**	**4.0**	**6.0**	**2.7**	**3.0**	**6.7**	**2.7**	**4.3**	**5.0**	**3.3**	**6.0**	**7.5**
2 	**3.7**	**7.3**	**8.8**	**2.7**	**4.3**	**5.3**	**4.0**	**4.7**	**6.3**	**4.0**	**4.8**	**5.8**
3 	**3.7**	**7.2**	**7.3**	**4.3**	**8.2**	**8.6**	**4.0**	**4.0**	**6.8**	**3.7**	**4.0**	**7.0**
4 	**4.0**	**5.0**	**5.0**	**4.3**	**7.2**	**8.2**	**4.0**	**7.0**	**9.3**	**4.3**	**5.5**	**5.3**
5 	**4.0**	**6.0**	**6.0**	**4.3**	**6.0**	**6.8**	**6.0**	**8.3**	**7.7**	**4.7**	**8.0**	**8.0**

2.2 – 3.3	**3.4 – 4.5**	**4.6 – 5.7**	**5.8 – 6.9**	**7.0 – 8.1**	**8.2 – 9.3**
Lowest	Low	Medium		High	Highest

Range

Figure 4.13: Three-way interaction plot for the back, leg and load interaction for the range.

Legs	1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
	Load 1	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**
1 	**0.6**	**1.3**	**1.8**	**0.4**	**1.0**	**1.9**	**0.7**	**1.4**	**2.0**	**1.0**	**2.3**	**3.5**
2 	**0.9**	**2.7**	**4.1**	**0.8**	**1.5**	**2.1**	**0.9**	**1.6**	**2.1**	**1.1**	**1.7**	**2.1**
3 	**1.2**	**3.0**	**4.3**	**1.2**	**3.3**	**5.2**	**0.9**	**1.4**	**2.1**	**0.7**	**1.4**	**2.2**
4 	**0.8**	**1.5**	**2.2**	**1.0**	**2.6**	**3.5**	**1.1**	**2.9**	**4.3**	**1.1**	**2.0**	**2.0**
5 	**1.2**	**1.9**	**2.2**	**1.2**	**2.1**	**2.5**	**1.4**	**3.1**	**4.6**	**1.4**	**4.0**	**5.5**

0.4 – 1.2	**1.3 – 2.1**	**2.2 – 3.0**	**3.1 – 3.9**	**4.0 – 4.8**	**4.9 – 5.7**
Lowest	Low	Medium		High	Highest

Mean

Figure 4.14: Three-way interaction plot for the back, leg and load interaction for Mean.

Legs	1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 
1 	0.6	1.5	1.4	1.0	1.3	1.1	1.5	1.3	1.3	1.3	2.4	3.1
2 	2.4	2.8	2.5	1.0	1.9	1.5	1.6	1.6	1.5	1.8	1.8	1.3
3 	1.8	3.2	3.5	3.1	3.3	3.3	1.1	1.7	1.5	1.4	1.6	1.3
4 	1.7	1.4	1.4	1.4	2.6	3.2	2.8	2.6	2.9	1.7	1.6	1.8
5 	2.0	1.9	1.4	1.9	2.0	1.8	1.9	3.6	3.6	3.7	3.8	3.4

0.6 – 1.1	1.2 -1.7	1.8 – 2.3	2.4 – 2.9	3.0 – 3.5	3.6 – 4.1
Lowest	Low	Medium		High	Highest

Mean

Figure 4.15: Three-way interaction plot for the arm, back and leg interaction for Mean.

Legs	1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
	Load 1	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**	**Load 1**	**Load 2**	**Load 3**
1 	**0.3**	**1.0**	**1.4**	**0.0**	**0.7**	**1.5**	**0.3**	**1.0**	**2.0**	**0.6**	**2.0**	**2.8**
2 	**0.3**	**1.8**	**3.2**	**0.4**	**1.0**	**1.7**	**0.3**	**1.3**	**2.0**	**0.4**	**1.3**	**1.7**
3 	**0.9**	**2.5**	**3.3**	**0.8**	**2.3**	**4.2**	**0.6**	**0.9**	**2.0**	**0.2**	**1.0**	**2.0**
4 	**0.3**	**1.0**	**2.0**	**0.5**	**2.0**	**3.0**	**0.6**	**2.5**	**3.7**	**0.7**	**1.3**	**1.7**
5 	**0.8**	**1.2**	**1.8**	**0.7**	**1.8**	**2.2**	**0.7**	**2.3**	**3.8**	**1.0**	**3.3**	**4.7**

0.0 – 0.7	**0.8 – 1.5**	**1.6 – 2.3**	**2.4 – 3.1**	**3.2 – 3.9**	**4.0 – 4.7**

Lowest Low Medium High Highest

Median

Figure 4.16: Three-way interaction plot for the back, leg and load interaction for Median.

Legs	1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 
1 	**0.4**	**1.2**	**1.2**	**0.7**	**0.9**	**0.7**	**1.3**	**1.0**	**1.0**	**0.8**	**2.0**	**2.7**
2 	**1.7**	**1.8**	**1.8**	**0.5**	**1.2**	**1.4**	**1.1**	**1.1**	**1.5**	**1.2**	**1.5**	**0.8**
3 	**1.4**	**2.7**	**2.7**	**2.2**	**2.6**	**2.5**	**0.9**	**1.3**	**1.3**	**1.0**	**1.2**	**1.0**
4 	**1.2**	**1.2**	**1.0**	**0.7**	**2.2**	**2.7**	**2.2**	**2.1**	**2.5**	**1.3**	**1.2**	**1.2**
5 	**1.3**	**1.5**	**1.0**	**1.8**	**1.7**	**1.3**	**1.3**	**2.7**	**2.8**	**3.0**	**3.3**	**2.7**

0.4 – 0.8	**0.9 -1.3**	**1.4 – 1.8**	**1.9 – 2.3**	**2.4 – 2.8**	**2.9 – 3.3**
Lowest	Low	Medium		High	Highest

Median

Figure 4.17: Three-way interaction plot for the arm, back and leg interaction for Median.

Visual examinations of the figures 4.11 - 4.17 suggested possible relationship between measures of spread and center. Therefore, additional analyses were conducted to explore the relationship. The scatter plots in Figures 4.18 to 4.21 describe the relationship between the two measures of spread and the two measures of center. An examination of these scatter diagrams suggested that the relationship between the measures of spread and those of center was positively correlated although not linear.

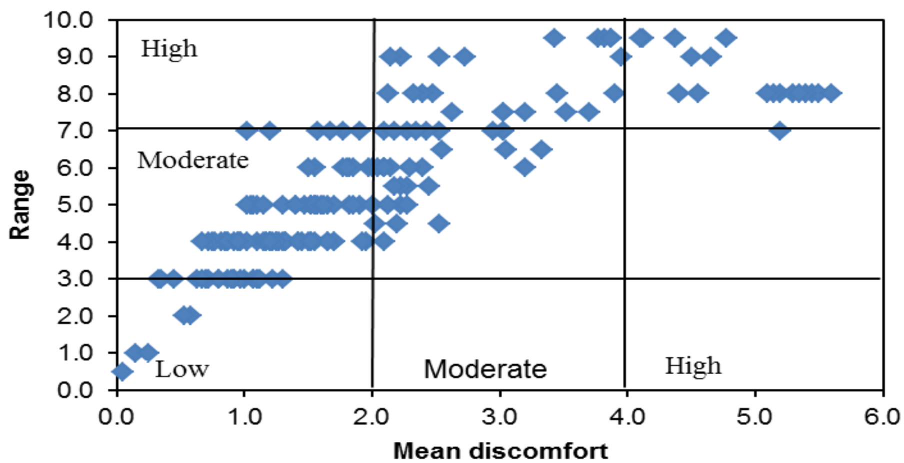


Figure 4.18: The relationship between Mean discomfort and Range within a specified SPH task. A total of 180 SPH tasks are considered.

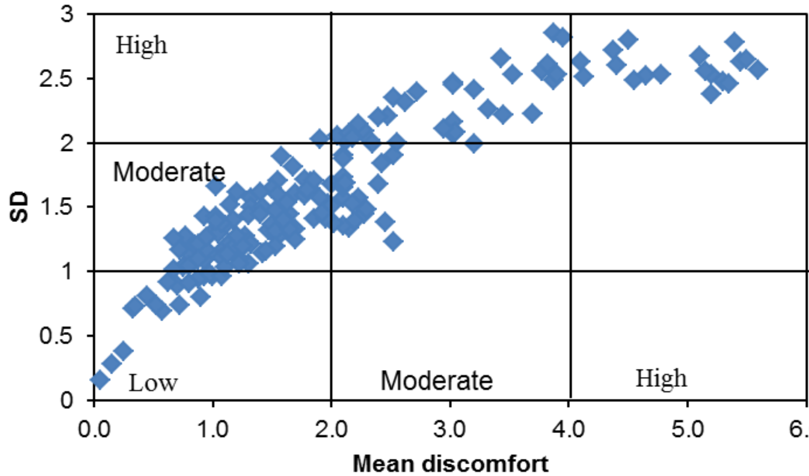


Figure 4.19: The relationship between Mean discomfort and the Standard Deviation (SD) within a specified SPH task. A total of 180 SPH tasks are considered.

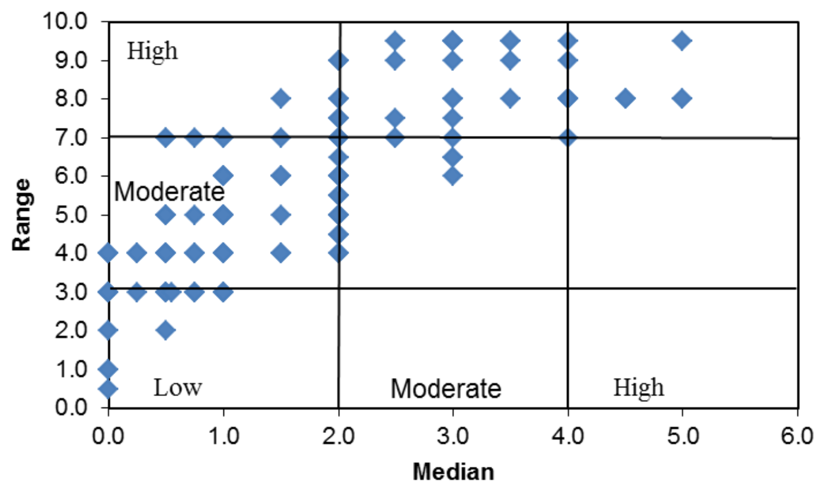


Figure 4.20: The relationship between Median and Range of discomfort within a specified SPH task. A total of 180 SPH tasks are considered.

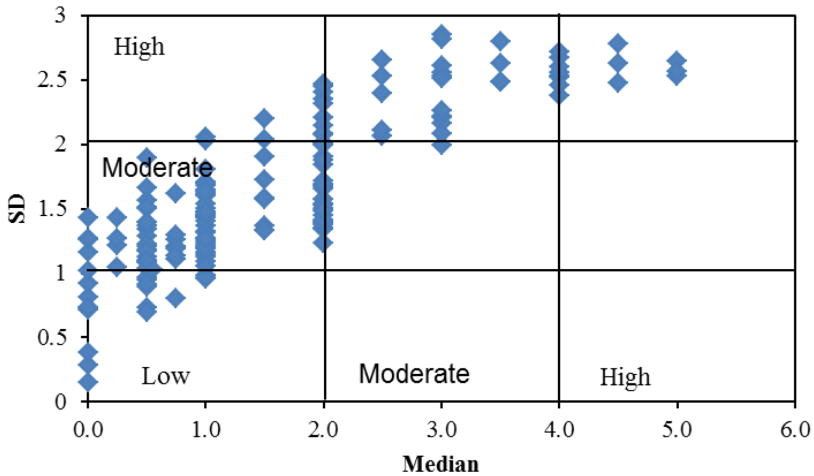


Figure 4.21: The relationship between Median and Standard deviation (SD) within a specified SPH task. A total of 180 SPH tasks are considered.

4.5 Discussion

This study empirically collected ratings of perceived discomfort for one-handed static object holding tasks in order to examine the inter-individual variation of perceived postural discomfort associated with SPH. Specifically, the study aimed to (1) examine the probability distributions that characterize different SPH tasks and (2) determine if the measures of spread- standard deviation and range- representing the magnitude of the inter-individual difference would vary across different SPH tasks and how the SPH task parameters affect the amount of inter-individual variability. Twenty subjects performed short period (20 seconds) object holding tasks for 180 posture-hand load combinations. Thus, each posture-load combination had a total of twenty data points representing discomfort ratings for twenty different individuals. The discomfort rating reflected what the individual would perceive under the defined postural conditions. The study utilized a 10-point rating scale to obtain the subjective ratings (Borg CR-10 scale).

The results of the distribution identification showed that there is no single well-known distribution family that can be used to robustly fit different SPH tasks. As can be seen from Figure 4.3, there is no common probability distribution type that works across different SPH tasks. In a number of the SPH tasks (one-third of the 180 datasets), none of the 14 distributions commonly used for probability modeling could adequately fit the data. The fact that one-third of the 180 datasets could not be modeled by any of the 14 Minitab distributions implies that the distributions are very arbitrary. Visual examination of the frequency histograms related to these datasets revealed them to be SPH tasks in which most subjects rated their discomfort relatively low resulting in a lot of values ranging between 0-3 (Figures 4.4 a - f and 4.5 g - j). The lack of fit could be attributed to a small range within the datasets. Additionally, a considerable amount of SPH tasks were fitted with either the Exponential family of distribution (30%) or the Weibull family of distributions (19%) . This could be attributed to sets of data with high range with most data points being on the lower end of the scale, in other words, an upper bound on the data resulted in the data being skewed left. Essentially, in these cases, majority of the data points were between 0-3 but there were few that were on the higher end of the scale resulting in a much larger range.

An implication of this finding no one particular distribution type accounting for datasets is that there is need to carefully examine each SPH task distribution in order to determine the SPH tasks stress level. When assumptions cannot be made about a particular distribution type, the utilities of simple descriptive statistics, such as, mean, median, range and standard deviation become very limited in determining an SPH tasks stress levels. The histograms shown in Figures 4.4 a - f and 4.5 g - l served as the rationale for conducting the individual distribution identification, i.e. visual examination of the histograms was indicative of the varying distribution type for each dataset.

Different SPH trials exhibited substantial variation in the amount of spread (Figure 4.6); this could be attributed to the different combinations of SPH task parameters posture-load combinations. To examine the effects of the SPH task parameters on the amount of inter-individual variability, the measures of spread were subjected to analysis of variance (ANOVA) using a general linear model. External load significantly affected the amount of inter-individual variability in SPH task trials (Table 4.2). Increasing hand load results in an increase in muscle load. Differences in performance tend to be magnified in high muscle loading tasks resulting in significant inter-individual difference in discomfort. Significant variability in discomfort translates into significant amount of inter-individual difference in SPH task trials. The back effects were insignificant although there was significant interaction between back and leg, the interaction accounted for 23% and 17% respectively of the total variation for SD and range. Similarly the back x leg x load interaction accounted for 9% and 8% respectively of the total variation for SD and range. Therefore we can conclude that although the back postures did not significantly affect the amount of inter-individual difference, they did have a significant effect when interacting with other body part postures.

One of the aims of this study was to examine the characteristics of SPH task tasks that exhibit large or small inter-individual difference. Careful observation of the shaded tables reveals some interesting trends. Generally, there was comparatively higher inter-individual variability in SPH tasks that involved higher load levels. As has already been stated earlier, increase in hand load increases muscle load resulting in larger discomfort values. This translates into large inter-individual difference in SPH task trials. SPH task trials that involved the participants adopt leg posture 5 were characterized by large inter-individual difference (Tables 4.11, 4.12 and 4.13). The level of variation was represented by cell treatment means; higher cell means imply larger variability. SPH tasks that involved leg posture 5 were mostly characterized by either high or highest treatment means. The reason for the high cell treatment means of these leg postures could be due to the fact that the participant essentially had to perform the SPH trial in an unbalanced leg posture for 20 seconds. The dominant leg was flexed at about 150 degrees and supported on a raised support. Most of the body weight ended up being distributed to his/her less dominant side. This unequal distribution of body weight could have resulted in larger inter-individual differences in discomfort perception. This subsequently translated into significant amount of inter-individual differences in SPH task trials.

Additionally, this study also examined the relationship between measures of spread (range and standard deviation) and those of center (mean and median). Visual examinations of Figures (4.18) to (4.21) depict such relationship .The general trend of these plots show increasing variability with increasing mean discomfort, i.e. as the measures of center increase, the measures of spread increase too. Specifically, it is seen that at higher discomfort levels there seems to be much higher variability. A possible explanation for increased variability at higher discomfort levels could be the result of the inter-individual differences being magnified when the task at hand is more stressful.

The findings of this study fill the knowledge gap that exists in our current understanding of SPH-associated discomfort. First, this study has shown that no single probability distribution or family of distributions can be used to accurately characterize different SPH tasks. This finding is generally interpreted to imply that the characterization of stress levels SPH tasks by measures of center alone may not be adequate. Secondly, this study showed the effect that the different task parameters-external load and posture - have on the amount of inter-individual differences in SPH task trials. Specifically, certain posture-load combinations like external hand-load and non-straight leg postures seemed to significantly affect the amount of inter-individual differences in SPH task trials (Tables 4.11, 4.12 and 4.13). These findings point towards the need for a more precise and informative method for characterizing an SPH task trial, one that would accurately characterize stress levels of different posture-load combinations.

This study has highlighted the inter-individual variations in discomfort associated with SPH tasks and in so doing demonstrated how SPH task parameters affect the amount of inter-individual variability in SPH tasks. There is an urgent need, therefore, to consider inter-individual differences in SPH task characterization if effective control and assessment of WMDS is to be achieved. In demonstrating and quantifying (using concepts such as lowest and highest treatment means of posture-load combinations as used in Tables 4.11 - 4.17) the amount inter-individual differences in SPH task trials, this study has provided an introduction into some future study that will seek to consider population distributions of perceived discomfort in characterizing SPH task trials. It is feasible, therefore, to take inter-individual differences into account in characterizing SPH tasks if we adopt methods that use empirical discomfort distributions. This will be a step forward in handling the variations in SPH tasks and would probably result in more individuals being accommodated while conducting SPH tasks. The current study was limited to 20-second static trials; future studies could investigate dynamic tasks and/or tasks longer than 20 seconds in duration.

Chapter 5

Quantifying discomfort levels of static posture holding tasks using empirical distributions of perceived discomfort.

5.1 Introduction

Static posture holding (SPH) tasks statistically maintaining working postures over certain time durations are common across various industrial sectors, including manufacturing, service and agriculture (Olendorf and Drury 2001; Chung et al. 2005). SPH tasks can impose large stresses on the musculoskeletal system and lead to significant discomfort to workers if they are designed without due consideration of human characteristics, capabilities and limitations.

Discomfort associated with SPH needs to be controlled as excessive discomfort may indicate high risks of work-related musculoskeletal disorders (WMSDs) - although the link between work-related discomfort and WMSD risks has not been conclusively established, many research studies pointed to its existence on the grounds that they are both related to exposure to biomechanical load on the musculoskeletal system (Nag 1991; Putz-Anderson and Galinsky 1993; Miedema et al. 1997; Bernard et al. 1997). Some researchers indeed view work-related discomfort/pain as a precursor of WMSDs (Corlett and Bishop 1976; Dickerson et al. 2007; Kee 2004; Kee and Lee 2012). Thus, it is possible that controlling SPH-associated discomfort contributes towards the reduction of WMSD risks (Putz-Anderson and Galinsky, 1993, Dul et al. 1994, Scott Schneider, 1998, Miedema et al., 1997, Kee and Lee 2012). Also, regardless of whether or not discomfort is associated with WMSD risks, it is certainly desirable to prevent excessive discomfort as it is a negative human experience that can significantly compromise the quality of work life and also work productivity.

An SPH task can be specified in terms of three task parameters: that is, posture, external load and posture holding time (PHT). These task parameters seem to greatly affect the level of perceived discomfort that an individual experiences from performing an SPH task. In addition, the performers individual characteristics, physical and psychological, also contribute. Thus, different individuals experience different levels of discomfort even when performing identical SPH tasks in terms of the three task parameters. A group or a population of workers therefore would give rise to a probability distribution of perceived discomfort for a particular SPH task. From an ergonomics viewpoint, design interventions for controlling SPH-related discomfort must aim to ensure that the majority of the target worker population experiences less than excessive discomfort. Such idea of population accommodation has been one of the most fundamental design principles in the field of ergonomics and human factors engineering (Marshall et al., 2008, Marshall et al., 2010, Jung et al., 2009, Reed and Flannagan, 2001, Vasu and Mital 2000).

Effective control of SPH-related discomfort necessitates as a prerequisite an ability/method for representing discomfort levels of different SPH tasks and further determining their acceptability. In other words, determining which SPH tasks are acceptable or unacceptable or whether current SPH tasks need to be redesigned or not requires a certain index/metric that operationalizes the construct of discomfort level of an SPH task in a manner that guides designers decision makings. Surprisingly, the fundamental question of how to quantify the level of discomfort of an SPH task has not been extensively studied. Numerous previous studies examined individuals perceived discomfort ratings data resulting from SPH tasks (Boussenna et al. 1982; Manenica 1986; Genaidy et al. 1995; Kee and Karwowski 2001; Olendorf and Drury 2001; Kee 2004; Park et al. 2009; Meijst et. al. 1995; Miedema et. al. 1996; Reneman et. al. 2001; Chung et al. 2003b; Kee and Lee 2010). However, these studies did not result in the development of a quantitative index for meaningfully representing discomfort levels of SPH tasks. They mostly examined the effects of task parameters and personal variables on perceived discomfort using statistical analysis techniques, such as analyses of variance and regression analyses. Understanding the effects of task and personal variables on discomfort is certainly important. However, it by itself does not shed light on the question of which SPH tasks are acceptable or unacceptable, especially in light of the goal of population accommodation.

The lack of means for meaningfully quantifying discomfort levels of different SPH tasks is problematic as it hinders decision makings involved in ergonomics design interventions for controlling SPH-related discomfort, especially, making the decisions on which SPH tasks are acceptable or unacceptable. As an effort towards addressing this problem, the current study presents a new quantitative index for characterizing discomfort levels of SPH tasks. This new index is named the population accommodation level estimate (PALE) and estimates the proportion of the target worker population that experiences less than excessive discomfort. This new index is predicated upon the use of empirical discomfort distributions. In what follows, the index as well as the data collection needed for the use of the index are described. Also, an illustrative example is provided to demonstrate the usage of the index.

5.2 The population accommodation level estimate (PALE) index

5.2.1 Data collection

Any given SPH task can be specified by three parameters: (1) the adopted posture (P), (2) the external load (L) and (3) the posture holding time (PHT). The posture can be defined by a combination of body part angles. The external load can be represented by hand-held load levels or loading exerted by pushing or pulling activities. The PHT represents the total time duration an individual performs an SPH task. The level of discomfort for a given SPH task can therefore be represented as follows:

$$\text{Discomfort level} = f(P, L, PHT) \tag{5.1}$$

Having defined an SPH task by its three parameters, the level of discomfort is empirically obtained from each individual performing the task by use of a psychophysical rating scale.

The experimental procedure including prior preparation for a SPH task study generally consists of five steps: (1) determination of posture-load combination to be used and the posture holding time; (2) Pilot testing the SPH task to determine if subjects will be able to adopt the postures and also determine if the posture holding time will result in excessive discomfort for the target population; (3) conduct subject recruitment. Depending on the objective and the target population, recruitment could be limited to a certain gender or a specific age group; (4) conduct a training session to familiarise subjects with the experiment and obtain an informed consent from the subjects; and (5) administer the SPH task and measure discomfort level at the completion of each task.

5.2.2 Probability histogram representation

An initial step in developing this new representation method is to establish a probability distribution associated with the discomfort level of a SPH task. The following notation will be adopted: Let y, denote the physical discomfort for a given SPH task and p (y) the probability that a SPH task trial has a discomfort rating y. For a given SPH task trial, the probability of occurrence for discomfort rating y will be computed as follows:

$$p(y) = \frac{\text{Number of subjects experiencing y}}{\text{Total number of subjects}} \tag{5.2}$$

The probability of a discomfort rating being within a specified range can now be characterized based on the probability histogram for each SPH task. Depicting the discomfort distribution by use of histograms implies that no prior assumptions need not to be made about the underlying probability distribution.

5.2.3 Population accommodation level estimate

An accommodation level is defined as the percentage of the total population performing a SPH task that would experience discomfort less than a specified design limit of discomfort. A designed limit is defined as the maximum acceptable discomfort level on a psychophysical rating scale.

The population estimate of the accommodation level is expressed as follows: accommodation level = Pr (discomfort level) $\leq$ (design limit). The estimate of the accommodation level can be computed as follows:

$$Probability(discomfort \leq y) = \sum_{Y=0}^{y} (Probability(discomfort = Y)) \quad (5.3)$$

5.3 An illustrative example

5.3.1 Experiment

Ten males and ten females participated in this study as paid volunteers. Prior to participation, the participants had a training session to familiarize themselves with the use of the Borg CR-10 rating scale (Figure 5.1). Each participant signed a written informed consent before participation. The Auburn University Institutional Review Board approved the experimental protocol.

0 -	Nothing at all
0.5 -	Extremely weak (just noticeable)
1 -	Very weak
2 -	Weak (light)
3 -	Moderate
4 -	Somewhat strong
5 -	Strong (heavy)
6 -	-
7 -	Very strong
8 -	-
9 -	-
10 -	Extremely strong (almost max)
•	Maximal

Figure 5.1: Borg's new category-ratio (CR-10) scale. Reprinted from Borg 1982.

The participants performed a short-period (20 seconds long) one-handed static object holding task in a total of 180 posture-hand load conditions: the one hundred and eighty posture-hand load conditions are a combination of sixty postures and three hand load levels. The sixty postures represent various one-handed static object holding postures that can be found in industrial workplaces and were generated by combining four back, three arm and five leg postures. The three hand load conditions were 0 kg (no hand load), 2.2 kg and 3.6 kg; cylindrical objects were used as the hand loads.

Prior to a box holding trial, a participant changed into a tight outfit (tight short and short sleeves). Also, spherical reflective markers were attached on body landmarks so that the body postures can be accurately recorded by the VICON motion capture system during the experiment trial (Figure 5.2). After this initial preparatory set up, the participant adopted the posture and performed the one-handed static object holding task the object was be brought to the participants dominant hand by the experimenter immediately after the participant adopted the posture. In each trial the VICON system kept track of the positions of the attached reflective markers over time and display the distances between their current and correct positions in real-time. When a body attached marker is farther away from its correct position the experimenter instructed the participant to correct the posture. For each SPH task, Subjects were asked to rate their level of discomfort at the completion of each 20-seconds long SPH task trial.

The 180 SPH trials were performed over three sessions by each participant. The three sessions were conducted on three separate days to prevent fatigue effects. The participants were given as much rest as they needed between consecutive trials. Even when the participated reported no fatigue, at least 1 minute rest period was provided before the next trial. Also, and after 9 experimental trials, the participant was given an extra 5 minute rest period before he/she could start the next trial. The subjects were also allowed to have additional

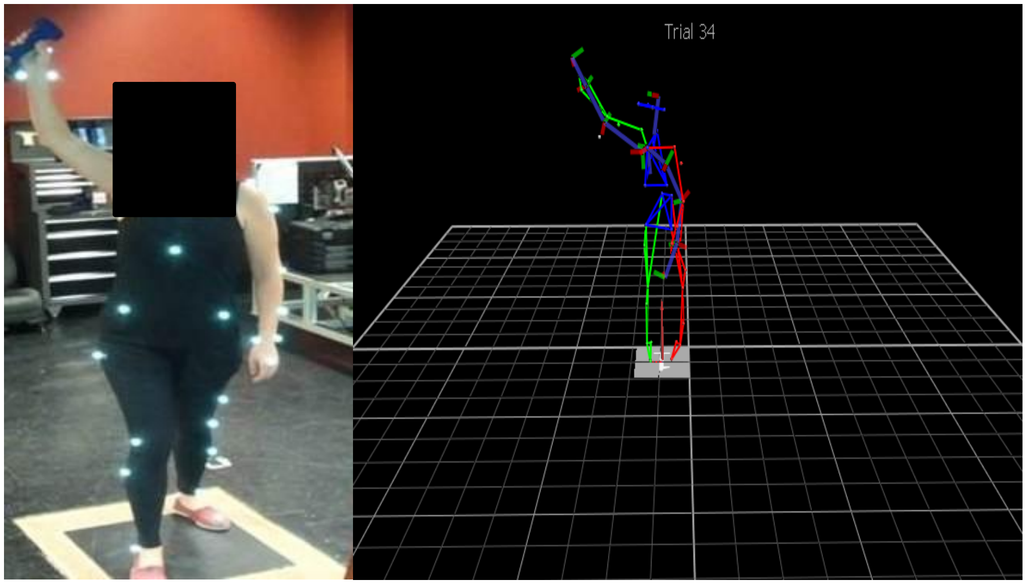


Figure 5.2: An illustration of the experimental set-up for the SPH task trials including the VICON capture shot of a static trial.

rest periods as they wanted. Similar rest patterns were reported by Olendorf and Drury (2001) who also had the participants in their study perform a 20 s long SPH task. In their study, participants were allowed 45 s breaks between consecutive trials.

To determine the probabilities associated with each discomfort level in a SPH task trial, a probability histogram for the discomfort levels was plotted. Therefore, a total of 180 distinct probability histograms were plotted to represent the 180 SPH tasks. The probability histograms allow for the computation of discomfort rating probabilities for the SPH tasks.

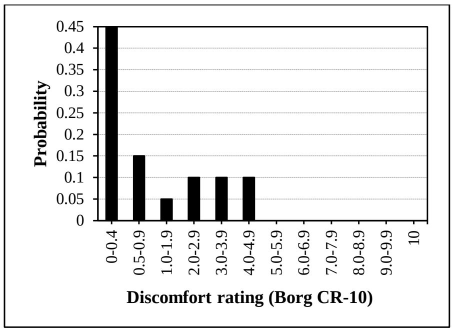
To determine the accommodation level for a SPH task, a design limit was set at 4 for our current study. $y = 4$ is the discomfort rating value at which a subject undertaking a SPH task will perceive somewhat strong discomfort based on the Borg CR-10 rating scale. At this point the discomfort is considered moderate. The probability of discomfort rating being less than or equal to 4 is computed as: Pr $(0 \leq y \leq 4)$. Population accommodation level is estimated based on this criterion. The population accommodation level estimate (PALE) in each SPH task and is computed as follows:

$$\text{PALE} = (0 \leq y \leq 4) \tag{5.4}$$

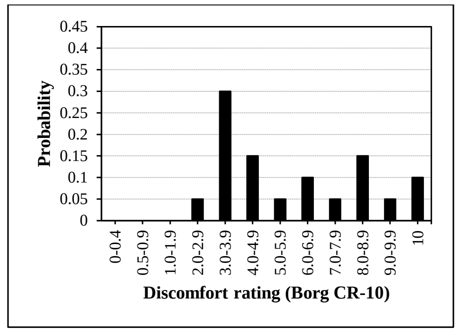
SPH tasks with accommodation levels greater than 95 percent are considered safe for a majority of the study population. The 95-100 percent probability range is used as a criterion for judging safe and acceptable SPH tasks in this study.

5.3.2 Results

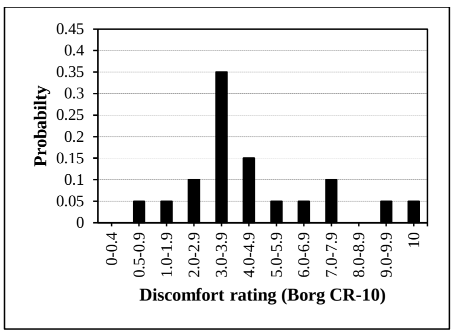
For each SPH task, and thus for a total of 180 SPH task trials, a probability histogram associated with it was plotted. For each SPH task, there was a distinct probability distribution associated with it. Figure 5.3 (a) Figure 5.3 (f) show examples of such histograms. Only few examples are included here for the sake of brevity.



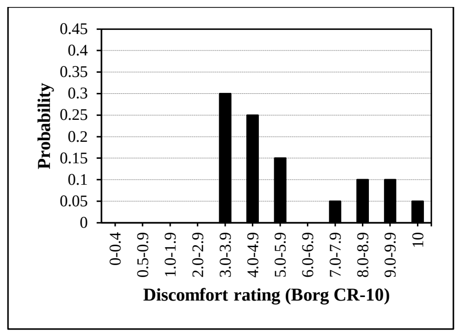
a). SPH 121



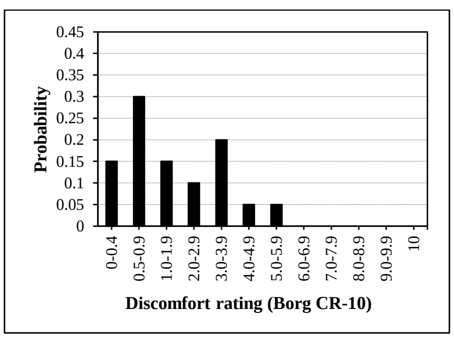
b) SPH 36



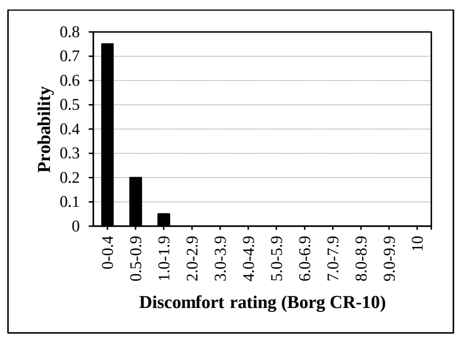
c). SPH 107



d) SPH 18



e) SPH 50



f) SPH 4

Figure 5.3: Examples of Probability histograms of discomfort ratings for selected SPH tasks.

To determine the percentage of our study participants that were accommodated at the design limit of y= 4, an accommodation level was computed for each SPH task. For our study population this value represented the percentage of the population that rated the task as acceptable based on the pre-determined discomfort design limit. Figure 5.4 shows the results. The following observations can be made from table 1: (1) in 60% of the SPH asks (108 out 180), the accommodation level was deemed to be within the acceptable limit (0.95-1.00); (2) of the remaining 72 SPH tasks that were considered unacceptable, 57% (41 out of 72) were tasks involved object holding in an elevated arm position (arm posture 3); and (3) out of the 108 tasks that had accommodation levels in the 0.95-1.00 range, 55% (59 out of 108) were tasks where there was no hand-held load (Load level 1).

		1.Straight Back 			2. Back Bent 			3. Back twisted 			4. Back bent & twisted 		
Legs	**Load Level**	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 	Arm 1 	Arm 2 	Arm 3 
1 	**1**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90
	2	1.00	1.00	0.85	1.00	1.00	0.75	1.00	1.00	0.75	0.90	0.95	0.70
	3	0.95	0.90	0.60	0.90	0.95	0.55	0.95	0.90	0.65	0.9	1.00	0.50
2 	**1**	1.00	1.00	1.00	1.00	1.00	0.95	1.00	1.00	0.95	0.95	1.00	1.00
	2	1.00	0.95	0.80	0.90	0.95	0.70	1.00	1.00	0.65	0.90	0.90	0.70
	3	0.90	0.90	0.65	0.90	0.85	0.60	0.95	0.95	0.45	0.95	0.85	0.50
3 	**1**	1.00	1.00	1.00	1.00	1.00	1.00	0.95	1.00	1.00	1.00	1.00	0.95
	2	0.95	1.00	0.80	1.00	0.90	0.75	1.00	0.95	0.70	0.90	0.90	0.70
	3	0.95	0.95	0.65	1.00	0.95	0.55	0.90	0.95	0.60	0.90	0.95	0.40
4 	**1**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.95	1.00
	2	1.00	1.00	0.65	0.95	1.00	0.75	1.00	0.95	0.80	0.80	0.80	0.65
	3	0.95	1.00	0.55	0.85	0.95	0.50	0.90	0.95	0.65	0.85	0.95	0.40
5 	**1**	1.00	1.00	1.00	1.00	1.00	0.95	0.95	1.00	0.95	1.00	0.95	1.00
	2	1.00	1.00	0.8	0.95	0.95	0.75	0.95	0.90	0.75	0.80	0.90	0.75
	3	0.95	1.00	0.60	0.85	0.85	0.55	0.95	0.9	0.55	0.85	0.75	0.55

Figure 5.4: Accommodation levels for the study population representing 180 SPH tasks.

5.4 Discussion

This study has presented a new approach to characterizing discomfort levels of SPH tasks, one that is based on empirical probability distribution of discomfort, named PALE (Population Accommodation Level Estimate). The goal was to use probabilities to characterize the discomfort distribution in SPH tasks and determine the percentage of the study population accommodated while performing an SPH task. The accommodation level is computed based on some predefined discomfort design limit. The researchers in this study are yet to find studies that do consider population distribution of discomfort levels. This study therefore, aimed to address the lack of consideration of population distribution of physical discomfort levels in SPH tasks.

As has been stated in the introduction, changes in discomfort levels in a SPH task are driven by the different parameters that specify the task it including; posture, external load and posture holding time. It is paramount that the population distribution of discomfort levels in a SPH task is examined if accurate characterization is to be made. Visual examinations of the probability histograms depicting the distribution of discomfort levels of SPH tasks show differences in distribution type in different SPH tasks (Figure 3). No single distribution type or family of distributions could be used to characterize these tasks. A new approach in discomfort level characterization is therefore necessary. The use of probabilities histograms does provide a simple, yet efficient method for quantifying population distribution of discomfort levels in SPH tasks.

To illustrate this new PALE approach, the percentage of the study population accommodated while performing SPH tasks was computed using the discomfort level probabilities.

The proportions of the study population that fell below the threshold limit were considered to be accommodated. Table 1 shows the accommodation levels for the 180 SPH tasks. Higher accommodation values imply the SPH task was less stressful to a majority of the study population. Two major observations were be made from Table 1. First, the low accommodation values of SPH tasks that involved the arm being raised above the shoulder level (Arm 3) seem to suggest that these tasks were more stressful and therefore resulted in discomfort values larger than the set threshold limit. This is in agreement with studies done by both Park et al., (2009) and Olendorf and Drury (2001), who identified elevated arm posture as a stress-increasing postural element. Second, a majority (108 out of 180) of the SPH tasks seemed to be less stressful, suggested by the high accommodation values ($\geq 95\%$) . This could be attributed largely to the fact that this study was limited to 20-seconds SPH tasks, maybe if the task duration was longer we could observe different patterns. An additional goal of this study was to determine which SPH tasks are safe for a majority of the study population. Setting a criterion for rejection of accommodation values helps to determine which tasks should be included when designing the tasks and which should be taken out. Specifically, the tasks that were found to be unacceptable could be re-designed.

The PALE index proposed here provides us with a novel strategy for evaluating SPH tasks. First, a discomfort level limit can be set using a psychophysical rating scale (Borg CR-10). Second, a target population accommodation level can be chosen (e.g. 95% of the population based on the threshold limit chosen). Third, PALE can be calculated and compared against the target accomodation level. If PALE is less than the target accomodation level, the task will be considered unacceptable. Using this approach effective intervention strategy can be made based on desired accommodation performance. Questions regarding well-defined population percentages can be addressed, since the proportions were established based on empirically obtained discomfort rating levels. Accurate recommendations can now be made based on population percentages that would find a SPH task stressful or less stressful.

This research study has proposed the use of probability histograms in characterizing perceived discomfort ratings of one-handed SPH tasks. It is thought that this study has sufficiently demonstrated a new method for SPH task evaluation detailing accommodation levels. Probabilistic statements that have not been made before with regard to physical discomfort level evaluation of SPH tasks can now be made. Overall, probability histograms of the discomfort ratings for a population of workers are a simple and effective means of characterizing discomfort levels of SPH tasks. It should be noted however, that this study has not developed an ergonomics evaluation tool, but rather an index for SPH task evaluation that quantifies physical discomfort level in probabilistic terms. In this regard, the threshold limit used in this study should not be considered as a general limit but rather as a guideline. Various threshold limits can be set based on specific conditions and requirements.

While this new quantitative index for characterizing discomfort levels of SPH tasks seems very promising, the accommodation levels computed in this study were only point estimates of the population accommodation level. A larger sample size will allow for the investigation of other statistical inferences and calculation of confidence intervals so that we are not just dealing with point estimates but appropriate interval estimates. Also, with a larger sample size we will be able to use parametric statistics to try and obtain the real underlying distribution of a SPH task. Future studies could look into the development of quantitative models that will realistically predict how people move and interact with systems and how the discomfort distributions vary in those environments. This will be a step forward from the current study as this will involve examining dynamic tasks that are commonly encountered in industry. With more data, future studies could also focus on the distribution of specific individual factors such as stature, BMI, gender and body part posture in relation to perceived discomfort.

Chapter 6

Conclusion and Reccomendations for Future Studies

6.1 Introduction

In ergonomics and related research areas, numerous studies have examined discomfort resulting from static posture holding (SPH). Many of these studies aimed to understand the effects of posture and external load on perceived discomfort. Some studies investigated the effect of task duration (posture holding time(PHT)) on discomfort of SPH. The results of these studies indicated that posture significantly affects perceived discomfort along with posture holding time and external load. Also, these studies reported that perceived discomfort monotonically increases over time during a prolonged SPH task trial. These research studies have greatly advanced our understanding of perceived discomfort from SPH. Nonetheless, some significant knowledge gaps seem to exist, which hamper adequately representing and evaluating discomfort associated with SPH. First, the existing reseach studies do not seem to have fully elucidated the mathematical characteristics of the discomfort-time relationship. Second, very few research studies seem to have examined SPH-associated discomfort with a focus on the inter-individual variation.

This study was able to demonstrate the different discomfort-time patterns of SPH tasks. Specifically, this study reports that the positively accelerated time increase patterns are found in some discomfort-time sequences of prolonged SPH trials in addition to linear and negatively accelerated time increase patterns, which were observed by previous studies. Additionally, this study also reports that there is no single well-known distribution family that can be used to robustly fit different SPH tasks. A population of workers of workers would give rise to a proabability distribution of perceived discomfort for a given SPH task. A consequence of lack of single distribution to describe an SPH task's stress levels is that simple descriptives statistics become limited in describing an SPH task's stress level. Individual differences have to be considered when characterizing discomfort levels of SPH tasks. A new approach for quantifying discomfort levels was proposed. This study has proposed a new methodology for characterizing discomfort levels of SPH tasks. A quantitative index, Probability-based Accomodation Level (PALE), has been proposed to quantify the discomfort levels of SPH tasks. Probabilistic statements that have not been made before with regard to physical discomfort level evaluation of SPH tasks can now be made.

6.2 Summary of findings

Two primary experiments were performed in this study. The objective of the first study was to elucidate the nature of the relationship between perceived discomfort of SPH and PHT. The main objective of the second study was to conduct an investigation on the inter-individual variation in perceived discomfort of SPH tasks. Data and results from study two were also used to propose a new methodology for characterizing discomfort levels of SPH tasks. This new method was used to estimate the population accomodation levels for the SPH tasks performed in this study.

The findings of the research are summarized below.

- Three different monotonically increasing time patterns (negatively accelerated, linear and positively accelerated) seem to co-exist in discomfort-time profiles of SPH trials.

- The power function form can serve as a general representation of the discomfort-time relationship. Previous research studies suggested that the relationship between perceived discomfort of SPH and PHT is linear in its nature, while others contended that a negatively accelerated logarithmic time function better depicts the discomfort-time relationship.

- The results of the distribution identification showed that there is no single well-known distribution family that can be used to robustly fit different SPH tasks. There is need, therefore, to carefully examine each SPH task distribution in order to determine the SPH tasks stress level. Simple descriptive statistics are limited in describing an SPH task's stress levels.

- Different SPH trials exhibited substantial variation in the amount of spread. External load significantly affected the amount of inter-individual variability in SPH task trials. Generally, there was comparatively higher inter-individual variability in SPH tasks that involved higher load levels. Increases in hand load increases muscle load resulting in larger discomfort values.

- At higher discomfort levels there seems to be much higher variability in SPH tasks. A possible explanation for increased variability at higher discomfort levels could be due to magnfied inter-individual differences when the task at hand is more stressful.

- Probability histograms of the discomfort levels for a population of workers are a simple and effective means of characterizing discomfort levels of SPH tasks. The fact that we are able to quantify the proportion of the study population that experiences a specified level of discomfort also allows us to quantitatively answer questions such as; what percentage of study population will experience a certain level discomfort while performing manual work tasks?

- The proposed Probability-based Accomodation Level Estimate (PALE) methodology seems very promising and may provide us with a better approach for quantifying an SPH task's stress levels. The PALE index seves as a quantitative index for meaningfully representing discomfort levels of SPH tasks. A target population accommodation level can be set and compared against a calculated PALE value to determine the acceptability or unacceptability of a given SPH task.

6.3 Limitations and reccomendations for future studies

Some limitations of the current research study along with reccomendations for future studies are presented.

- The first study only considered two-handed static box holding tasks and one hand-load weight. Collecting and analyzing more data would be beneficial especially for confirming the validity of the research findings over a wider range of conditions.

- Most study participants in this research study were young adults and of normal weight category. Future studies will need to examine discomfort-time profiles of older and/or obese individuals to understand the effects of age and obesity level and also confirm the validity of the study findings with those segments of the population.

- This study examined only subjective ratings of perceived of perceived discomfort without employing other stress/strain measures. Collecting and analyzing physical and physiological response data along with perceived discomfort ratings would further enhance our understanding of the discomfort-time relationship in SPH.

- The second study was limited to 20-second static trials; future studies could investigate tasks longer than 20 seconds in duration.

- The accommodation levels computed in this study were only point estimates of the population accommodation level. Future studies could look into the use of statistical inferences and confidence intervals to describe the discomfort levels of SPH tasks. A larger sample size will allow for the calculation of such confidence intervals so that we are not just dealing with point estimates but appropriate interval estimates.

- Future studies could look into the development of quantitative models that will realistically predict how people move and interact with systems and how the discomfort distributions vary in those environments. These outcomes will represent an important step towards developing and perfecting not only a method that can be used to accurately simulate variability in indviduals' performing industrial tasks, but also a new Digital Human Modeling Approach for postural stress evaluation and control.

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Appendices

Appendix A

Informed consent for the two experiments conducted for the purposes of this dissertation.

Auburn University

Auburn University, Alabama 36849-5346

Department of
Industrial and Systems Engineering
3310 Shelby Centre

Telephone: (334) 844-1424
Fax: (334) 844-1371

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT

You are invited to participate in a research study to study the relationship between perceived discomfort of static posture holding and posture holding time**.** The study is being conducted by Jack Ogutu, Graduate Student, under the direction of Dr. Woojin Park, Assistant Professor, in the Auburn University Department of Industrial Engineering. You are invited as a possible participant because you are a male adult aged between 19 to 48 years, and,

a) You have no noted history, symptoms and/or risk factors associated with musculoskeletal disorders and, currently have no back pains or joint pains, *and*,
b) You are willing to complete health and fitness-related questionnaires to establish your level of habitual physical activity and aerobic fitness, and will have physical measurements taken. This information will be used to determine your eligibility to participate.

If you meet the criteria above and the information we collect about you indicates that you will most likely be at low risk for injury, you will be qualified to participate.

What will be involved if you participate? Your participation is completely voluntary. If you decide to participate in this research study, you will be asked to come to the Auburn University's Ergonomics Lab, Shelby Centre for pre-participation evaluation. We will take your blood pressure and measure your height and weight. In addition you will complete the health questionnaires as noted above.

If you qualify to participate, you will be asked to perform 12 pre-determined Posture Holding Tasks (holding a box that weighs 4.4 pounds) over a number of sessions. Your total time commitment will be approximately 3 hc including the 1 hour pre-participation evaluation testing.

To prepare for the experiment you will be asked to refrain from strenuous physical activities or exercises on the day before and the day of the experimental trial.

On the day of the session you will,

a) Be asked to put on tight-fitting clothing made of nylon and spandex (coverall).
b) Have reflective markers attached to the right shoulder, the back of the left hand and on the right knee kneecap to monitor your motions.
c) Be audio-recorded as you describe your perceived stress during the trials.
d) Complete a set of posture holding tasks.

Participant's Initials___________________ **Page 1 of 2**

Figure A.1: The IRB consent form for study 1

Are there any benefits to yourself or others? There are no direct benefits to participants. However your participation may benefit others by protecting workers from excessive work-related postural stress.

Are there any risks involved? There is risk of injury from dropping the 4.4 pounds box on your foot. Other risks may include muscle spasms, soreness, back pain, strain and sprain. In the event of an injury that requires medical attention, all expenses will be your responsibility. You may need to check in advance that your insurance will cover any injuries. If you sustain an injury, we can share information about where you might receive medical attention.

Will you receive compensation for participating? For full participation, you will receive a check for $180 in the mail. However, if for any reason you quit the study, your compensation will be pro-rated based on hours completed. Information to send your compensation to you will be collected in a separate file and will not be linked to your study responses. If you are not an AU student, you will need to register with Auburn University as a vendor using your SSN (a link will be sent to you separately for registration) for your compensation to be processed. For AU students your student ID will be required for compensation to be processed.

If you change your mind about participating, you can withdraw at any time by notifying the experimenter. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Once you've submitted your data, it will be kept confidential until the end of the study when your contact information will be destroyed. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the Department of Industrial Engineering.

Any data obtained in connection with this study will be made anonymous at the end of the study and will then be kept indefinitely. We will protect your privacy and the data you provide. After your contact information is destroyed, your data will be anonymous. Information collected through your participation may be published in a professional journal.

If you have questions about this study, please ask them now or contact the Investigator at 334-750-4268 or by e-mail at joo0002@auburn.edu, or the Faculty advisor, Dr Woojin Park at wzp0006@auburn.edu or 334-844-1311.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Research and Compliance or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.
A copy of this document will be given to you to keep.

____________________________________ Participant's signature Date	____________________________________ Investigator obtaining consent Date
____________________________________ Printed Name	____________________________________ Printed Name

Participant's Initials **Page 2 of 2**

Figure A.2: The IRB consent form for study 1

Auburn University

Auburn University, Alabama 36849-5346

Department of
Industrial and Systems Engineering
3310 Shelby Centre

Telephone: (334) 844-1424
Fax: (334) 844-1371

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT

You are invited to participate in a research study develop an efficient method of determining an individual's perception of posture stress while performing static single-handed box holding tasks .The study is being conducted by Jack Ogutu, Graduate Student, under the direction of Dr. Woojin Park, Assistant Professor, in the Auburn University Department of Industrial Engineering. You are invited as a possible participant because you are an adult aged between 19 to 48 years, and,

a) You have no noted history, symptoms and/or risk factors associated with musculoskeletal disorders and, currently have no back pains or joint pains, *and*,
b) You are willing to complete health and fitness-related questionnaires to establish your level of habitual physical activity and aerobic fitness, and will have physical measurements taken. This information will be used to determine your eligibility to participate.

If you meet the criteria above and the information we collect about you indicates that you will most likely be at low risk for injury, you will be qualified to participate.

What will be involved if you participate? Your participation is completely voluntary. If you decide to participate in this research study, you will be asked to come to the Auburn University's Ergonomics Lab, Shelby Centre for pre-participation evaluation. We will take your blood pressure and measure your height and weight. In addition you will complete the health questionnaires as noted above.

If you qualify to participate, you will be asked perform short-period **(20 seconds)** one-handed static object holding trials for 180 pre-generated posture-hand load weight combinations, the boxes weigh 4.4 pounds and 8.8 pounds. Your total time commitment will be approximately 6 hours (= 3 sessions x 2hr /session). Each session will be conducted on a separate day.

To prepare for the experiment you will be asked to refrain from strenuous physical activities or exercises on the day before and the day of the experimental trial.

On the day of the session you will,

a) Be asked to put on tight-fitting clothing made of nylon and spandex (coverall).
b) Have reflective markers attached to the right shoulder, the back of the left hand and on the right knee kneecap to record your motions with a motion capture system.
c) Be audio-recorded as you describe your perceived stress during the trials.
d) Complete a series of 20 seconds holding tasks.

Are there any benefits to yourself or others? There are no direct benefits to participants. However your participation may benefit others by protecting workers from excessive work-related postural stress.

Participant's Initials ____________ **Page 1 of 2**

Figure A.3: The IRB consent form for study 2

Are there any risks involved? There is risk of injury from dropping the 4.4 pound and 8.8 pound box on your foot. Other risks may include muscle spasms, soreness, back pain, strain and sprain. In the event of an injury that requires medical attention, all expenses will be your responsibility. You may need to check in advance that your insurance will cover any injuries. If you sustain an injury, we can share information about where you might receive medical attention.

Will you receive compensation for participating? For full participation, you will receive a check for $200 in the mail. However, if for any reason you quit the study, your compensation will be pro-rated based on hours completed. Information to send your compensation to you will be collected in a separate file and will not be linked to your study responses. If you are not an AU student, you will need to register with Auburn University as a vendor using your SSN (a link will be sent to you separately for registration) for your compensation to be processed. For AU students your student ID will be required for compensation to be processed.

If you change your mind about participating, you can withdraw at any time by notifying the experimenter. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Once you've submitted your data, it will be kept confidential until the end of the study when your contact information will be destroyed. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the Department of Industrial Engineering.

Any data obtained in connection with this study will be made anonymous at the end of the study and will then be kept indefinitely. We will protect your privacy and the data you provide. After your contact information is destroyed, your data will be anonymous. Information collected through your participation may be published in a professional journal.

If you have questions about this study, please ask them now or contact the Investigator at 334-750-4268 or by e-mail at joo0002@auburn.edu, or the Faculty advisor, Dr Woojin Park at wzp0006@auburn.edu or 334-844-1311.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Research and Compliance or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.
A copy of this document will be given to you to keep.

______________________________	______________________________
Participant's signature Date	Investigator obtaining consent Date
______________________________	______________________________
Printed Name	Printed Name

Participant's Initials ___________ **Page 2 of 2**

Figure A.4: The IRB consent form for study 2

Appendix B

IRB Participant screening document

Occupational Safety & Ergonomics Laboratory
Dept. of Industrial & Systems Eng.
Auburn University

Subject # __________ Date ________________

Subject Health Questionnaire

a) Age_________
b) Male________ Female________
c) Height____________
d) Weight____________
e) Blood Pressure___________ (BP >140/90 will be excluded from this study).

Note: If you respond "Yes" to any question you will be excluded from this study.

General Medical Questions

1. Have you ever passed out while exercising?	YES	NO
2. Have you ever passed out for any reason?	YES	NO
3. Have you ever had chest pains while exercising?	YES	NO
4. Has anyone in your family died before age 50 secondary to a stroke or Heart Attack?	YES	NO
5. Have you ever been told you have arthritis?	YES	NO
6. Do you have any pins, screws or other implants?	YES	NO
7. Are you now taking any medications for blood pressure, ADD/ADHD or any medications that affect your circulatory or neurological systems?	YES	NO

Orthopedic Medical Questions

8. Have you ever sustained neck pain, e.g Stinger, Pinched Nerve, etc?	YES	NO
9. Have you ever had numbness, burning, or sharp pain in your arms/hands?	YES	NO

Figure B.1: The IRB screening document

10. Have you ever injured your back?	YES	NO
11. Have you ever been told you have a congenital spinal defect?	YES	NO
12. Have you ever been told you have a spondyloliothesis/spondylolysis?	YES	NO
13. Have you ever been told you have a bulging or herniated disc?	YES	NO
14. Have you ever had a significant hip or thigh injury?	YES	NO
15. Have you ever had a significant knee injury?	YES	NO
16. Have you ever had a significant ankle injury?	YES	NO
17. Have you ever had a significant foot or toes injury?	YES	NO
18. Have you ever dislocated a joint?	YES	NO
19. Have you ever broken a toe?	YES	NO

Is there any other medical condition, disease, injury, illness or hospitalization that might prevent you from participating? Please explain – include dates and medications.

Figure B.2: The IRB screening document.

Appendix C

IRB Participant screening document.

"An Efficient Method for Modeling an Individual's Perception of Postural Stress"

EMERGENCY ACTION PLAN

Personnel

Two of the following researchers will be present during all testing sessions. In addition, a qualified researcher will be present to conduct first aid at all sessions.
Jack Ogutu, First aid (cell number-334-750-4268)
Woojin Park, First aid (cell number-334-707-5229)

Communication

Auburn University Medical Clinic: 844-4416
East Alabama Medical Centre (Emergency Department): (334) 528-1150
East Alabama Medical Centre (Hospital): (334) 749-3411
Lee County EMS (Ambulance): (334) 749-8504
Emergency: 911
TigErgonomics Laboratory: (334) 844-1432

Emergency Equipment

A first aid kit is present during all testing sessions. An AED is present at the entrance to each stairwell in the Shelby Center. In addition, as ramp/full access entrance is available for any emergency responders to enter the facility.

Emergency Procedures

1. Use emergency equipment (if applicable), and perform emergency CPR and first aid – if qualified to do so.

2. Instruct investigators to call 911 or EMS and provide the following information:
   - Who you are
   - General information about the injury or situation
   - Where you are: 345 west Magnolia St. Shelby Center for Engineering Technology. We are located in the 3rd Floor. Come in the front of the Shelby center to the right wing of the building. Take the elevator to the 3rd floor of the building, the Lab is in Room 3325.
   - Any additional information
   - BE THE LAST TO HANG UP!

3. Meet the ambulance and direct it to the site you described in the phone call

4. If directed, assist EMS with care of injured person.

5. The primary research investigator must report the adverse event to the IRB via the Office of Human Subjects Research.

Physical Street Address: 3325 Shelby Center for Engineering Technology
Directions to the front of Shelby Center for Engineering Technology

- **345 west Magnolia St. Shelby Center for Engineering Technology. We are located in the 3rd Floor. Come in the front of the Shelby center to the right wing of the building. Take the elevator to the 3rd floor of the building, the Lab is in Room 3325.**

30

Figure C.1: Emergency Action Plan

Appendix D

Manuscript 1: The Thirteen Inadequate Discomfort-Time Profiles.

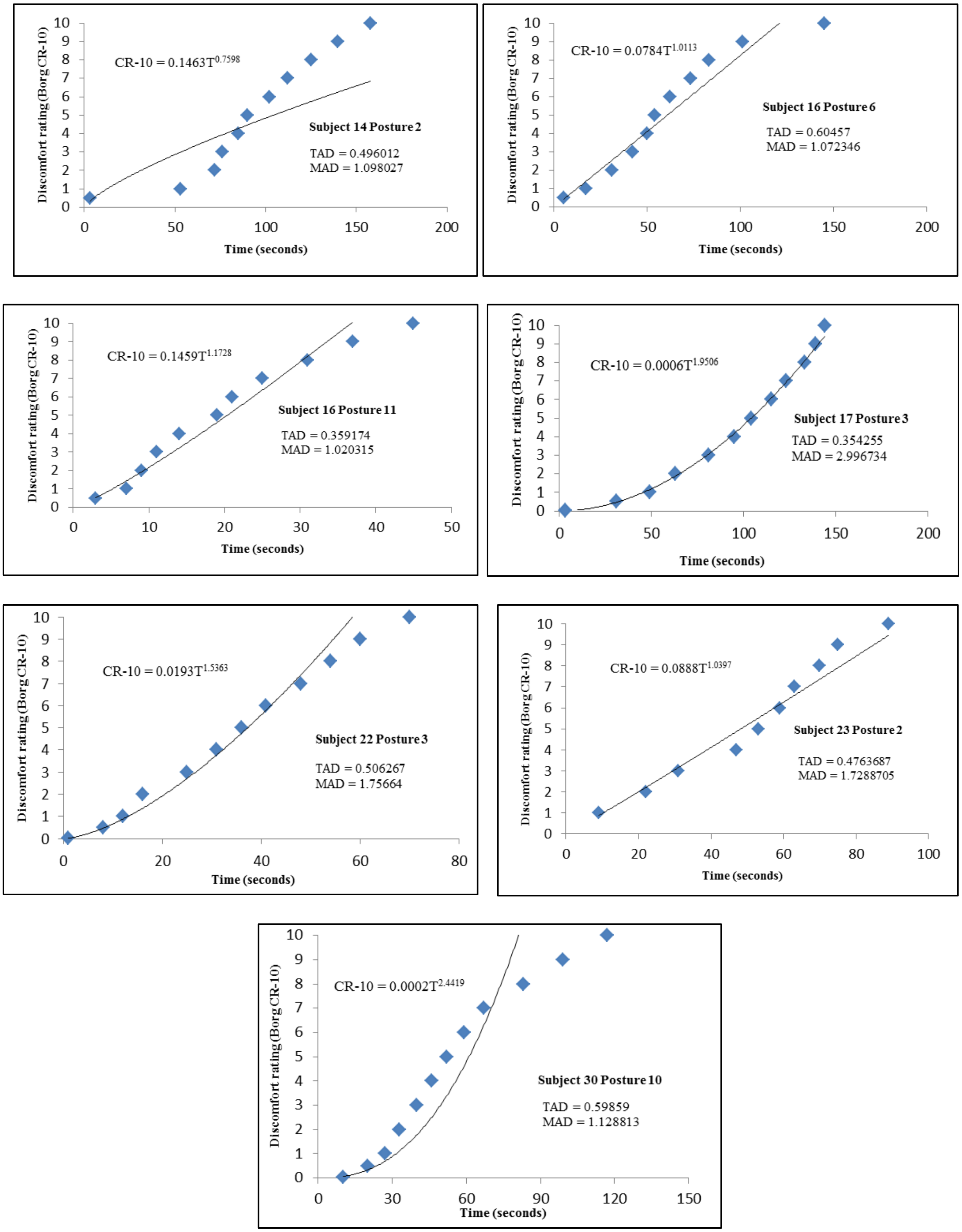

Figure D.1: The Discomfort-time sequences that could not adequately fit the power function f

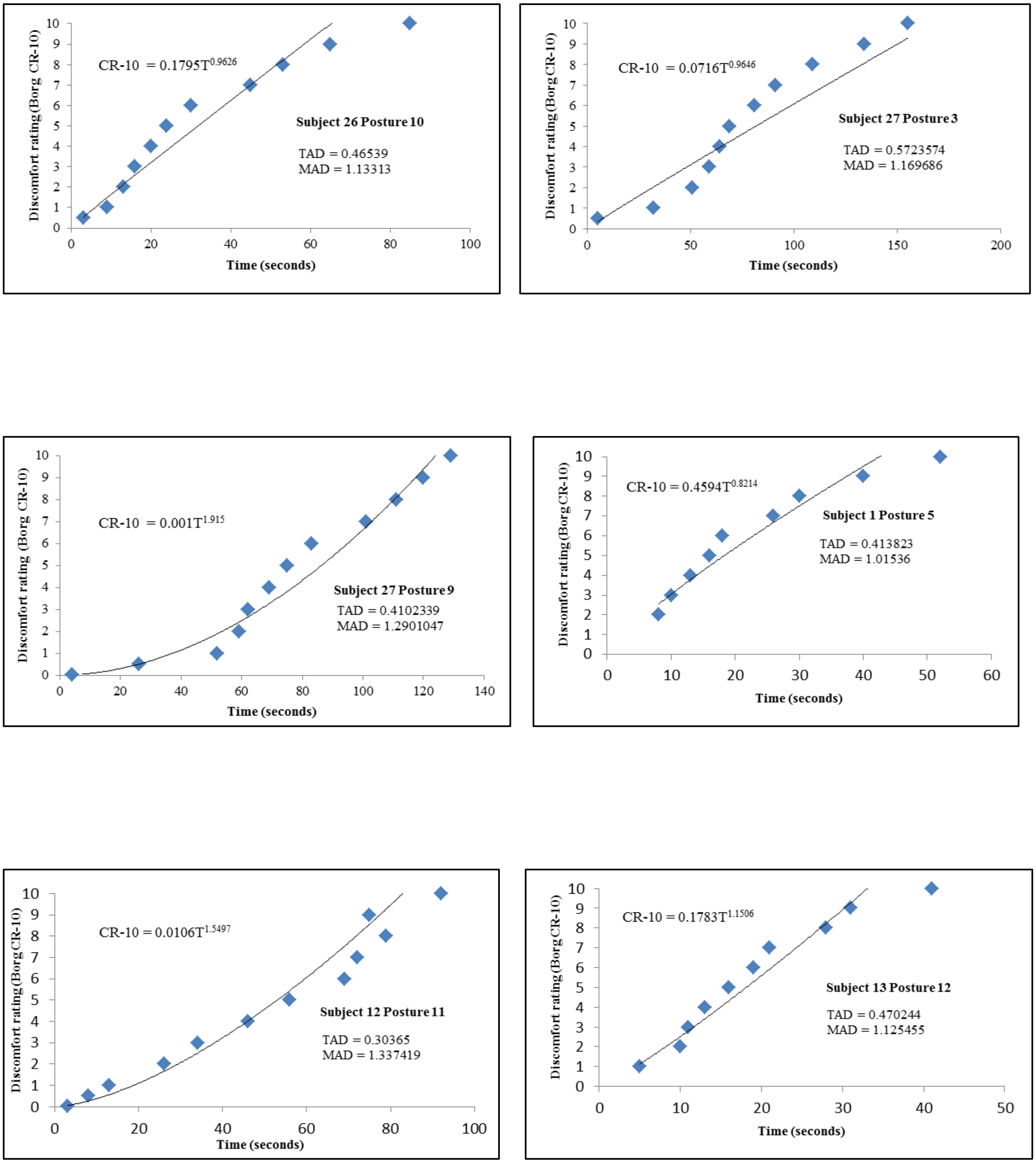

Figure D.2: The Discomfort-time sequences that could not adequately fit the power function form.