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Tissue Oxygenation and Blood Volume and Whole-body Metabolic Responses During Low-back Intensive Occupational Tasks

by

Rammohan Venkata Maikala ©

A dissertation submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Rehabilitation Science

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Name of Author: Rammohan Venkata Maikala

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H.No. 25-85, Ashok Road
Mancherial, Dist. Adilabad
Andhra Pradesh, INDIA 504208

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Tissue Oxygenation and Blood Volume and Whole-body Metabolic Responses During Low-back Intensive Occupational Tasks* submitted by *Rammohan Venkata Maikala* in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Rehabilitation Science.

Dr. Y. Bhambhani (Co-Supervisor)

Dr. M. Crites-Battie (Co-Supervisor)

Dr. G. Bell

Dr. R. Jones

Dr. P. Gervais

Dr. A. Hargens (External Examiner)

16th April, 2002

Dedication

To my beloved brother 'Karunamohan Maikala' who is the spine of my life.
I am not sure what I will do without you.
Your kindness, patience, unselfishness, and generosity brought our family to what it is today.
You are everything one brother can wish for.
Many thanks for helping me throughout my academics and encouraging me to follow my heart.

Also to my parents, 'Padma' and 'Mohan Rao' for teaching me the importance of education, sharing and caring.
You both are my almighty god.
Your love and compassion carried my dreams throughout my educational pursuits.
Thanks to both of you for giving me such a great brother, and lovely and good hearted sister 'Jyotsna'.

ABSTRACT

This research examined tissue and whole-body physiological responses during seated whole-body vibration [WBV] *(Study #1)* and repetitive pushing-pulling/arm cranking *(Study #2)* in healthy men and women. The acute physiological responses were measured using open circuit spirometry and tissue oxygenation was monitored using near infrared spectroscopy.

Study #1: Each subject was exposed to 3 Hz, 4.5 Hz, and 6 Hz WBV in random order on three separate days. The protocol included a six-minute baseline, eight minutes of WBV 'With' and 'Without' backrest, with four-minute recovery periods following each exposure. In each WBV session the subject performed maximal rhythmic handgrip contractions during the final minute.

In both genders, oxygenation and blood volume monitored on the right pre-frontal cortex increased significantly during WBV and were not influenced by the dose 'With' and 'Without' a backrest. In contrast, oxygenation and blood volume on the right lumbar erector spinae significantly decreased with exposure to WBV. Cerebral oxygenation and blood volume were not influenced by backrest support, whereas muscle blood volume was significantly higher without backrest support in both genders. Addition of hangrip contractions significantly increased the cerebral oxygenation and blood volume with concomitant decreases in these variables in the erector spinae muscle. These changes were not related to grip strength in both genders. Exposure to WBV significantly increased oxygen uptake, heart rate and ventilation in both genders but did not elicit significant changes in cardiac output and stroke volume. These differences were more evident in the absence of a backrest.

Study #2: During incremental exercise to voluntary fatigue, the peak oxygen uptake, power output, ventilation rate and oxygen pulse were significantly higher during arm cranking compared to pushing-pulling, with men showing greater values than women. Despite the lower cardiorspiratory responses during pushing-pulling, localized muscle oxygenation was significantly higher, suggesting a greater peripheral limitation during this task. Significant deoxygenation was observed in the right lumbar erector spinae during both these exercise modes, but the values were not significantly different. These findings strengthen the argument that occupational fitness screening should focus on task specific rather than standardized upper body exercise protocols.

PREFACE

"The nature of light is unknown and yet light itself is the key to explain many unknown things"

Hammamatsu Photonics

My interests in "optical investigations of physiology" started the day I joined Dr. Yagesh Bhambhani's Work Physiology Research Laboratory at the Faculty of Rehabilitation Medicine, University of Alberta in 1996. As a result of his mentorship, my personal interests became directed more into understanding of *Photon Propagation in Tissue* than just application of the Near Infra-red Spectroscopy (NIRS) per se. Being an engineer, I was fascinated by the theory and principles behind NIRS, and spellbound by its enormous potential in its noninvasiveness and user-friendliness (of course, the burns on my hands and low-back might prove otherwise). My appreciation of Physiology strengthened with studying its fundamentals, mainly the infamous *Fick equation*, which I believe is so simple but at the same time crucial, as it defines blood flow in the vascular system or fluid mechanics in engineering.

For this doctoral work, I combined my main research interest - Industrial Ergonomics, with the toughest field I have ever come across - Work Physiology. I sincerely hope you enjoy reading this doctoral work of an engineer who attempted to explain occupational physiology in its simplest form.

This dissertation is divided into seven chapters. Chapter 1 introduces the rationale of studying low-back intensive occupational tasks. There is a brief review of injury statistics related to occupations susceptible to mechanical loading and low-back complaints, specifically Whole-body Vibration and Pushing-Pulling. The Introduction extends to various physical risk factors, and provides the impetus of studying both central and peripheral physiological variables. The final pages give details of the NIRS, and conclude with a brief description of this technique to both cerebral and skeletal muscle tissue.

In the context of investigating the role of vibration dose, backrest support, work during vibration, and the influence of gender, Chapters 2,3, and 4 describe a variety of research methodologies. Chapter 2 explores the application of NIRS in studying the cerebral region during exposure to Whole-body Vibration. Chapter 3 evaluates the lumbar erector spinae muscle physiology with NIRS during exposure to Whole-body Vibration. Chapter 4 describes the whole-body physiological responses using the Open Circuit Spirometry during exposure to Whole-body Vibration. These chapters also examine the role of upper body aerobic fitness of the exposed population on their physiological responses.

Chapter 5 examines both biceps brachii (oxygenation and blood volume) responses and cardiorespiratory responses in healthy men and women during repetitive pushing-pulling, and compares them with a standardized arm cranking protocol till exhaustion.

Chapter 6 studies the role of lumbar erector spinae muscle oxygenation and blood volume responses in healthy men and women during both repetitive pushing-pulling and standardized arm cranking protocols.

Chapter 7 is a general discussion of the overall research, and finally the Appendices contain further details of study protocols, and statistical adjustments.

Have fun surfing!

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Dr. Gordon Bell, the ever-friendly professor who always encouraged me to think "what am I asking for" in a research project and, subsequently, "how should I interpret the physiological data". Thanks for showing me in 1996 how muscle biopsies are done and analyzed.

When I bought the book *Principles of Exercise Testing and Interpretation* by Karl Wasserman et al., I was not sure If I was going to read that book thoroughly. However, Dr. Richard Jones! your advice before my Candidacy made me read it and understand the Bohr Curve. Thanks for teaching me the importance of interpreting correlations [during my Candidacy] and the importance of presenting and explaining the graphs.

The one course that stands out in my doctoral program is Seminars in Biomechanics. Dr. Pierre Gervais! you made the course simple but challenging. I am not sure how often a student can say "the course I took is worth the money", and certainly your course was worth every penny. Thanks for your advice on how to interpret the vibration data.

To all of you! Umpteen times I showed up at your door without prior notice and still every one of you had time for me. That indicates how much you care for your students' work. I am touched by such humbleness and sincerity regarding my future.

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Table of Contents

List of Tables

List of Figures

CHAPTER 1
Introduction

Injury Epidemiology:

Gatchel et al. (1995) reported that industrial back injuries are costing employers and insurers billions of dollars in lost time, compensation wages, litigation, and rehabilitation. According to the International Social Security Association, four to seven percent of all employees in the US, Canada, and some European countries are exposed to potential harmful whole-body vibration (Bovenzi 1996). In Great Britain, Palmer et al. (2000) reported that 7,200,000 men and 1,800,000 women at the workplace were exposed to whole-body vibration in a one week period. National health survey comparisons from the United States of America and Canada found that prevalence of low-back complaints in workers exposed to vibration was higher than that estimated in the male working population of USA (Guo et al. 1995), and also compared to controls not exposed to vibration (Liira et al. 1996). Aircrew and helicopter pilots (Simon-Arndt et al. 1997) and drivers of earth-moving vehicles (Miyashita et al. 1992), agricultural tractor drivers (Boshuizen et al. 1990, Bovenzi and Betta 1994), and buses and transit drivers (Bongers et al. 1988) are some of the occupational groups who are at a greater risk for low-back complaints than the control groups unexposed to whole-body vibration. However, the effects of whole-body vibration on the lower back and its relationship with low-back pain are not well understood.

Manual material handling is defined as the application of human effort (including lifting, lowering, pushing, pulling or carrying) for transporting or supporting a load such as an object, person or animal (Dickinson 1995). Injuries resulting from manual material handling are mostly due to overexertion when workers exceed their ability to perform the task (Genaidy et al. 1992). According to the Annual Cumulative Trauma Disorders (CTD) News Cost & Incident Survey, industrial workplaces in the United States of America account for more than 81% of CTD compensation costs and 55% of recordable CTD cases (CTD

News 1998). This article also reported that, between the years 1995 and 1997, manual material handling cases cost employers about $2.56 billion annually in direct compensation. In the definition of cumulative trauma disorders, *cumulative* indicates that these injuries develop gradually over periods of weeks, months, or even years as a result of repeated stresses on a particular body part; *trauma* signifies bodily injury from mechanical stresses; and the term *disorders* refers to physical ailments or abnormal conditions (Putz-Anderson 1990). It should be noted, however, that the concept of cumulative trauma to explain the growth with ill-defined soft tissue disorders is controversial.

In the province of Alberta, during 1995 and 1996, twenty nine-percent of total compensation claims were related to the lower back with lifting, pushing or pulling most frequently cited as the cause. Industries that showed the highest lost-claim rates were Agriculture and Forestry, Manufacturing and Processing, Construction and Transportation, and Utilities (Alberta Labor 1997). In the first quarter of 1998, more than 40% of the clients attending the Millard Rehabilitation Center at the Workers Compensation Board of Alberta were suffering from lower back injuries, followed by upper extremity claims representing 22% (Graham 1998). In the state of Washington, USA, from 1989 to 1996, workers in industries characterized by manual material handling were at the highest risk for back and shoulder disorders. Back disorders represented 55% of direct compensation costs and 12.8 million lost work days whereas upper extremity claims constituted 36% resulting in 12 million lost workdays. The percentage of female claimants increased over this period. According to the National Institute for Occupational Health and Safety (NIOSH), overexertion injury, defined as a temporary or permanent disruption of normal musculoskeletal function due to the demands of a job which exceed the worker's capacity, is the greatest concern of any industry (NIOSH 1991). In the United States of America, 60% of the low-back related patients claimed overexertion as the cause of low back pain (NIOSH 1981). Based on type of accidents, Statistics Canada (1994) showed that for the years 1991 to 1993 overexertion injuries represented 29% of all the injuries reported.

In a two-year prospective Canadian study on nurses at a tertiary care hospital, lifting (22.6%) and transferring of patients with assistance (23.3%) were the two most common risk factors for back injury (Yassi et al. 1995). McCoy et al. (1997) studied 437 patients with severe disabling low-back pain due to work-related injuries and concluded that lifting was the most common cause of injury (66%), followed by pushing and pulling (13%). Damkot et al. (1984) also indicated that pushing and pulling of loads were important risk factors for low-back pain. In a long-distance transport company, Bari-Gingras and Lortie (1995) studied the activities of handlers and reported that pulling (26%) and pushing (22.2%) were the most frequent types of efforts. Unlike lifting, pulling was performed in two-thirds of the handlings (62.3%) and pushing 44.2% of the time. Thus, these statistics show pulling and pushing related injuries are serious problems encountered in the workplace.

Whole-body Vibration:

Whole-body vibration is the vibration transmitted to the entire body through a supporting structure such as a vehicle seat in a car, tractor, ship, aircraft, and snowmobile or through lifts, escalators in buildings, and from the shop floor. Epidemiological investigations (Boushuizen et al. 1990, Bovenzi and Betta 1994, Burdorf and Sorock 1997, Frymoyer et al. 1980, Pope et al. 1998) and literature reviews (Bernard and Fine 1997, Bovenzi 1996, Bovenzi and Hulshof 1999, Dupuis and Zerlett 1986, Hulshof and van Zanten 1987, Lings and Leboeuf-Yde 2000, Pope 1989, Seidel and Heide 1986) have indicated that human exposure to whole-body vibration is an occupational risk factor for the development of low-back disorders.

Using magnetic resonance imaging, Luoma et al. (1998) studied the risk factors of lumbar disc degeneration with special emphasis on occupational load and back accidents. In this cross-sectional study of 53 machine drivers, 51 construction carpenters, and 60 municipal office workers, they identified posterior disc bulges in the carpenters and anterior disc bulges in the machine drivers. Their study concluded that disc degeneration was not related to body height, overweight, smoking, or the frequency of physical exercise and cautioned the smaller sample size of this study might have affected such results. They attributed the signs of disc degeneration to a history of back accidents and car driving reported by the subjects.

Between 1991 and 1993, a case-control study by Simon-Arndt et al. (1997) on US navy pilots and aircrew members, showed that aircrew members have a higher risk of diagnosed back problems than pilots. This conclusion was contrary to their hypothesis which predicted higher back complaints in pilots. They suggested that this phenomenon may be due to frequent carrying of heavy equipment by aircrew than pilots or greater tendency of aircrew members reporting problems to a flight surgeon than pilots. However, back problems related to spinal curvature (classification based on International Classification of Diseases code: 737.1 - 737.99) were higher in pilots, suggesting that different factors of their work environment or their lifestyle might have contributed to these complaints.

Bovenzi and Betta (1994) investigated the occurrence of low-back pain in 1155 tractor drivers exposed to whole-body vibration and 220 office staff (control group). They used, both a questionnaire (to identify work- and subject-related risk factors) and vibration field measurement methods to quantify the exposure. They also calculated vibration dose for each tractor driver in terms of vibration magnitude and duration of exposure. Effect of postural stress was also assessed in terms of frequency and/or duration of awkward postures at work. Their logistic modeling showed that low-back disorders were significantly associated with both vibration dose and postural load independently. This study also showed that the duration of exposure to vibration was more highly related to low-back pain than was equivalent vibration magnitude. Even though vibration dose was measured and postural load was subjective, this is the only study so far which has looked at the effect of both postural load and vibration dose on the occurrence of back pain complaints.

Using a questionnaire approach, Johanning (1991) studied back pain complaints of subway train operators associated with whole-body vibration. The results indicated that operators had a higher prevalence of back problems than control group (switch-board operators), especially in the cervical and low-back region. Even though this study couldn't establish a dose-response relationship, the author recommended improved working conditions and a decrease in exposure of vibration to the operator. Boshuizen et al. (1990a) analyzed self-reported back pain in tractor drivers exposed to whole-body vibration. They observed a 10% higher prevalence of back pain in the tractor drivers compared to a control group of workers not exposed to vibration. They showed that back pain increased with the duration of exposure, but not with the estimated mean magnitude of vibration. In another study (Boshuizen et al. 1990b), the authors found that long-term absenteeism due to back disorders was high in the tractor drivers exposed to whole-body vibration compared to a control group.

Bongers et al. (1988) showed that crane operators with more than 5 years of exposure had almost three times the risk of occurrence of disability due to intervertebral disc disorders compared to a control group (floor operators and maintenance workers). Using incidence density ratio, they suggested that crane operators with long-term (15-20 years) exposure will have a greater overall risk for spinal disorders. They attributed these ill effects to the combination of exposure to whole-body vibration, awkward postures, and climatic conditions. They also cited an American study that investigated the long-term effects of whole-body vibration on interstate drivers and a control group of office workers and drivers with less than 5 years of professional driving experience. This American study also concluded the combined effect of posture, off-balanced movements due to fatigue, and whole-body vibration exposure resulted in spinal disorders.

Based on interviews and medical examinations, a cross-sectional study of earth-moving machine operators (with three years of exposure to whole-body vibration) was conducted by Dupuis and Zerlett (1987). The percentage of operators reporting spinal discomfort (68.7% lumbar column, 6.8% thoracic column, and 18.2% cervical column) was much higher than a non-exposed control group of the same age category exposed to same working conditions of cases except vibration. A dose-response relationship was not clear in this study. However, the researchers identified a trend indicating that operators exposed to higher vibration loads had an increased prevalence of pathological lumbar spinal disorders.

In their explanation of pathogenesis of backaches in helicopter pilots, Delahaye et al. (1982) reasoned synergistic action of two main factors for their back pain: poor flying posture due to the constant and coordinated use of all four limbs during flying; and vibration of the helicopter itself. Frymoyer et al. (1980) studied 3920 patients during a three year interval in which 11% of males and 9.5% females reported an episode of low-back pain. Their low-back complaints were significantly ($p<0.001$) related to truck driving, lifting, carrying, pulling, pushing and twisting and also non-driving exposure to vibration. However, this study couldn't quantify risk factors in the causation of low-back pain.

Establishing dose-response relationships in humans is important, as driving has become an integral part of life for everybody including those specific occupational groups mentioned. However, most of the above studies couldn't establish a quantitative relationship between exposure (dose) and effect (response). One of the reasons may be due to concomitant exposure of individuals to whole-body vibration, prolonged sitting, awkward postures adopted, frequent twisting of the spine during work, and frequent heavy manual material handling associated with their job. From these points, it is understood that individuals engaged in the occupational activities are prone to more than a single risk factor associated with back complaints.

Influential Factors:

Many factors influence human response to whole-body vibration - the source (vibrating base, vehicle dynamics), interface such as seat cushion and finally the host (humans). The host's physical characteristics (e.g. anthropometry), psychological differences (e.g. experience), and physiological differences (e.g. fitness) play a vital role in the performance and response during exposure to vibration (Boff and Lincoln 1988). The effect of whole-body vibration on human exposure depends on the direction of exposure (linear motion in x, y, and z axis and also angular motion), duration of exposure, its intensity (in terms of frequency [cycles/second or Hz], and acceleration [expressed in gravitational units 'g': meters/sec^2 or in decibels]).

Low-frequency vibration below 20 Hz and high amplitude vibration energy is more prevalent and harmful especially to the low-back region of tractor drivers, military tank operators, aviation pilots, machinery personal and passengers in cars (Cornelius et al. 1994, Guinard 1985, Ramos et al. 1996, Wikstrom et al. 1994, Zagorski et al. 1976). The most sensitive frequency range in the vertical 'z' direction for the whole-body is from 4 to 8 Hz with the transfer of maximum mechanical energy to the spine resulting at about 5 Hz (Griffin 1990, Panjabi et al. 1986). The first resonant frequency of the seated human was in the range from 4.5 to 5.5 Hz due to compression of the buttocks tissue and the interaction of the vertical response with rotational motion of the pelvis (Pope et al. 1989b and 1990). At this frequency range, the lumbar spine stretches the most resulting in the internal amplification thus increasing the effects of vibration (Wasserman et al. 1997). Unfortunately, it was also identified that most of the vehicles (trucks, buses, tractors, etc.) produce frequencies between 3 to 6 Hz (Wilder et al.1982).

According to International Labor Office Codes of Practices (ILO 1984) on *Protection of workers against noise and vibration in the working environment*, low-frequency whole-body vibration (between 1 and 20 Hz) causes a wide range of pathological phenomena including lumbago, sciatica, neck ache, disc herniation and other spinal disorders. These manifestations may occur after a period of exposure in persons who are initially in good health. The common vibration exposure at the workplace is in the 1- to 10-Hz range except in aeronautics, which lies between 2 and 20 Hz (Delahaye et al. 1982, Kjellberg and Wikstrom 1987). Frequency of above 20 or 30 Hz applied to the whole-body may not significantly affect morbidity in the workplace. These higher frequencies do not transmit substantial amounts of vibration to humans and are effectively attenuated by human body surface, by seating and floor material (Guinard 1985).

Vibration at Resonance:

The frequency of greatest amplification, also known as resonance frequency, depends on the individuals exposed, different parts of human body, and changes with the body posture we adopt. These resonance frequencies transfer maximum mechanical energy, resulting in an optimum tuning between the vibration source and the host, together with an amplification of 1.5 to 3 times the exposed vibration. The natural frequency is determined by the acceleration transmissibility, in which the output acceleration (e.g. at the host) in the simple structure is compared with the input acceleration (e.g. at the source of vibration), and at resonance, the ratio of input to output exceeds unity (Pope et al. 1990).

Griffin (1975) and Pope et al. (1987 and 1990) established that resonant frequencies for the seated operator occur between 4 and 6Hz due to vertical vibration and also between 10 and 14 Hz, indicating a bending vibration of the upper torso with respect to lumbar spine, resulting in a back slap against a back rest. According to Dupuis (1989), lumbar spine stretches the most in the frequency between 2 and 6 Hz with a maximum at 4 Hz. In vivo measurements in the spinal column showed that resonance in the lumbar region is at 4.5 Hz (Panjabi et al. 1986). Hence, the *recommended limits* in ISO 2631/1 for exposure to WBV take into account the direction, magnitude, duration, and frequency (to avoid resonance) of the harmful vibration (Thalheimer 1996).

International Organization for Standardization - 2631 document (ISO 2631/1-Part 1, 1985 and 1997):

International Organization for Standardization (ISO) document 2631-Part 1, is applied to human subjects exposed to whole-body vibration transmitted through a supporting surface such as the feet of a standing worker in the vicinity of machinery, buttocks of a seated person in a car or supporting area of a reclining sick or injured person in an ambulance (ISO 2631/1 1985). In 1995, the American Conference of Governmental Industrial Hygienists (ACGIH) published an official document based on ISO 2631/1, incorporating whole-body vibration exposure into their annual recommended guidelines: *Threshold Limit Values and*

Biological Exposure Indices. These ISO limits are also adopted all over the world with some minor changes in Europe. Other ISO documents are also in existence for human exposure to vibration and shock in buildings, and crew exposure to vibration on board sea-going ships.

This ISO 2631/1-part 1 document, contains numerical values for limits of exposure to vibration, specified according to the direction of exposure (linear movements in x, y, z coordinates), intensity (frequency of 0-80 Hz) and duration of exposure (1min-24 hours). These limits are set to define three boundaries known as the *Reduced Comfort boundary* (for preserving comfort of passengers), the *Fatigue-decreased Proficiency boundary* (to maximize performance of drivers or machine operators who are exposed to vibration), and finally the *Exposure limit* (for safety and health). These limits are based on the data available from both practical experience and laboratory experimentation on humans. Some of the limitations of this document include:

1. Insufficient information on the inter- and intra-subject variability of the populations exposed (Griffin, 1990).
2. No information on the human physiological responses for various values of vibration dose.
3. Development of these ISO limiting curves on the basis of research conducted primarily on men (Bovenzi 1996, Seidel 1993).
4. Limited data pertaining to the extent of vibration transmissibility through the body (Lundstrom et al. 1998).

Vibration from Seat to Head:

According to Boff and Lincoln (1988), transmission of seat vibration to the head is affected by posture, muscle tension, body size, head position, sustained acceleration, and attachment of extra masses such as helmets to the head. Minor variations in the orientation of the lower back and the angle of the head can cause substantial changes in the vibration transmitted through the spine to the head (Griffin 1990). In Australian farmers, Scutter et al. (1997) showed a prevalence of headache (79.2%) and neck pain (77.7%) during exposure to driving tractors. They attributed these symptoms to combination of whole-body vibration and frequent rotated neck postures during farming. Their study did not show any time-dependent exposure relationship to the frequency of neck pain or headache. They hypothesized that vibration induced tonic contractions in the jaw muscles and their relationship to the temperomandibular disorders may lead to the development of symptoms of face and head pain in farmers.

Wilder et al. (1982) showed that transmissibility of vibration from the buttocks to head was amplified 1.79 times, i.e., 1 g of acceleration at the buttocks will result in 1.79 g at the head. Griffin et al. (1982) showed that vertical transmission to the head was slightly greater in women than in men at frequencies > 5 Hz and slightly greater in men than in women at frequencies < 5 Hz. Boff and Lincoln (1988) showed that vibration transmitted through the body to the head and eyes reduced visual acuity by causing images to move on the retina.

While explaining vibration interference with the performance of a continuous manual control task, McLeod and Griffin (1994) suggested one of the mechanisms that may contribute to this cause is the *central effect of cognitive process*. Arousal, motivation, anxiety, attention were some of the examples cited in their study. Their group also showed that performance decrements during vibration (between 1.6 and 10 Hz) were mainly due to visual impairments arising from relative translational movement between the subject's eyes and display.

Role of Vibration Dose on Cardiorespiratory Responses:

Vibration exposure in the region of 2 to 20 Hz at intensities of 0.1 to $0.5g_{rms}$ elicits cardiopulmonary responses similar to moderate exercise, with variable increases in heart beat, respiration rates, cardiac output, pulmonary ventilation, and oxygen uptake (Griffin 1990, Guinard 1985). Hoover and Ashe (1962) studied respiratory responses in five healthy volunteers exposed to whole-body vibration. Subjects, in a sitting posture, experienced vibration frequencies = 2, 4, 6, 8, 11 Hz, at acceleration of 0.03 to 2.88 g, and amplitude = 0.062 and 0.125 inches. Experimental protocol consisted of 20 min control period, 20 min exposure period, and finally 15 min recovery. Their results showed changes in the respiratory rate and/or tidal volume. At lower amplitude, respiratory rate was affected and at higher amplitude tidal volume was affected and these changes in tidal volume were more than adequate to provide ventilation. They suggested that the response at lower amplitude may be due to correction of ventilation to decrease tidal volume. Hoover and Ashe (1962) concluded that results obtained in this study may be similar to those seen in hyperventilation. However, they did not indicate the gender of these volunteers participated in the study. The same group, in another study (Gaeuman et al. 1962) suggested that, at vibration levels of 6-15 Hz (near the primary and secondary body resonant points), the increase in oxygen consumption was nearly linear with increasing frequency of vibration, indicating such an increase in metabolic load may fatigue the subjects over extended periods of exposure to such vibration frequencies.

Duffner et al. (1962) showed no interaction between the subjects, frequencies and acceleration intensities during exposure to whole-body vibration. Ten healthy males were subjected to a 4 min control, exposure (frequency = 2 - 7 Hz and acceleration 0.15 g and 0.35 g), and recovery phases respectively. Their results showed the greatest increase in alveolar ventilation during the first minute of vibration and the increase observed was greater at 0.35g than at the lower level. Ventilation values showed a decline toward 'control' levels more slowly at frequencies of 4 - 5 Hz, with the most prolonged hyperventilation occurring at 4 and 5 Hz (at both intensities). After the exposure period, alveolar ventilation immediately returned to control period or near control period values, with a further decline during the 2nd, 3rd, and 4th min of the recovery period.

As large vertical displacements were needed to obtain forces of 0.15g and 0.35g at these low frequencies, Duffner et al. (1962) showed a greater increase in oxygen consumption at lower rather than resonant frequencies (4-5 Hz for a seated human body), which may be a reflection of the physical effort essential to maintain the state of equilibrium and posture of the unrestrained body. However, the increase in oxygen consumption (in this study) did not correlate with the degree of hyperventilation observed at different frequencies of vibration.

According to the authors, the drop in resting mid position (for end-expiratory level) during vibration, probably reflected both the increased tidal volume associated with hyperventilation, and increased abdominal muscular tension needed to maintain posture. The return of effective ventilation toward control period values during the vibration period after an initial marked elevation may be the result of normal physiological control. They concluded that a decrease in ventilation observed during vibration in this study proves the concept of a physiological adaptation to vibration.

Hood et al. (1966) studied four subjects sitting with helmets in a semi supine position on an adjustable table with vibration transmitted in the direction of x-axis. Experimental protocol consisted of a control period of 3 min, exposure period of 7 min (at frequencies 2, 4, 6, 8, 10, 12 Hz at accelerations 0.6g and 1.2g), and finally a recovery period of 15 min. They showed changes in mean arterial blood pressure, heart rate, cardiac output, and oxygen consumption, at a higher level of acceleration and in the frequency range of 8 - 10 Hz. These maximal changes were accompanied by increased arterio-venous oxygen difference, decreased peripheral vascular resistance index, and a minor increase in stroke index, thus indicating a similar physiological response pattern of an 'exercise'.

At the lower intensity of vibration (0.6g) and at frequencies on either side of the 8-10 Hz range, the small increase in cardiac index without increased heart rate or metabolic rate indicates the presence of over perfusion relative to the control period (Hood et al. 1966). This suggests that at lower intensities of vibration a venous pump mechanism is usually activated. This study also indicated increase in ventilation during vibration. Their findings also supported the hypothesis that the physiological changes observed are due to maximal stretching of muscle spindles and reflex muscular contraction under optimal vibratory conditions. They also indicated that vigorous mechanical movements of the whole body, particularly movement of the extremities, act as a mild circulatory stress suggesting that patients with severe cardiovascular disease should avoid rough means of transportation.

Benett et al. (1977) showed that, while performing a motor task (tracking) during exposure to vibration, the level of performance may be effected by the physiological cost (heart rate, and oxygen consumption). Based on a locus of control scale, twelve males were divided into internal and external groups. This scale measures a person's general belief about his/her ability to influence events. Subjects, while sitting on a vibration chair, were exposed to both sinusoidal (frequency of 6 Hz), and random vibration (0 - 6 Hz with 125 msec shocks superimposed at regular intervals) at accelerations 0.21, 0.28, and 0.35g r.m.s. Exposure period was for 30 min. Compared to external subjects, internal subjects experienced smaller performance decrements under all levels of vibration, with greater responses resulting during higher acceleration levels and random vibration. Oxygen uptake measurements showed small increments at vibration onset, however, no differences were related to locus of control. Heart rate also increased in all the subjects at the vibration onset. However, a highly significant difference in heart rate was shown in internal than external subjects, with more predominant values during random and high acceleration vibration levels.

In the real world, vibration conditions are usually of a random rather than a sinusoidal nature, and therefore individuals may show different physiological and/or psychological responses. However, Cole and Withey (1977) found that, exposure to different wave forms didn't result in significant physiological differences in humans. They investigated the human responses in 12 young males while exposed to both sinusoidal and random vibration of 6 Hz in a seated upright posture on a hydraulic vibrator. Experimental protocol consisted of 10 min control period, 30 min exposure period (with accelerations at 0.21, 0.28, and 0.35g r.m.s), and finally 10 min recovery period. No statistical significant differences were observed in oxygen consumption, pulmonary ventilation, tidal volume, and heart rate values during sinusoidal and random vibration at all the acceleration levels. These investigators concluded that only sinusoidal wave input studies are valuable in establishing exposure limits for human vibration.

Magnusson et al. (1987) studied the relationship of the oxygen consumption and posture during exposure to whole-body vibration. Five male subjects, sat on a flat, rigid, wooden plate bolted to a vibration machine without a back rest, for a period of 10 min while exposed to a constant frequency of 5 Hz and acceleration 2.0 m/sec2. Experimental protocol started by monitoring oxygen uptake during sitting (without vibration) in a relaxed symmetric posture, sitting erect without vibration (erect posture - adopting pelvis, thoracic spine and occiput in a plane perpendicular to the seat), axial trunk rotation to the left without vibration, and vibration plus axial rotation respectively. Their results showed an increase in oxygen uptake during the erect posture compared to the relaxed posture with the highest increase (32.1%) observed during twisting and vibration exposure. They concluded that occupations such as farming, forestry, driving fork-lift trucks involve these coupling motions, thus resulting in higher oxygen uptake values.

Pope et al. (1990b) also evaluated the effect of posture, intermittent (at 5Hz) and continuous (0, 2.5, 5, and 8 Hz) sinusoidal vibration on oxygen uptake in five healthy men and women. For each combination of posture and frequency, subjects were exposed for a period of 30 min. They also monitored subjects' discomfort using the Visual Analog Scale. Intermittent vibration was given every minute for a period of ten seconds. Both relaxed and erect postures were adopted during the experimental protocol. Their results showed increase in oxygen uptake during vibration when compared to sitting at rest without vibration. However, they did not observe increase in oxygen uptake with the increase in the frequency of vibration. Their results did not identify gender differences clearly. In intermittent vibration, they did not find any differences in the oxygen uptake values during erect and relaxed postures. They indicated a positive linear relationship between frequency and discomfort ratings. Based on the results, the authors concluded that changes in oxygen uptake during vibration resembles light machining work and attributed such an increase in oxygen uptake to postural maintenance in erect position.

Further, Pope et al. (1990b) suggested that monitoring physiological variables such as oxygen uptake during whole-body vibration is useful and relevant to the assessment of the energy demands of populations exposed in the industries. The review of Seidel and Heide (1986) stressed that whole-body vibration cannot be ruled out as an additional risk factor for ischemic heart disease. However, the literature review of Wikstrom et al. (1994) suggested that exposure to vibration doesn't significantly increase the risk of diseases in the cardiovascular system. With such mixed opinions of various authors, it is essential to evaluate both the central physiological responses and peripheral limitations of human system during exposure to whole-body vibration.

Role of Postures adopted during Whole-body Vibration:

Posture also has a great influence on the amount of vibration transmitted to a person either in a standing, sitting or reclining position. In a sitting position, the effect of postural change increases with increasing frequency (Griffin 1990). Effects of sitting posture are widely studied in office ergonomics and human vibration. It is the primary concern of most vibration-induced complaints, distraction and injuries to health (Dupuis and Zerlett 1986). Sitting is defined as a body position in which the weight of the whole-body is transferred to a supporting area such as a seat or chair mainly by the ischial tuberosities of the pelvis and their supporting tissues (Chaffin and Andersson 1991). Some percent of weight is also transferred to the floor, backrest and armrests based on the posture adopted and type of seat.

With a vibration exposure in the sitting position, the load applied along the moment arm (created by the anterior offset of the ischial tuberosities) may be transmitted by the spine (Wilder 1993). Such transmission induces an additional rocking motion, thus amplifying the vibration motion transmitted to the spine. Since the seated human has a resonance frequency close to those frequencies encountered in an occupational environment, the possibility of failure of the spine mechanism vibrating at this resonance frequency is serious (Wilder 1993). Wilder et al. (1988) also reported that in vivo, in vitro, and modeling studies have shown that pressure within the intervertebral disc increases during compression, flexion, and also during sitting posture. While explaining the vibration induced low-back fatigue, Bongers (1990) in her doctoral dissertation cited a study that showed prolonged sitting in a constrained posture decreases the nutrient supply of the disc and may disturb the balance of metabolites.

During driving of tractors or earth-moving vehicles, twisting of trunk combined with whole-body vibration may result in excessive compressive load and shear stress on soft and bone tissues of the spine (Bovenizi and Betta 1994). While explaining the pathogenesis of backache, Delahaye et al. (1982) reported that theoretically the thoracic and lumbar spine should be firmly held against the seat back by straps of restraint harness. However, during flying, pilots need continuous visibility which results in pilots not tightening the suspension straps and supporting themselves by leaning forward on the straps. Thus, the back is separated from the seat and cervical spine is hyper-extended, and the resulting hyper-extension becomes even worst due to the placement of instrument panels on the top, or if the pilot is shorter. They also reported that unchanging and asymmetrical posture leads to involuntary muscular contractions in some parts of the limb, and as the spine is laterally twisted this posture increases the lumbar spine's sensitivity to the vibrations of the aircraft. This phenomenon is aggravated in landing, take-off, hovering flight, and at low-speeds.

Effect of combined stresses during Exposure to Whole-body Vibration:

Previous studies have suggested that most of the occupants, especially drivers and pilots, often have to spend their job in prolonged sitting and manually operating controls (Boff and Lincoln 1988, Delahaye et al. 1982, Griffin 1990). The controls generally used in vehicles are steering wheels, push-buttons, hand-operated levers, rotating knobs, joysticks, foot pedals, etc. (Boff and Lincoln 1988). For example, a pilot uses the right arm to operate the cyclic pitch control resulting in movement in translation; uses the left arm controlling the lift which operates the collective pitch lever; and uses the feet to operate the rudder bars, thus turning the helicopter and allowing the flight heading to be selected (Delahaye et al. 1982).

Operating controls during prolonged sitting, in addition to whole-body vibration can also be taxing on the forearm muscles. Research on hand-control interface or static work such as usage of isometric or isotonic controls during flying, and while driving vehicles, such as tractors, fork-lifts and snow-removal vehicles, is not reported in the literature so far. Multi-axis moving of controls (e.g. joy stick controls) can also be one of the activities of a driver to accomplish certain tasks during his/her job. The wrist movements of flexion, extension, deviation (ulnar/radial) depend on the situation desired, and the holding time may last from couple of seconds to minutes and may be hours. Maintaining a posture during this static activity for a prolonged period of time also depends on the level, duration of effort, and variation of the load, task performed which in turn increase the risk of acute discomfort, thus resulting in cumulative trauma disorders (Miedema et al. 1997).

Griffin and coworkers (Griffin 1990, McLeod and Griffin 1994) pointed out that transmission of vibration from the seat to the hands could impede performance during manual control. These investigators, as well as Boff and Lincoln (1988) published extensive reports on human performance during tracking targets (with supported and unsupported arms), keyboard digit punching, navigational plotting, data entry, etc., and showed that in the frequency ranges of 3 - 8 Hz, manual tracking is most sensitive to disruptions during whole-body vibration. They also showed that force-operated, isometric controls may be more vulnerable to frequencies > 5 Hz than conventional spring-centered controls due to greater amounts of vibration-induced control activity, and at 4 Hz of vibration rotary controls behave the same way as that of joysticks. However, all these studies investigated psychological responses and did not consider the effects of force of exertion or effect of holding period of these controls on the wrist or forearm muscles.

Role of Combined Stressors on Physiological Responses:

Grether et al. (1971 and 1972) studied the effect of heat (120F), noise (105dB) and vibration (5Hz at peak 0.5g) stressors, individually and/or in combination, on psychological and physiological responses. They tested ten male military personnel while sitting in a temporary heat enclosure constructed around the subject's seat on a mechanical vibration table. Noise, voice communication inputs, displays and controls were also provided, thus reflecting a real world situation. The physiological measures monitored were: body temperature (17 locations on the skin, rectal), heart rate, weight loss, and biochemical urine analysis, and performance measures monitored were: tracking, choice reaction time, voice communication, mental arithmetic, visual acuity, and subjective severity ratings on a 7 point scale. They also measured transmissibility of vibration by placing an accelerometer at the right shoulder. Except mental arithmetic tests and subjective ratings, their results showed lower values in physiological and performance measurements during exposure to combined stressors. They concluded that additive or synergistic interactions among the three stressors are absent. However, subjective stress severity ratings increased with the number of stressors in the combination.

Manninen (1984) studied the effect of noise, whole-body vibration (sinusoidal and random) and dynamic muscular work (2 W, 4 W, 8 W) on human performance. The author attempted to establish a relationship between the changes in the heart rate and the temporary changes in the hearing threshold. Ninety male student volunteers, sitting in a vibration chair, were exposed to combined stresses inside a special chamber controlled with noise (no noise and a stable, broad band noise of 90 dbA), vibration (sinusoidal frequency of 5 Hz and random frequency of 2.8-11.2 Hz), and dynamic task arrangements. The experimental protocol consisted of a control period of 30 min, exposure of 60 min (three consecutive exposure periods of 16 min, each followed by a 4 min post-exposure interval), and a 15 min recovery period. All the subjects were exposed to vibration alone, noise alone or a combination of the two during dynamic work. The results showed increase in heart rate values during all exposures and in all exposure combinations than during control period values, suggesting the change in heart rate was not only accomplished with the dynamic work but also with the quality of noise and vibration exposure. This study was an important contribution to the existing whole-body vibration literature because these combined stressors represent traffic and practical work situations.

Manninen (1985) showed that psychic load caused by 'competition' increased the temporary hearing threshold, the heat rate, and systolic blood pressure when subjects were simultaneously exposed to noise or a combination of noise and vibration. The author classified 108 male students into competitors and non-competitors and exposed them to a combination of noise and vibration at dry bulb temperatures of 20°C and 30°C while working on a choice reaction apparatus. Subjects were seated in a chamber and exposed to the same experimental protocol as mentioned in Manninen (1984). The author monitored hearing threshold, heart rate, R wave amplitude, systolic and diastolic blood pressure, pulse pressure, and reaction time. Relatively high correlation coefficients between the hearing threshold values at 4 kHz and heart rate values and between the hearing threshold values at 6 kHz and the systolic and diastolic blood pressure values emphasized that hypertension in the systemic circulation contributes to the changes in the cranial circulation and further in the metabolism of the inner ear. A combination of sinusoidal vibration and noise reduced the R wave amplitude values than random vibration and noise exposures which showed an increase at 20°C.

Thus, contrary to the study conducted by Cole et al. (1977), Manninen (1984) showed significant differences in exposure to sinusoidal and random vibration. The author also stressed that as the control chamber reflects the driver's working environment, in the future research, attention should be given to various design factors such as: exposure combinations; prolonged exposure periods; and investigating how the reactions of the organism of young, previously non-exposed persons differ from those of people who have worked as drivers for some time.

Role of Gender during Whole-body Vibration:

Besides vibration dose variability (intensity, direction, duration and input position) in general, responses and performance of the inter- and intra-subjects exposed, is important to understand and prevent any harmful effects on humans.

Based on psychophysical experiments, it was reported that women are relatively more sensitive than men to frequencies of vertical seat vibration in the range 3.15 - 5Hz, but no significant difference was found between standing males and females in the range of 2.4 - 60 Hz (Griffin 1990).

In a recent investigation, Lundstrom et al. (1998) stressed the need for differential guidelines for men and women. They also argued that ISO 2631 document gives a poor description about the amount of vibration actually being transmitted to the body, as it gives only acceleration magnitude on the vibrating surface. The authors suggested a new concept i.e., employing the amount of vibration energy either absorbed or exchanged between the source and body, thus giving a better measure of physical stress imposed on the body. They evaluated absorbed power (also known as transmitted power to any structure, which is a sum of absorbed part of the power and the elastic power of any structure) on 15 males and 15 females during exposure to vertical whole-body vibration in a sitting posture. Lundstrom et al. (1998) showed the maximal absorption of vibration energy at lower frequencies for women than men. They hypothesized that these results may be due to differences in the structure of their body and/or due to a higher fat-mass/muscle-mass ratio of women. This higher ratio resulted in a decrease in the stiffness-to-mass ratio which eventually lowers the resonance frequency, thus, frequency for maximal power absorption. They also suggested in general, a higher fat content in women gives more damping, and thus, more absorption of power of vibration input.

Surprisingly, there are no controlled studies so far which investigated both central and peripheral physiological differences simultaneously in men and women to whole-body vibration. Also, as Bovenzi (1996) pointed out most of the epidemiological studies and conclusions are limited to only men, thus requiring a comprehensive understanding of gender responses and their differences to whole-body vibration. The author reported some studies that looked into the disorders of the female reproductive organs and adverse effects on pregnancy, however, the reasons for such an increase was were not given in the paper. The author also reported on an epidemiological survey study of coal miners that was conducted in Poland. According to this survey, women reported a more elevated occurrence of low-back pain than men. Even though this Polish study did not include a control group nor did it control for other confounding factors, it gave a new direction to whole-body vibration research due to the rapid rise of women in the workforce.

Bovenzi (1996) and Seidel (1993) also criticized the widely applied ISO 2631 document which doesn't take women in to consideration for the exposure limits. Review of Seidel and Heide (1986), reported a study which examined the effects of whole-body vibration on the blood supply of the organs of the minor pelvis in women. The results indicated that whole-body vibration exposure induced a distinct increase of blood volume during the phases of ovulation and menstruation. From this sub-section, it is evident that studies on women, exposed to whole-body vibration and related low-back studies are lacking. Research comparing the physiological responses of women and men are vital for developing gender specific standards in order to protect the general health of the workforce exposed to whole-body vibration.

Low-Back Muscle Fatigue during Exposure to Whole-body Vibration:

Compared to a rested or healthy worker, a worker fatigued from lack of sufficient rest or one who is recovering from an illness may be at a greater risk of developing a cumulative trauma disorder (Putz-Anderson 1990). While oxygen consumption and heart rate are used to assess whole-body work, these measurements are insufficient to monitor the localized load on either specific muscles or muscle groups. Muscle fatigue is defined as either "inability to sustain a specified force and power output during exercise" or a transient loss of work capacity due to the preceding work irrespective of whether or not the current performance is effected (Massen and Schneider 1997). Electromyography (EMG) is one of the techniques by which we can evaluate the localized stresses in terms of the muscular electrical activity either in a single muscle or group of muscles. For the last two decades, studies of physiological responses of the spinal musculature under whole-body vibration, in particular

EMG studies, have been widely reported (Andersson et al. 1977, Hansson et al. 1981, Hosea et al. 1986, Seidel et al. 1986, Seroussi et al. 1989, Wilder et al. 1982, Zimmerman et al. 1993).

Wilder et al. (1982) evaluated the stiffness, impedance, and resonant characteristics of 30 males and 15 females. EMG measurements were taken in subjects with neutral, neutral and valsalva position, forward flexion (5°), extension (5°), left and right lateral bend (5°), maximal left/right axial rotation, from both the right erector spinae and external oblique muscle groups at the Lumbar 3 level. They found that greatest transmissibility of vibratory input occurs at 5 Hz. During an exposure period of 30 min (1-20 Hz frequency sweep), subjects (without a back support throughout this study), showed a frequency shift of raw EMG signals from higher to lower values indicating a fatigue of both muscles under vibration. They did not find any statistically significant changes in the EMG activity due to postural variations. However, Hosea et al. (1986) evaluated the responses of myoelectrical activities of 12 paraspinal muscles during a 3.5 h period of car driving on a road. They did not find any EMG evidence of fatigue (measured by decrease in mean power frequency and increase in amplitude for equal function) to the duration of exposure. No vibration magnitude and frequency values were reported.

Seidel et al. (1986) estimated the strain in the lumbar spine during exposure to sinusoidal whole-body vibration (1-15 Hz in steps of 0.5 Hz and at accelerations 1.5 and 3.0 $m.sec^{-2}$ r.m.s). The exposure duration was 30 sec (1-8 Hz) or 15 sec (9-15 Hz). Accelerometers were placed on the head (bite-bar in the mouth), shoulder, at 5th thoracic, and on the seat, respectively. Surface EMG recordings were registered from the back muscles (at rectus abdominus and at 12th thoracic/1st lumbar region). They estimated highest compressive forces at 7.5, 8 and 4.5 Hz and suggested the possibility of fatigue failures at the end plates of lumbar vertebrae after intense long-term exposure to whole-body vibration.

Hansson et al. (1991) studied the EMG activity of erector spinae muscles in six males during two types of sitting (forward bent position of 20° and carrying an extra weight of 4 kg on the front of chest), with and without whole-body vibration (of 5 Hz and 0.2 g acceleration). During 5 min of testing, they showed that vibration increases both the speed and the magnitude of the development of muscle fatigue. The authors hypothesized that the onset of muscle fatigue may be due to the constriction of the arterial supply to the back muscles.

Zimmerman et al. (1993) measured the effects of three different unsupported seated postures (neutral upright, forward lean, and posterior lean) on the EMG responses of the erector spinae muscle in 11 healthy men. Data were collected 30 sec pre- and post-vibration and during 2 min of vertical vibration (at 4.5 Hz and 6.12 $m.sec^{-2}{}_{rms}$). The EMG magnitude was greater for the anterior (highest) and neural postures than for the posterior lean posture, indicating greater cyclic compression of the spine secondary to increased muscle activity results during anterior lean posture. They hypothesized that this compression may result in decreased nutrient diffusion, thus leading to earlier onset of erector spinae muscle fatigue during prolonged periods in this position.

Wilder et al. (1994) studied the effect of posture (leaning forward; seated upright; and seated back against the back rest), and seat suspension (gas spring suspension and standard spring seat) design on discomfort and back muscle fatigue during simulated truck driving. Six males were vibrated for a period of 10 min (1-20 Hz), during which magnitude and phase of acceleration transfer functions both from the vibrating base to the seat pan and from the seat pan to the bite bar were calculated. They used visual analog pain scale for subjective estimation of discomfort. Muscle fatigue was monitored using surface EMG, and is defined in terms of shift of median frequency to lower value. EMG results showed that upright sitting causes more fatigue than during any other posture. Seat suspension did not effect the EMG responses. They suggested that these results may be reflective of testing for only short-duration.

Thus, above electromyographical studies demonstrated that exposure to whole-body vibration in the seated posture accelerated the occurrence of back muscle fatigue, possibly due to a reduced blood flow to the muscles.

Role of Physical Fitness related to Low-back Intensive Tasks:

It has been often mentioned in the vibration-related literature, that physical fitness plays an important role in the effects of vibration on humans exposed to vibration (Boff and Lincoln 1988, Griffin 1990). However, there are no established studies so far which have examined this phenomenon. Most of the above studies showed that monitoring the cardiorespiratory system provide useful information on the acute effects of whole-body vibration exposure. To this effect, several manual material handling studies reported conflicting evidence of the role of aerobic fitness in low-back complaints. Investigations of the correlation of workers' cardiovascular capacity to work-related musculoskeletal injuries are challenging but potentially important in understanding injury risk.

Scientific research in determining the effects of aerobic capacity and cardiovascular risk factors on injury occurrence in manual material handling tasks has been an on going endeavor for years (Battié 1989, Cady et al. 1979, Craig et al. 1998, Kujala et al. 1996). In an epidemiological study of industrial back injury claims conducted at an air-craft industry, Battie et al. (1989) showed that aerobic capacity is not a risk factor for the back pain complaints. When controlling for age and sex, the maximal aerobic capacity (VO_{2max}), the best index of cardiovascular fitness, was not a predictor for future back pain complaints. However, for jobs of high fitness requirements such as fire fighters, Cady et al. (1979) showed a strong correlation between the physical fitness and back injury. They evaluated muscular and aerobic fitness and the subsequent occurrence of back injuries. Their results showed that firefighters with high physical fitness had both fewer and less costly back injury claims. But their conclusions were based on the sum of strength and aerobic fitness measurements which makes it difficult to attribute any specific measure such as aerobic fitness as the sole predictor for back pain complaints.

In a five-year Finnish prospective study, Kujala et al. (1996) showed that baseline aerobic power was not predictive of subsequent back pain. However, heavy occupational musculoskeletal loading, defined as work involving daily heavy lifting loads more than 35 kg and more frequent bending and twisting, and physically heavy manual work predicted future back pain. During a high-frequency manual material handling tasks (10-20 lifts/lowers per minute), Craig et al. (1998) analyzed the correlation between injury occurrences, absolute and relative maximal aerobic power, and body composition. Their results indicated no significant relationship between injury occurrence and absolute maximal aerobic power or percentage of body fat. However, relative maximal aerobic power values suggested significant relationship with occurrence of injury. Since a higher percentage of the body part affected in this study was the back, the investigators hypothesized that a higher aerobic capacity was associated with a lower injury severity. Their results were in contrast to the conclusions of Battie et al. (1989) in which a wide variety of work tasks were evaluated. Craig et al. (1998) suggested that this discrepancy might have been due to the high frequency of lifting. Also, it is difficult to compare these findings with those of Kujala et al. (1996)'s because the frequency of lifts per day was not quantified in their study.

From these findings we can say that highly strenuous work such as reported in Cady et al. (1979) and Craig et al. (1998), may elicit different cardiovascular responses compared to either light or medium work. Also, the aerobic protocols of Battie et al. (1989), Cady et al. (1979), Craig et al. (1998) and Kujala et al. (1996) are standardized testing protocols and not task-specific thus, making it difficult to compare differences in their aerobic responses. Also, conclusion of these studies is only based on central physiological responses and not peripheral ones, which rises an important question: *Are individuals peripherally limited during repetitive manual material handling tasks?* Such conflicting results in the scientific literature led me to investigate the role of central (oxygen consumption, heart rate, etc.) and peripheral (tissue oxygenation and blood volume) physiological responses and their relationship during manual material handling.

Repetitive Pushing-Pulling:

Pushing and pulling activity is defined as the application of one or two hand force, with feet either stationary (Chaffin et al. 1983, Gagnon et al. 1992, Garg et al. 1978) or moving (Lee et al. 1991, Snook and Ciriello 1991), on an object or person. The application of hand force can be either in the horizontal (Esmail et al. 1995), vertical (Warwick et al. 1980) or in the inclined direction (Garg and Beller 1988, Imrhan and Ramakrishnan 1992). For example, cart pushing or pulling can be achieved with feet moving or walking (Lee et al. 1991, Mack et al. 1995, Resnick and Chaffin 1995), whereas floor mopping or shovelling of snow can be treated as effort applied with feet stationary (Franklin et al. 1995, Søgaard et al. 1996). Similar to repetitive lifting activity, pulling and pushing is also accompanied by isometric muscle activity in the trunk and upper extremities, thus influencing the cardiovascular system (Hoozemans et al. 1998). Sanchez et al. (1979) showed that during pushing and pulling without walking, both heart rate and oxygen uptake increased linearly with the load. Hence by understanding the combined static and dynamic responses (Sanchez et al. 1979, Garcin et al. 1996), we can develop guidelines for the pushing and pulling mechanism.

Past and present research has shown that pushing and pulling without feet moving depends on posture adopted, shoe/floor friction, height of force applied and individual's anthropometry (Ayoub and McDaniel 1974, Chaffin et al. 1983, Gagnon et al. 1992, Garg and Beller 1990, Imrhan and Ramakrishnan 1992, Kromer 1974, Kumar 1994a). Kromer (1974) studied horizontal push and pull forces exerted on various surfaces during standing in different positions. The author found that forces exerted varied from 100 N to 750 N for pushing and pulling on surfaces whose coefficient of friction varied from 0.2 to 0.9. Ayoub and McDaniel (1974) evaluated the effects of posture on the strength of subjects in isometric pushing and pulling against a wall and found an optimal height of hands at about 70-80% of shoulder height, approximately 36-45 inches from the floor. Using biomechanical analysis, they also estimated torque and compressive forces on the low-back. Pushing forces increased with increase in the foot distance and subject weight, whereas both foot distance and handle height contributed equally to the increase in pulling forces with change in the body weight of the subjects. Chaffin et al. (1983) studied the effects of volitional postures during maximal pushing and pulling in the sagittal plane at three different heights (67, 109 and 152 cm) and showed that foot displacement, handle height, and body postures play a crucial role in the application of strength. Maximal strength of males was observed at the lowest height, resulting in high compressive forces on the low-back.

Gagnon et al. (1992) also studied low-back loading during pushing a 22 kg box onto shelves of different heights (58 cm, 99 cm, and 141 cm) and showed that lowest position resulted in high back compressive forces and larger amounts of energy. Kumar (1994a) showed that males and females were stronger in isometric pulling action at a handle height of 100 cm than at the heights of 35 cm and 150 cm respectively. The isokinetic strength values observed were lower than isometric strengths. When isometric pushing strength values were normalized against mean pulling strengths of males at medium height, strength values ranged between 41% and 68%, and between 27% and 44% for males and females respectively. However, on the same population, Kumar (1994b) reported the back compressive forces during pushing to be significantly higher (129% to 627%) than that of the corresponding pull conditions. Also in this study, peak external moments on the back were much higher in pushing compared to pulling. The author concluded that even though one is capable of exerting much less force in pushing, this activity generates much higher back compressive forces than pulling action.

In a one-hand dynamic pulling activity, Garg and Beller (1990) studied the effects of pulling speed (2.5, 3.6 and 3.96 km/hr), handle height (40%, 50%, 60% and 70% of shoulder height) and angle of pull (15°, 25° and 35°) from the horizontal plane on the pulling strength. They showed that strengths decreased with an increase in handle height from 100% at 40% shoulder height to 83% at 70% of shoulder height, with strengths highest at the medium angle of pull. The optimal height and the angle of pull suggested were at 50%-60% of shoulder height and 25° respectively. Imrhan and Ramakrishnan (1992) examined the effects of arm elevation (45°, 90° and 153° with respect to the shoulder), direction of pull (toward and across the body), and speed of pull (1.58 and 2.38 km/hr) on isokinetic pull strength. Their results showed that pulling toward the body was 9% stronger than pulling across it and the speed of pulling on the strength depends on the body posture adopted.

Only few physiological studies have been reported in terms of the energy expenditure during pushing and pulling with feet stationery (Esmail et al. 1995, Garg et al. 1978, Sanchez et al. 1979). Garg et al. (1978) developed regression equations for pushing and pulling of loads at different heights. In their regression model, body weight, gender, force applied, horizontal distance were some of the dependent variables and found significant difference between genders during pushing and pulling. Sanchez et al. (1979) reported static, dynamic and combined static and dynamic activities results. For loads (6 to 24 kg) pushed, pulled or held without feet moving, the oxygen uptake and heart rate increased linearly with the load. Esmail et al. (1995) established biomechanical and physiological normative data in healthy males and females during a push-pull task on a work simulator for a period of 4 min. Their results showed that significant differences exist between genders in their relative VO_{2max} and energy expenditure per unit amount of work done (men showed 19% lower values than women). It is evident from the above details that physiological studies related to repetitive pushing and pulling are few.

Aerobic protocols:

In the field of Occupational Health and Safety, it is still a standard practice to evaluate the worker's fitness for work using traditional incremental aerobic protocols on a treadmill, cycle ergometer or arm ergometer, instead of task-specific maximal aerobic test (VO_{2max}) protocols. VO_{2max} is dependent on age, sex, heredity, and body composition of the individual, state and type of training or work (McArdle et al. 1996). These diagnostic protocols, though informative, may or may not identify the individual's actual physical capacity to do the job due to the different movements involved in the tasks compared to cycling, running or arm cranking (Garg et al. 1992, Khalil et al. 1985, Sharp et al. 1988, Waters et al. 1994, Wenger 1991). The NIOSH guidelines recommend that 33% of the maximum energy expenditure rate should not be exceeded for an eight-hour workday, however, the testing mode to determine VO_{2max} is not clearly addressed.

A recent study by Nindl et al. (1998) showed a modest correlation between repetitive lifting and treadmill running peak oxygen uptake values ($r = 0.73$ and $r = 0.60$ for men and women, respectively). Sharp et al. (1988) estimated VO_{2max} of repetitive lifting as 78% of treadmill, 89% of cycle and 125% of arm cranking values whereas for various lifting tasks, Khalil et al. (1985) showed VO_{2max} as 91% of cycle values. In Petrofsky's study (1978a), depending on the weight of the load lifted or lowered, and rate of the activity performed, average VO_{2max} values were 19% to 47% lower than the bicycle values. These exercise and task specific aerobic values indicate that there is a considerable variation between them. Also, to our knowledge aerobic protocols and VO_{2max} values during maximal or submaximal pushing or pulling have not been reported in the literature to date. These protocol results indicate that any exercise mode selected to measure aerobic capacity should simulate the specific task performed. Hence it is imperative that task-specific protocols for various occupational activities be developed (Sharp et al. 1988). To our knowledge aerobic protocols and peak aerobic power values during maximal pushing or pulling have not been reported in the literature to date.

Role of Gender:

It has been reported that there are several physiological differences between men and women during manual material handling that cause differences in aerobic capacity, energy expenditure and functional work capacity (Evans et al. 1983, Esmail et al. 1995, Sharp 1994). For the last two decades, the number of women involved in the manual material handling workforce has increased and industries need more comprehensive research investigations in establishing work protocols. Physiologically, women tend to have lower VO_{2max} values than men due to the smaller fat-free mass, lower hemoglobin content and lower maximum cardiac output values (Astrand and Rodahl 1986, Sharp 1994).

However, a study reported by Evans et al. (1983) demonstrated that women are comparable to men in physical capacity to work. In their study of self-paced hard work while carrying loads on four different terrains, both genders showed similar and constant relative energy expenditure values close to 45% VO_{2max}. From the various military investigations reported by Sharp (1994), it was identified that for the tasks that do not require maximal effort or during self-paced work, women tend to perform at the level of man's standards. In a report submitted by Singh et al. (1991) to the National Defence Head Quarters of Canada, women showed lower scores than men on laboratory and field task measures. Absolute aerobic power values were 64.3% of male scores. During anaerobic tests, women showed greater relative leg peak power (61.9% of male scores) than arm peak power tests (49.6% of male scores). Their static and dynamic muscular strengths ranged from 59.3% to 77.8% of that of men. Some of the women soldiers performed similar to that of men soldiers in both laboratory and field investigations. Esmail et al. (1995) also showed no gender differences in the energy expenditure of simulated tasks when expressed relative to the VO_{2max} of the subjects. However, women were less efficient than men when the energy expenditure was expressed per unit of work accomplished.

Nindl et al. (1998) compared the gender differences in peak oxygen uptake between treadmill running and repetitive lifting. Their results indicated significant differences in gender, mode of exercise, and interaction effects for peak oxygen uptake. They reported lower physiological responses in women (20%) than in men (26%), and also for repetitive lifting than for treadmill running. In a pushing and pulling study, Hoozemans et al. (1998) reported that on average, male postal workers showed a higher absolute level of energy expenditure but a lower HR than females. Thus, comparing physiological work capacity in men and women during such repetitive manual material handling activities enhance our understanding of the gender responses at the workplace.

Central and Peripheral Factors Influencing Physical Work Capacity:

The well-known Fick equation in physiology expresses oxygen consumption or uptake as the product of blood flow and arterio-venous oxygen difference. Cardiac output, a primary determinant of person's aerobic capacity, is defined as the amount of blood pumped per minute from the left side of the heart, and is not studied extensively in the field of ergonomics (Eastman Kodak, 1986). In other words, blood flow in the Fick equation or cardiac output is essential in evaluating the individual's capability to meet the increased oxygen needs of working muscles (Antonutto et al. 1995).

Cardiac output is also a product of stroke volume and heart rate where stroke volume is defined as the volume of blood ejected into the main artery by each ventricular beat. Cardiac output and stroke volume are fundamental descriptors of cardiovascular function. Arterio-venous oxygen difference in the Fick equation, is the difference in oxygen content between the blood entering and that leaving the pulmonary capillaries (Astrand and Rodahl 1986).

Maximal Aerobic Power (VO_{2max})

Maximal aerobic power is defined as the maximal oxygen consumption per unit time, and is also known as maximal oxygen uptake per unit time. Garg (1997) suggested the following important factors that affect aerobic capacity:

age: holds an inverse relationship (30% lower at age 65 compared to age at 25),

gender: females, on average have 30% lower aerobic capacity than men,

physical fitness: aerobic capacity increases with physical fitness,

whole body vs upper-body work: on average, aerobic capacity is 30% lower for arm work because of small muscle mass involved,

nature of work: each task has its own maximum aerobic capacity as determined primarily by number of muscles available for work (bicycle, treadmill, arm, lifting, vibration, pushing/pulling etc.).

As Wagner (1988) pointed out, there is no single factor either controlling or limiting VO_{2max}, however there is a strong correlation between the compound variable oxygen delivery (QO_2) and VO_{2max}. Oxygen delivery (through convection process) is the product of blood flow and arterial oxygen content, which is also represented as the product of blood flow, hemoglobin concentration and arterial oxygen saturation. This simple relationship reveals that change in any of the determinants of QO_2 (blood flow, hemoglobin, or saturation) result in change in VO_{2max}. Intramuscular factors such as oxygen in the venous blood exiting the exercising muscle (through diffusion process) also play an important role in determining the VO_{2max}. Thus, VO_{2max} can be equated to both convection and diffusion processes.

Energy expenditure:

Evaluating energy expenditure (in terms of oxygen uptake) during a physical activity has been widely applied and reported both in exercise and occupational physiology (Astrand & Rodahl 1986, Eastman Kodak 1986). Prediction models of energy expenditure during manual material handling, developed by Garg et al. (1978), suggest that average energy expended per day varies from task to task. This variation can be attributed to the amount of musculature involved during a specific task. In addition to energy expenditure, cardiovascular and respiratory measurements such as heart rate, cardiac output, blood pressure and blood lactate are also essential to understand the physiological stress on the worker (Ayoub and Mital 1989). Many occupational activities such as lifting, pushing, pulling, and carrying are combinations of combined static and dynamic muscular work. Since these two types of muscle contractions elicit different physiological responses, it is important that these responses be examined when these muscular efforts are combined. Sanchez et al. (1979) reported that energy cost during combined work is higher than the additive cost of static and dynamic work separately.

Muscle Metabolism:

The dominant source of energy for skeletal muscle during exercise or work is oxidative metabolism and is evaluated by the Fick equation as shown below (Ferrari et al. 1997):

oxygen consumption (VO_2) = blood flow * arterio-venous (a-v)O_2 difference

O_2 availability to the tissue is either measured invasively such as blood sampling, biopsy, with laser fluorimetry or noninvasively such as Nuclear Magnetic Resonance (NMR) and NIRS (Sahlin 1992). Need of adequate O_2 to tissues is possible by an increase of O_2 delivery (DO_2) and by an increase of O_2 extraction from oxyhemoglobin (HbO_2) making sure oxidative metabolism proceed at a rate equal to the energy demands of the cell (Simonson and Piantadosi 1996). Muscle oxygenation, defined as the relative saturation of oxyhemoglobin (HbO_2) and oxymyoglobin (MbO_2) depends on the balance between O_2 delivery and metabolic rate or VO_2 (Belardinelli et al. 1995a). During circulation, O_2 is transported to tissues by blood flow (known as convection) and extracted by mitochondrion via diffusion (Piantadossi 1993).

Myoglobin is an O_2 binding protein that is available exclusively in skeletal muscle. This chromophore serves as an extra intracellular source of O_2 and helps in the transfer of O_2 to mitochondrion (Mancini et al. 1994a). Oxygen is delivered to the tissue capillary as HbO_2 where it diffuses into the muscle cell and binds to myoglobin (Mb). It is subsequently accepted by the terminal cytochrome - cytochrome oxidase (Cyt a,a_3) in the electron-transport chain, discharging its electrons directly to an oxygen atom (Simonson et al. 1996). Oxidation is complete when two electrons and two protons (H+) join with oxygen to form water (H_2O). The redox state (oxidation of hydrogen and subsequent reduction of oxygen) of Cyt a,a_3 in mitochondrion is determined by the flow of electrons through the electron-transport chain and by the availability of oxygen indicating the overall activity of oxidative metabolism in the cell (Simonson and Piantadosi 1996). During any physical activity, the limitation of aerobic ATP production results in inadequate O_2 delivery to mitochondrion leading to cellular hypoxia (Mancini et al. 1994a).

Tissue Oxygenation and Blood Volume

A brief description of both brain and muscle oxygenation and blood volume relevant to the present thesis are explained below.

<u>Cerebral Physiology:</u>

The brain is the primary organ that demands greater blood supply than any other organ of the body (Mchdelishvili 1986). Due to its high metabolic rate, the local hematocrit in the brain tissue is higher than either the working or the resting muscle. According to Nioka et al. (1998), during exercise, the brain relies primarily on mitochondrial oxidative phosphorylation for energy, and is more prone to hypoxic conditions than skeletal muscle. Hypoxic limitation in the brain results in less capacity for anaerobic metabolism (Mchedlishvili 1986). Also, in the brain during normal physiological conditions, about 95% of the adenosine triphosphate is produced from the aerobic pathway, and the rest of the energy (0-5%) comes from lactate production that is not further oxidized, but is lost from the brain as it is carried away with the venous blood (Roland 1993). However, Ide and Secher (2000) commented that the brain, including neurons and the astrocytes, has the ability to use lactate as an energy source.

Glucose from the blood is the major respiratory fuel in the brain that is used for energy metabolism and has an average respiratory quotient of 0.99 (Roland 1984). Since glucose consumption increases during cerebral activation, measuring its regional glucose consumption over a period of time is equivalent to a measurement of energy expenditure for that period (Roland 1993). Additionally, oxygen is essential for oxidizing glucose into carbon dioxide and water. Therefore, measuring regional oxygen consumption is also important to understand oxygenation during functional activation of the brain. However, during this metabolic process of extra demand on the glucose and oxygen supply, dilation of pre-capillaries occurs, resulting in the opening of additional capillaries. Consequently, regional cerebral blood volume and blood flow are elevated. Hence, monitoring regional cerebral blood volume can also be used as a marker for cerebral activation during a specified activity (Roland 1993).

According to the *Cortical field activation hypothesis* (Roland 1985a), the cerebral cortex facilitates the brain work of awake humans by activating multiple cortical fields, and each activated field occupies an area of a few square centimeters. The author further defines 'activation' as an increase of the biochemical activity of the synapses and neurons in such a field, thus leading to increases in transmembraneous ion transport and the rate of regional cerebral metabolism or regional cerebral blood flow (Roland 1993). During functional activation of brain, it was also shown that in the normal (healthy) brain there is a significant positive correlation between regional cerebral oxygen consumption and regional blood flow (Raichle et al. 1976, Heistad and Kontos 1983), with the increase in regional cerebral blood flow being greater than the regional metabolic oxygen demand (Buxton and Frank 1997, Ide and Secher 2000).

The amount of oxygen delivered to the brain depends mainly on the concentration of Hb and its affinity for oxygen, oxygen transport, characteristics of the capillary blood, and cerebral blood flow (Buxton and Frank 1997, Wardle et al. 2000). Even though blood flow is a function of perfusion pressure and vascular resistance, in the cerebral region, flow is independent of perfusion pressure, and under physiological conditions, it is predominantly regulated by changes in the resistance of cerebral arteries (Wahl and Schilling 1993). Thus, any variation in perfusion pressure results in concomitant opposite changes in cerebrovascular resistance, thus regulating the cerebral blood flow [known as autoregulation] within a constant range of 80 and 180 mmHg (Wahl and Schilling 1993). A decrease in the cerebrovascular resistance results in an increase in the cerebral blood flow and cerebral blood volume, and an increase in the resistance results in a reduction in the cerebral blood flow and cerebral blood volume (Cold 1990).

During physical exercise, the (global) cerebral blood flow is acutely affected by various physiological factors such as cardiac output, heart rate, blood pressure, changes in pH, arterial CO_2 tension, etc. (Doering et al. 1998, Jorgensen 1995, Olesen 1971). However, based on the techniques adopted, conflicting evidence of variability [increase or decrease or no change] in cerebral blood flow has been shown by several authors (Friedman et al. 1992, Globus et al. 1983, Ide and Secher 2000, Olesen 1971, Pott et al. 1996, Roland and Larsen 1976, Zobl et al. 1965).

During cycling exercise, Globus et al. (1983) demonstrated no significant increase in the cerebral blood flow, but demonstrated an increase in the cerebrovascular resistance and a concomitant decrease in the peripheral vascular resistance in humans. In addition to increase in blood pressure and heart rate responses, Olesen (1971) demonstrated a significant increase in the regional cerebral blood flow in humans during arm work. Friedman et al. (1992) found a 20% increase in the regional cerebral blood flow in the sensorimotor area of humans during rhythmic handgrip contractions. Interestingly, Zobl et al. (1965) concluded no significant role for the brain during muscular exercise in humans. These authors showed a minor increase (not statistically significant) in the cerebral blood flow accompanied by a greater increase in cardiac output during cycling exercise. Cerebral vascular resistance remained constant and peripheral vascular resistance decreased during this activity. Zobl et al. (1965) further postulated that the brain behaves as a steady-state organ during vigorous physical work with minor changes in global cerebral circulation and metabolism.

Jorgensen et al. (1992) hypothesized that a combination of muscle, tendon, and joint activation during cycling are associated with an increase in cerebral perfusion that is linked to the exercise intensity. In describing the importance of circulation to the brain, Jorgensen et al. (1999) suggested that during both rest and exercise, the cerebral blood flow has to compete with the perfusion of capillary beds of various tissues including muscle. During leg cycling, Hollmann et al. (1990) suggested that cardiac neurohormones affect regulatory processes in the peripheral hemodynamics and muscle metabolism. They further demonstrated an increase in the regional cerebral blood flow during cycling at different intensities, and suggested such an increase in blood flow may be due to the speedy transport of neurotransmitters. Such variations in the cerebral blood flow during exercise are consistent with the hypothesis of Sokolff et al. (1955) who postulated that the increase in regional blood flow and metabolic rate in one region of the brain is balanced by a decrease in regional blood flow and metabolic rate in some other region of the brain.

Regional brain activity induces local arteriole vasodilation, resulting in an increase in blood volume and blood flow (Villringer and Chance 1997). Neuronal activation during an activity is coupled with an increase in regional cerebral blood flow, and is accompanied by an increase in cerebral blood volume either with volumetric expansion in blood vessels already perfused or with an increase in recruitment of vessels actually perfused (Narayan et al. 1995). Cerebral blood volume is only 3-4% of the total brain volume, which is defined as the blood volume from the internal carotid and vertebral arteries to the internal jugular veins (Keyeux et al. 1995). Effectively, it is a summation of: 75% relative venous blood volume (due to its wide lumina), 20% of blood in the arterioles, and 5% in the capillaries (Mchedlishvili 1986).

Muscle Physiology:

In human skeletal muscle, the motor units are classified into two broad categories according to their structural, functional, and metabolic characteristics (Fox et al. 1988, McArdle et al. 1996). These are slow-twitch (Type I) and fast-twitch fibers (Type II). Slow-twitch fibers are rich in blood supply, and have relatively greater aerobic and smaller anaerobic capacity compared to fast-twitch fibers (Fox et al. 1988). Due to larger quantities of mitochondrion, capillaries, and myoglobin, these fibers demonstrate a greater oxidative capacity than the fast-twitch fibers. Further, the vascular beds of slow-twitch fibers consist of greater blood flow at rest, and do not demonstrate greater increase in blood flow during exercise because of a limited vasodilatory capacity. These fibers are preferentially recruited during postural and endurance type of activities, thus demonstrating a greater resistance to fatigue (Fox et al. 1988). Based on the energy production, fast twitch fibers are further divided into two categories. These are the fast-oxidative-glycolitic (Type IIa), and fast-glycolitic (Type IIb). However, Fox et al. (1988) reported the presence of a third category known as fast-unclassified (Type IIc) whose fiber distribution range from 0 to 4% in all muscles. Fast-twitch fibers are preferentially recruited during high intensity activities, and have a greater vasodilatory capacity compared to slow-twitch. These authors suggested an oxidative hierarchy of the different fiber types as: slow-twitch > fast-oxidative-glycolitic > fast-glycolitic.

Since the present thesis is concentrated on low-back intensive tasks, a brief description of spine and back muscle physiology is given here. Jorgensen (1997) reported that paraspinal muscles are predominantly slow twitch, consisting of small fiber cross-sectional areas associated with a well-developed capillary network. Further, these muscles are supplied with blood from dorsal branches of the lumbar and intercostals arteries and veins. The author also demonstrated that the isometric endurance time of the trunk extensor muscles was similar to the soleus muscle and significantly greater than other skeletal muscles, hence its higher fatigue resistance properties. Moreover, at a higher percentage of the maximum voluntary contraction, paraspinal muscles are able to maintain a higher steady state level of oxygenation than muscles with a lower capillary density and a lower percentage of slow twitch fibers (Jensen et al. 1999). Interestingly, Jorgensen (1997) found anaerobic capacity (glycolytic activity) of these muscles to be significantly higher than other skeletal muscles. According to Haldeman (1999), a strong relationship between the muscles and the paraspinal ligaments and fascia forms a physiological corset and behaves as a primary defense mechanism against trauma. This author further emphasized that these paraspinal muscles consist of unencapsulated nerve endings and mechanoreceptors that have been attributed to the muscular pain experienced.

From the spinal cord, special capillary loops and blood pools reach the hyaline cartilage of the vertebral disc, thus providing nutritional supply and (waste removal) to the intervertebral disc through diffusion, and eventually extensive networks of veins that run in the spinal cord facilitating the venous return (Junghanns 1990). Interestingly, although the intervertebral disc is avascular in nature, it still depends on the nutritional diffusion through the intervertebral body-intervertebral disc boundary. Each intervertebral disc also consists of fine nerve endings in the outer one third of the annulus, and these nerve endings seem to be immunoreactive to pain-related neuropeptides such as substance P, calcitonin-gene-related peptide, and vasoactive intestinal peptide (Haldeman 1999). Impulses from these nerve endings and the adjacent longitudinal ligaments travel via a number of sensory nerves to the spinal cord. Thus, the intervetebral disc can also be a source of low-back pain.

For example, in a typical motorized vehicle when an occupant is exposed to whole-body vibration, the impact is absorbed by the spine and its muscle corset, and with long term exposure of relatively high intensity vibration, this stimulus may further damage the intervertebral motion segment (Junghanns 1990). Further, the author emphasized the importance of the relationship between the spinal movements and diffusion of nutrition to the intervertebral discs. The author theorized that exposure to whole-body vibration and prolonged sitting (without movement) may lead to muscle fatigue in the low-back and eventually damage the intervertebral body-intervertebral disc boundary. Lack of motion due to prolonged sitting may slow down the pumping mechanism, resulting in inefficient removal of waste metabolites and thus exacerbating the intervertebral disc disorders.

Regional Distribution of Blood Flow:

Like any other tissue, efficiency in the skeletal muscle function is disturbed if there is a mismatch between oxygen supply (delivery) and oxygen demand (consumption) (Pittman 2000). Further, oxygen extraction is defined as the ratio of oxygen demand and oxygen supply. In a healthy tissue, decrease in oxygen delivery is always matched by increase in oxygen extraction, thus meeting the necessary oxygen demand. In the skeletal muscle, Pittman (2000) reported that oxygen extraction varies from approximately 0.25 (resting condition) to 0.75 (contraction). According to Sibbald et al. (2000), blood flow is regulated at three levels of the circulatory system: (a) centrally by the cardiac output, (b) regionally by the distribution of blood flow between organs, and (c) microvascular distribution of blood flow within organs. In explaining the importance of tissue oxygenation and blood circulation, Sibbald et al. (2000) stated:

> "when anemia coexists in critical illness, the reduction in the content in arterial blood is compensated for by (a) increasing the cardiac output, (b) altering the distribution of blood flow between organs, and (c) altering the distribution of blood flow within organs, thereby to increase tissue oxygen extraction. When the capacity of these compensatory mechanisms is exhausted, tissue injury supervenes."

Similarly, Calbet (2000) proposed that during submaximal work, fluctuations in the content of arterial blood are compensated by equal changes in muscle blood flow and cardiac output, thus maintaining constant oxygen delivery to the tissue. They indicated that increased arterial content shows no significant affect on muscle blood flow or cardiac output, however, during maximal work with reduced content of arterial blood and under hypoxia, muscle blood flow is decreased with the maximal cardiac output of the heart.

Cardiac output increases linearly with exercise intensity until maximal aerobic power is attained. Depending upon the intensity of exercise, the majority of the increase in cardiac output is directed towards the muscles directly (e.g. leg, arms) and indirectly (e.g. heart and respiratory muscles) involved in the exercise. However, blood flow to the relatively inactive organs decrease significantly (McAllister 1997). As well, there is a significant increase in blood flow to the brain during exercise (McArdle et al. 1996). However, when expressed in relative terms (as a percentage of maximal cardiac output) blood flow to all the exercising muscles increases from approximately 20% at rest to 84% during maximal exercise, whereas in the brain, it actually decreases (global not regional) from 14% to 4% (McArdle et al. 1996). This 'redistribution' of blood flow is achieved through vasoconstriction in these inactive organs and vasodilation in the active muscles.

In an example of 'total muscle blood flow' in humans, Rowell (1988) stated that:

"in a 75-kg sedentary individual with 30 kg of muscle mass and a maximal cardiac output of 25 l/min, the maximal total muscle blood flow would be 22 l/min and rest of the blood (3 l/min) is directed to the heart, brain, visceral organs, and skin".

Further, this author suggested that limited cardiac pumping capacity in a human is exceeded by the greater ability of skeletal muscle to vasodilate. This example given by Rowell (1988) suggests that certain amount of blood is distributed to the brain as well, and such a distribution may depend on the work intensity.

During incremental cycling exercise till exhaustion, Bhambhani et al. (2000) monitored both cerebral and vastus lateralis muscle simultaneously (Figure 1.1). These authors demonstrated that the pre-frontal cortex region was activated and both oxygenation and blood volume increased systematically until volitional fatigue. However, muscle oxygenation decreased during the incremental exercise and blood volume leveled off until approximately 50% to 60% of peak oxygen uptake. Similarly Nioka et al. (1998) hypothesized that the ability of skeletal muscle to metabolize energy anaerobically via glycolytic pathway gives the muscle an advantage over the brain during the hypoxic conditions. However, this reverse phenomenon may not be always true. During hypovolemic shock and fainting, Jorgensen et al. (2000) demonstrated a decrease in the cerebral blood flow (subsequently oxygenation) while blood flow in the muscle increased at the same time.

Review of Near Infrared Spectroscopy:

In a recent conference on tissue oxygenation in acute medicine, Sibbald et al. (2000) emphasized the needs of studying tissue oxygenation, and stated:

"..measurements of global hemodynamics and oxygen-related parameters are considered to be poor surrogates for the quality of tissue oxygenation. The pulmonary artery carries blood from all vascular beds of the organism that previously was in equilibrium with tissue in individual organs. Parameters derived from *mixed venous blood* might therefore serve as a parameter of global tissue oxygenation but cannot reflect the adequacy of tissue oxygenation in critical organs. Changes in *mixed venous oxygen saturation* are therefore indicative only of possible changes in the relationship between whole-body oxygen delivery and consumption."

To this effect, Near Infrared Spectroscopy (NIRS) is a noninvasive optical technique that has been used to study tissue physiology (oxygenation and blood volume) during rest and work in the skeletal muscle (Bhambhani et al. 1998a, Boushel 1998, Chance et al. 1992, Murthy et al. 1997, 2001) and brain (Fallgatter and Strik 1998, Obrig et al. 1996, Obrig and Villringer 1997, Villringer et al. 1994). NIRS is based on the principle that light energy in the near-infrared region is differentially absorbed by the oxygenated and deoxygenated forms of hemoglobin and myoglobin (Jobsis 1977, Belardinelli et al. 1995b). Light in the near infra-red region is able to measure the relative *changes* in oxyhemoglobin and oxymyoglobin concentration rather than the *absolute* concentration with much less scattering than that possible at the shorter wavelengths of light (Simonson and Piantadosi 1996, Taylor and Simonson 1996).

In a typical investigation using NIRS technique, a known amount of incident near infra-red light is impinged on the tissue to be studied, e.g. vastus lateralis muscle during leg cycling, and is recovered by a receiving optode. Part of this light energy transmitted is either absorbed by chromophores in the tissue or scattered in the tissue. The amount of light recovered during this process depends on both absorption and scattering properties. Any changes monitored in the recovered light reflect changes in the relative amounts of chromophores in the illuminated region.

Modified Beer's Law applied to the Human Tissue:

When light illuminates a live human tissue, its transmission characteristics depend on a combination of absorption, scattering, and reflectance properties. Absorption and scattering are wavelength dependent and reflectance is represented by the inclination of light beam to the tissue surface. *As the wavelength increases, scattering decreases thus benefiting the transmission of* *infra-red light* (Jobsis 1977). Propagation of light into a highly scattering medium such as living tissue follows Modified Beer's Law, thus converting the measured *changes in the absorbance* or attenuation to *changes in the absolute chromophore concentration* (Delpy et al. 1988, Simonson and Piantadosi 1996). Three tissue chromophores: hemoglobin (Hb), myoglobin (Mb), and cytochrome c oxidase (Cyt a, a_3) are the only biological compounds that show variable oxygen-dependent absorption spectra in the near-infrared range (Simonson and Piantadosi 1996).

The amount of light recovered (resulting from the reflectance) from an illuminated tissue depends on the intensity of incident light on the tissue, the physical separation of optodes, the degree of light scattered by tissue, and the amount of tissue absorbency due to the concentration of chromophores in the tissue. This relationship (DeBlasi et al. 1994, Simonson and Piantadosi 1996, Taylor and Simonson 1996) is expressed as follows:

$$OD = a\,c\,L\,B + G \quad \text{or} \quad \Delta OD \cong \Delta c$$

where OD = absorption of light expressed as the optical density

a = extinction coefficient of chromophore for the wavelength in $\mu M^{-1}cm^{-1}$

c = chromophore concentration in μM

L = distance between the point of light entry and exit *or* simply a physical optode spacing on the skin surface being tested in *cm*

B = pathlength factor of light through the tissue accounting for scattering (also known as differential pathlength factor)

G = a geometric correction factor to account for the geometry of tissue and optode positioning

ΔOD = change in the absorbance or optical density

Δc = change in the chromophore concentration

Factor 'a' is a physical constant and is usually estimated from *in vitro* (Simonson and Piantadosi 1996) measurements. Extinction coefficients of Hb, Mb, and the oxidized minus reduced Cyt a,a_3 were obtained from the brains of hemoglobin-free rats whose blood had been exchanged with a fluorocarbon blood substitute (Edwards et al. 1993, Piantadosi et al. 1986). Inter-optode separation between the source and detector is always a function of optical pathlength and depends on the degree of light scatter in a tissue. Optical pathlength used in the Beer's

Law must be increased to consider the effects of multiple scattering in the human living tissue which is considered in factor B of the equation. Because of the usage of continuous wavelength monitoring, the mean pathlength of the photons cannot be simultaneously measured (Obrig and Villringer 1997). However, in the transmitted phase calculation of minimum optical pathlength known as inter-optode separation is feasible, thus the identification of upper limit on the chromophore concentration measurements (Delpy et al. 1988).

For estimating change in the chromophore concentration, some researchers used approximate or average pathlengths of photons through various configurations such as neonatal brain, adult brain, or forearm which varied between 4-6 times the inter-optode distance (Simonson and Piantadosi 1996, Taylor and Simonson 1996). Due to the scattering effect, the distance traveled by the light is greater than L (by a factor B) and equal to the product of L and B (Edwards et al. 1993). Factor B is estimated based on the photon migration models or measured separately by time resolved spectroscopy. Since factor B also depends on individual skin pigmentation, skull thickness (while monitoring brain activation) and doesn't take individual anatomy into consideration, the volume illuminated may differentiate between subjects and between different brain areas (Obrig and Villringer 1997). As G varies with both the type of tissue studied and the optode geometry it is very difficult to quantify. Even though theoretical research in this area suggests the feasibility of calculating absolute concentration changes in tissue chromophores in an illuminated region, currently this remains a challenging task. Assuming 'a, L, B and G' as constants, changes in the absorbance of light (ΔA) thus can be attributed only to the changes in the chromophore concentration in a tissue (Δc) and trends can be calculated relative to a starting point considered as zero (De Blasi et al. 1994, Simonson and Piantadosi 1996). In some experimental settings, change in absorbance is expressed as a percentage of the full optical signal (Simonson and Piantadosi 1996, Taylor and Simonson 1996).

Light in the near infra-red (NIR) region is able to measure these *changes* rather than the *absolute* concentration with much less scattering than that is possible at the shorter wavelengths of light (Simonson and Piantadosi 1996, Taylor and Simonson 1996). According to Villringer and Chance (1997), increased activity of brain cells (e.g. during cognitive, visual, or motor stimulation) is associated with an increase in glucose and oxygen consumption. Also, the increase in cerebral blood flow exceeds the increase in oxygen consumption leading to an increase in intravascular hemoglobin oxygenation. Thus, any changes in these chromopheres during functional brain activation can be monitored by the modified Beer's law. Hence by applying the modified Beer's Law to human living tissue, near infra-red spectroscopy can be successfully applied *in vivo* to quantify the range or change in the chromophore concentrations continuously during rest, exercise, or recovery, and also in the clinical, research and occupational investigations (Belardinelli et al. 1995a, Bhambhani et al. 1997&1998a, Maikala and Bhambhani 1999b, Mancini et al. 1994a, Mohler et al. 1997, Murthy et al. 1997 & 2001, Simonson and Piantadosi 1996, Villringer and Chance 1997).

Theoretical Basis:

The relative transparency of biological tissue such as brain, skin, bone, and muscle to the light in the near-infrared region (700-1000 nm) results in much less scattering and less absorbency thus more penetration (up to 6 cm) than at the shorter wavelengths of light such as visible light (first 1 to 2mm) and first 500 μm of tissue in the ultraviolet range (Edwards et al. 1993, Piantadossi 1993, Simonson and Piantadosi 1996). The principle of NIRS is that light energy in the near-infrared region can transmit through tissues with an average path length of 7-8 cm and at specified wavelengths it is differentially absorbed by the oxygenated and deoxygenated forms of Hb and Mb (Belardinelli et al. 1995b). With the availability of oxygen, variability in the absorption spectra of the iron (heme) or copper centers of the chromophores can be seen and the relative change in the chromophores can be measured using the modified Beer's Law explained in the above section (Simonson and Piantadosi 1996). NIRS bases its principle on this law and was developed to monitor changes in tissue oxygenation noninvasively during rest or physical activity. Tissue oxygenation, defined as the relative saturation of oxyhemoglobin (HbO_2) and oxymyoglobin (MbO_2) depends on the balance between oxygen delivery and metabolic rate (Belardinelli et al. 1995a).

Absorption of light in the NIR range monitors changes in tissue oxygenation at the levels of small blood vessels (arterioles, capillaries, and venules) and intracellular sites of oxygen consumption. Since near infra-red light propagation through a single red blood cell is minimal, majority of the light is absorbed at the level of the arterioles, capillaries, and venules. In arteries with greater than 1mm diameter NIR is more than 90% absorbed (Manicini et al. 1994b).

The possibility of using NIRS for measuring muscle cytochrome Cyt a,a_3 is still questionable (Ferrari et al. 1997) due to the overlapping spectra in the NIR region and the low intensity of oxidized copper (Cu_a) band of cytochrome Cyt a,a_3 (Piantadosi 1993). Also in the NIR range, the absorption spectra of Mb is not distinguishable from that of Hb as it is an insignificant contributor [the ratio of Hb: Mb = 10:1 in the human skeletal muscle] (Belardinelli et al. 1995a, Mancini et al. 1994b, Piantadossi 1993). However, the concentrations of (HbO_2+MbO_2) can be distinguished from (Hb+Mb). Hemoglobin absorbs light differentially while it is carrying O_2 and blood changes from deep red to bright red as it becomes saturated with O_2 (Mohler et al. 1997). Mancini et al. (1994a) showed a higher degree of HbO_2 without any concomitant MbO_2 during exercise. They also showed that HbO_2 changes precede MbO_2, suggesting that NIRS monitors mainly muscle Hb and not Mb deoxygenation.

The absorption band of water in the NIR range can be monitored at about 1000 nm, and therefore changes in water content in the muscle do not affect the NIR signals in the range 700 to 900 nm (Piantadossi 1993). Assuming (MbO_2+Mb) as constant, we can attribute the changes in the concentration of [(HbO_2+MbO_2) and (Hb+Mb)] from the observed changes in the optical density to the change in HbO_2 and Hb alone entering or exiting the capillary bed of exercising muscle (Piantadossi 1993). Hence changes in the tissue total hemoglobin volume (tBV) which normally amounts to only about 5% of the total tissue volume can also be equated simply to the changes in the sum [(HbO_2+MbO_2) + (Hb+Mb)] (Piantadossi 1993).

Millikan (1937) demonstrated deoxygenation in cat soleus muscle using visible light (400-650 nm) during contraction and ischemia but this study was limited by poor penetration to the tissues. NIR absorption spectrum of a human muscle was first produced by Norris in the 1960s at the United States Department of Agriculture (Smith 1977). In 1977, Jobsis demonstrated the changes in the concentrations of cerebral (cat and human) oxy, deoxy hemoglobin, cerebral Cyt a, a_3 and blood volume in the near infra-red range. So far numerous NIRS techniques have been developed to investigate tissue oxygenation. They differ in *the type of light source adopted* such as lamps, lasers and light emitting diodes and *the modality of the light sources* such as continuous wave, continuous wave spatially resolved, pulsed or time resolved spectroscopy and phase modulation (Ferrari et al. 1997).

One of the very popular and reliable NIRS tools, known as a continuous dual wave spectrometer was developed by Britton Chance. It measures the reflected light at wavelengths of 760 and 850 nm (MicroRunman, NIM Inc., PA). At 760 nm, Hb absorbs more light whereas HbO_2 absorbs more light at 850 nm, suggesting that as Hb is oxygenated the absorption of light at 760 nm decreases while the absorption at 850 nm increases. As mentioned earlier, Mb also absorbs light at these wavelengths but is known to be insignificant (Mancini et al. 1994b). The difference between the amount of light reflected at these two wavelengths indicates a change in the concentration of HbO_2. The sum of the signals at these wavelengths indicates a change in the blood volume (Mohler et al. 1997, Belardinelli et al. 1995a). Further, it has been shown that NIRS signal predominantly reflects the oxygenation state of Hb in the mixed [cerebral or muscle] venous blood in the 'focal' optical volume *[not 'regional' as correctly suggested by Cruz (1993)]* of the tissue under study (Mancini et al. 1994b).

The changes in tissue oxygenation during ischemic conditions or varying levels of physical activity are scaled to the overall change in the signal which has been termed as Total Labile Signal (TLS) [(Piantadossi et al. 1986, Simonson and Piantadosi 1996, Taylor and Simonson 1996)] or 'physiological calibration' [Wilson et al. 1989]. TLS, is the difference in absorbence of a chromophore (e.g. Hb) between *fully reduced conditions* created through restricting the O_2 supply by cuff ischemia or arterial clamping and *maximum oxidation* obtained by increasing the O_2 delivery to the tissue (hyperoxygenation) or breathing simply room air (Piantadossi et al. 1986, Simonson and Piantadosi 1996, Taylor and Simonson 1996). Depending on the muscle group studied, one can use cuff ischemia for establishing TLS. An example of vascular occlusion to the biceps brachii at suprasystolic pressure of 250 mm Hg is illustrated in Figure 1.2 (Maikala and Bhambhani 1999a). However, it is not possible to occlude blood flow to trunk muscles using this protocol. Recently, Maikala et al. (2000) established minimum and maximum oxygenation and blood volume limits for the lumbar extensor muscles during maximal trunk extension in both sitting and standing postures (Figure 1.3). Jensen et al. (1999) reported submaximal limits for this lumbar muscle using local compression. McGill et al. (2000) also demonstrated submaximal limits for this muscle. Another alternative is the static isometric back endurance approach called the Sorensen test (Biering-Sorensen 1984). Yoshitake et al. (2001) studied maximal trunk extension for a brief period with this approach, and reported both minimum and maximum values for oxygenation and blood volume.

However, one can also establish minimum and maximum muscle oxygenation during incremental exercise till exhaustion using an equation developed by Belardinelli et al. (1995a). This equation states:

$$\text{Percent Tissue oxygenation during exercise} = \frac{y - M}{m - M} * 100$$

where y = O_2 saturation value observed during exercise (in milli Volts)

M = minimal saturation or minimum NIRS value at the peak exercise (in milli Volts)

m = maximum saturation value during recovery of the exercise (in milli Volts)

This equation applied during incremental arm cranking exercise till exhaustion (Bhambhani et al. 1998a) is illustrated in Figure 1.4. Thus, NIRS only assesses directional *changes* in tissue oxygenation from one phase (e.g. rest) to another phase (e.g. incremental exercise).

Validity of Near Infrared Spectroscopy:

The validity of NIRS in evaluating changes in cerebral oxygenation and blood volume has been well established in humans (Holzschuch et al. 1997, Pollard et al. 1996, Punwani et al. 1998, Quaresima et al. 2000). Correlation of brain tissue oxygen pressure (measured in the frontal white matter with a Clark-type electrode) and hemoglobin oxygenation (on the forehead using NIRS) were studied in severe head injury patients (Holzschuch et al. 1997). These authors showed that under the conditions of a stable NIRS signal and a diffuse brain lesion, changes of oxygen pressure were highly correlated with NIRS ($r > 0.7$). Cerebral oxygen saturation was also validated against jugular venous saturation ($r=0.88-0.99$) in healthy volunteers during hypoxia (Pollard et al. 1996). Further, measured tissue oxygenation and calculated cerebral venous oxygen saturation were compared in healthy volunteers during partial venous occlusion (Quaresima et al. 2000). They showed that oxygen saturation measured at the right and left forehead using the spatial NIRS technique reflects mainly the intracranial venous compartment saturation ($r=0.76$).

NIRS is a valid technique in measuring muscle venous oxygen saturation under a variety of experimental conditions in humans (Boushel et al. 1998, Hamoka et al. 2000, Mancini et al. 1994, Sako et al. 2001, Tran et al. 1999). During dynamic handgrip exercise, Sako et al. (2001) obtained a significant correlation of 0.97 for muscle oxidative metabolism between continuous wave NIRS spectroscopy and magnetic resonance spectroscopy measurements. During exercise and cuff ischemia, Tran et al. (1999) showed NIRS signal in the gastrocnemius muscle closely matches with nuclear magnetic resonance spectra (no correlation values reported). They demonstrated a decline in the oxygenation (obtained by NIRS) and myoglobin desaturation (obtained with nuclear magnetic resonance spectra), and suggested that NIRS signal monitors myoglobin desaturation as well. During ischemia and dynamic handgrip exercise, Boushel et al. (1998) showed significant oxygen saturation correlations ranging from 0.60 (ischemia at rest) to 0.56 (rhythmic handgrip exercise at 30% maximal voluntary contraction) between continuous wave NIRS method and venous blood sampling measurements. Mancini et al. (1994b) also measured oxygen desaturation during both work and cuff ischemia in the forearm flexors. They obtained a significant correlation (0.82 to 0.97) between the absorption band and venous blood oxygen saturation.

Despite the abundance of research that supports the validity of NIRS both in vivo and in vitro under variety of experimental conditions, some researchers have questioned the validity of this technique during exercise in humans. Using continuous wave NIRS during prolonged submaximal cycling exercise, Costes et al. (1996) reported a significant correlation (r=0.55) between the NIRS signal and femoral venous oxygen saturation under hypoxic conditions but not under normoxic conditions. Further, MacDonald et al. (1999) showed a significantly higher correlation between NIRS signal and femoral venous oxygen saturation (r value ranging between 0.53 and 0.61) during kicking exercise under hypoxic conditions only. During isometric contractions of forearm flexors, Hicks et al. (1999) compared muscle oxygenation measured with NIRS and venous oxygen saturation obtained from direct blood sampling from the deep forearm vein. At 10% of maximum voluntary contraction during both normoxic and hypoxic conditions, the NIRS signal did not show any significant change in muscle oxygenation. However venous blood oxygen saturation was significantly reduced in normoxia, with greater reduction obtained in hypoxia. At 30% of maximum voluntary contraction, oxygenation in the muscle represented by the NIRS signal showed significant reduction in normoxia, however, this signal was not influenced during hypoxia. In contrast, blood oxygen saturation demonstrated a significant reduction in both normoxia and hypoxia.

Majority of the above studies (Costes et al. 1996, Hicks et al. 1999, McDonald et al. 1999) used continuous wave NIRS technique to determine the validity. Recently, Hamoka et al. (2000) stressed the importance of using a time-resolved technique to demonstrate the validity of NIRS. Minimum oxygenation saturation obtained during cuff ischemia in the resting forearm muscles with time-resolved spectroscopy was 24.1 ± 5.6%, and direct measurement of venous blood hemoglobin saturation was 26.2 ± 6.4%. However, these authors did not report any correlation values.

Reliability of Near Infrared Spectroscopy Measurements:

The reliability of NIRS in evaluating cerebral oxygenation and blood volume during rhythmic handgrip exercise has been recently reported (Bhambhani et al. 2000b). Eight men and five women performed intermittent maximal rhythmic handgrip contractions for a period of one minute with two minutes of recovery between each trial. These authors reported significant correlations between the two trials: 0.86 for oxygenation; and 0.89 for blood volume. Totaro et al. (1998) demonstrated significant correlations for cerebral oxyhemoglobin (0.68), deoxyhemoglobin (0.76), and flow velocity (0.60) reactivity index measurements with NIRS during breathing different concentrations of carbon dioxide.

Under ischemic conditions induced by 250 mm Hg blood pressure for a period of 8 min in the vastus lateralis at rest, Bhambhani et al. (1998b) reported correlations of 0.88 to 0.96 (between sessions), and 0.95 to 0.97 (within sessions) for oxygenation measurements. Using a similar protocol for biceps brachii at rest, Maikala and Bhambhani (1999) reported correlations of 0.89 to 0.94 (between sessions), and 0.98 to 0.99 (within sessions) for oxygenation measurements. Maikala et al. (2000) established the reliability of NIRS in the lumbar erector spine muscle during maximal back extension for a period of 2 min. These authors reported significant correlation coefficients of 0.83 and 0.84 for minimum oxygenation [measured in milli volts] during sitting and standing respectively, and 0.99 for the minimum blood volume during both postures. The higher reliability of these studies emphasized the fact that with tissue oxygenation and blood volume measured by NIRS are fairly stable over time and therefore, repeated measurements are not mandatory.

Applications of Near Infra-red Spectroscopy:

In the last fifteen years application of NIRS has increased rapidly. In this section, only few relevant applications have been reported. However, each following chapters cited specific NIRS studies pertinent to the respective tissue under investigation.

Monitoring Cerebral Oxygenation and Blood Volume

In evaluating the application of NIRS to study cerebral oxygenation levels, Simonson and Piantadosi (1996) stated that:

> "near infrared spectroscopy provides a continuous noninvasive window to the central nervous system in a way not otherwise possible."

In normal, awake humans the hemodynamic trends have shown increases in both 'focal' cerebral oxygenation and blood volume trends during functional activation, suggesting an increase in the neuronal activity in the 'focal' area monitored by the NIRS sensor (Fallgatter and Strik 1998, Obrig et al. 1996, Obrig and Villringer 1997, Villringer et al. 1994). In a typical NIRS investigation on a 'focal' cerebral region, these authors showed that there is an increase in the concentration of oxy-Hb, a decrease in the cocnetration of deoxy-Hb, and an increase of total Hb (an indicative of increase in cerebral blood volume). Villringer and Dirnagl (1995) attributed such an increase in oxy-Hb molecules to arteriolar vasodilation and increase in velocity, leading to a decrease in deoxy-Hb. While clarifying such a decrease in deoxy-Hb, these authors stated:

> " ..if recruitment of erythrocytes into previously only plasma perfused capillaries occurs, the increase in total blood volume may counteract this tendency and prevent deoxy-Hb changes within the capillary space. The drop in deoxy-Hb may then best be explained by an increase in venous oxygenation. Hence, the interpretations of NIRS findings leads to different conclusions on the underlying hemodynamic changes depending whether

recruitment of erythrocyte flux is a major mechanism of cerebral blood flow increases during stimulation or not".

Using NIRS, Villringer et al. (1994) monitored cerebral oxygenation during cognitive (performing calculations) and visual tasks (observing a picture) for a duration of one minute. They evaluated the feasibility of testing whether NIRS measurements were sensitive enough to monitor changes in the brain hemodynamics and oxygenation due to physiological changes in the brain function, and also to determine its assessment during pathological changes in the brain. They used a multi-wavelength spectrometer (Hamamatsu NIRO 500) with optodes placed at a distance of 3.5 to 7 cm at various positions of the head. Cognitive and visual simulations were monitored in 17 healthy subjects and three patients. Their results showed two interesting trends. Majority of the subjects showed the usual increase in local oxygenated hemoglobin (HbO_2) and blood volume, and a decrease in deoxygenated hemoglobin (Hb), suggesting that during cognitive stimulation, the increase in cerebral blood flow is larger than the increase in cerebral oxygen consumption. Some of them also showed an increase in Hb (even though its concentration relative to HbO_2 overall is decreased). This trend was also true with visual stimulation. The authors concluded that NIRS was a useful tool to assess brain function.

In a review article, Obrig and Villringer (1997) reported that most of the studies published showed an increase in blood volume in response to the stimulus applied, indicating an evidence of cortical activation. They also suggested that an increase in blood volume is usually caused by an increase in HbO_2. However, the changes observed in Hb varied between their studies. During a performance of sequential motor task by 56 subjects at 1, 2, and 3 Hz, Obrig et al. (1996) demonstrated an increase in oxygenated hemoglobin concentration and a decrease in deoxygenated hemoglobin concentration. These trends increased in amplitude with increase in the frequency rate. Fallgatter and Strik (1997) demonstrated significant cerebral activation in both left and right frontal regions during a continuous cognitive performance test. Thus, using the optical properties of different tissue chromophores, NIRS seems to be a sensitive technique for monitoring 'focal' changes in the 'activated area' of a specific cerebral region. Although there is a considerable database of cerebral NIRS measurements during various psychophysical activities (e.g. visual, cognitive, auditory, sensory motor), to date, no studies have monitored cerebral oxygenation and blood volume responses during whole-body vibration.

Skeletal Muscle Oxygenation and Blood Volume

Several studies have reported the assessment of human skeletal muscle physiology using NIRS during various physical activities. Murthy et al. (1997) demonstrated that NIRS can monitor changes in extensor carpi radialis brevis muscle oxygenation at low levels of isometric maximum voluntary contraction. Mean tissue oxygenation reduced from100% to 47% as they reached the 50% Maximal Voluntary Contraction (MVC). In their recent work (Murthy et al. 2001), a significant correlation (r=0.78) was reported between the extensor carpi radialis brevis muscle twitch force and muscle oxygenation, suggesting force reduction in the muscle depends on the reduced muscle oxygenation. Based on the percent change in muscle oxygenation, they hypothesized that ishemia associated with a reduced muscle oxygenation (7% or greater) results in muscle fatigue. Kahn et al. (1998) studied isometric elbow flexions from 25% to 100% MVC and showed that maximal deoxygenation of the brachi radialis muscle occurs at 50% MVC and not at 100% MVC. They concluded that at 50% MVC, there is a greater activation of slow and fast oxidative muscle fibers coupled with a reduced arterial inflow, thus, resulting in maximal deoxygenation. During rhythmic handgrip contractions at 15% and 30% MVC, Boushel et al. (1998) demonstrated that deoxygenation in the forearm flexor was proportional to the %MVC.

Bhambhani et al. (1998a) established a significant exponential relationship (r = ->0.93) between muscle oxygenation and maximal oxygen uptake during arm cranking for both genders. The percent change in biceps muscle oxygenation was significantly lower in women compared to men indicating that the women deoxygenate to a greater degree than the men at the same relative exercise intensity. They concluded that the rate of decline in percent change in muscle oxygenation for a given increase of VO_2 between 30% and 90% of the peak VO_2 was independent of exercise mode and gender. During moderate arm cranking Ogata et al. (2001) demonstrated a decrease in both oxygenated hemoglobin and muscle blood volume in the inactive vastus latearlis muscle. However, when arm cranking was combined with leg exercise, such a decrease in both variables diminished in the active vastus lateralis muscle, suggesting metabolites in the active muscles cause vasodilation and "counteract sympathetic vasoconstriction" (Ogata et al. 2001).

Jensen-Urstad et al. (1995) studied the effect of hypoxia (12% O_2 in N_2) and normoxia (21% O_2, N_2) conditions on muscle oxygenation and metabolism in six healthy men during submaximal arm exercise. All subjects performed an arm exercise at an absolute work load (54% of their peak VO_2) for 30 min in both conditions. Results showed that increase in VO_2 at the onset of exercise was slower in hypoxic compare to normoxic conditions. In both conditions, NIRS measurements showed an initial decrease in oxygenation in the biceps and reversed at a slower rate in hypoxia (than normoxia), thus reaching steady state values at the end of exercise. The authors concluded that higher anaerobic energy production at the onset of exercise was associated with both an increase in O_2 extraction, and decrease in muscle oxygenation.

Rundell et al. (1996) studied the effect of posture on Hb/Mb desaturation in the capillary bed of five muscle groups (vastus lateralis, vastus medialis, rectus femoris, biceps femoris and gluteus maximus) during speed skating. These authors demonstrated that oxygenation was greater during low-skating position compared to upright position. Based on the lower blood volume changes during low-skating position, these authors concluded a compromised blood flow and limited oxygen delivery in the low-speed skating position. In a recent investigation, Szmedra et al. (2000) demonstrated a similar reduction in blood volumes in giant slalom during alpine skiing. Whole-body passive postural variations (from -10° to 75° in increments of 15°) in subjects restrained to a bed and changes in calf muscle oxyhemoglobin and deoxyhemoglobin values were monitored by Ferrari et al. (1997) and Binzoni et al. (1997). They showed that changes in deoxyhemoglobin and total blood volume increased as the bed angle increased and returned to base line when the bed position is changed to initial set up, thus suggesting that near infrared spectroscopy can be sensitive enough to monitor postural changes.

These above near infrared spectroscopy studies indicate that by monitoring the specified muscles during exercise, we can evaluate local muscle physiology. However, muscle oxygenation and blood volume studies in the back muscles during either occupational or exercise activities are few to date (Jensen et al. 1999, McGill et al. 2000, Maikala et al. 2000, Maronities et al. 2000, Yoshitake et al. 2001). Yoshitake et al. (2001) used simultaneous EMG, mechanomyography, and NIRS to study low-back muscle fatigue during subjects lying in the prone position on a table. They recorded all the three measurements from the erector spinae muscle at the 3rd lumbar level during back extension, and showed a rapid decrease in muscle oxygenation and blood volume suggesting anaerobic muscular activity results in the low-back muscles. However, they did not report any correlations between these three physiological measurements. Based on their results, Yoshitake et al. (2001) concluded that restriction of blood flow due to high intramuscular mechanical pressure is one of the primary factors in developing low-back muscle fatigue.

Other researchers arrived to similar conclusions as well (Jensen et al. 1999, McGill et al. 2000, Maikala et al. 2000). Jensen et al. (1999) demonstrated that during brief and prolonged submaximal trunk extension in an erect position, oxygenation in parvertebral muscles is significantly reduced, and local homeostatic adjustment over a period may assist in establishing a constant capillary oxygen tension, thus preventing a further decrease in oxygenation in the erector spinae muscles. Also, Maikala et al. (2000) showed a similar rapid decrease in oxygenation and blood volume during the first minute of maximal back extension in both sitting and standing positions. Further decreases in both blood volume and oxygenation ceased after the minute of extension. However, during recovery from maximal extension, both oxygenation and blood volume trends reached either baseline or increased further. Yoshitake et al. (2001)

reported similar observations in blood volume responses as well. During submaximal back extension in a seated posture, McGill et al. (2000) monitored both NIRS and EMG responses, and showed a similar decrease in oxygenation values.

From the above studies it is evident that near infra-red spectroscopy (NIRS) can be a reliable and valid investigative tool to study the deoxygenation of trunk muscles in various activities. During repetitive lifting, Maronitis et al. (2000) showed no significant correlation between oxygenation (from NIRS measurements) and either right (-0.09) or left erector spinae EMG values (-0.31). However, application of NIRS to study local tissue physiology during occupational activities is still at infancy.

Role of Adipose Tissue Thickness on NIRS measurements:

Absorbency of NIRS signals from the measurement site on the muscle is inversely related to the skinfold thickness (Feng et al. 2001, Homma et al. 1996, van Beekvelt et al. 2001, Yamamoto et al. 1998), implying that the sensitivity of the NIRS signals reduce with increasing adipose tissue thickness. Sensitivity also increases with increase in the source-detector distance (Feng et al. 2001). In other words, penetration depth of light is lower (thus less light absorption) if the thickness of adipose tissue is greater. van Beekvelt et al. (2001) reported that adipose tissue metabolism is lower than muscle metabolism, hence muscle oxygenation determined using NIRS is underestimated. During cuff ischemia, McCully and Hamaoka (2000) demonstrated a greater change in the physiological range in a subject with less subcutaneous fat compared to a smaller change observed in subjects with higher subcutaneous fat.

In the flexor digitorum super-ficialis muscle during rest and sustained isometric handgrip contractions, van Beekvelt et al. (2001) demonstrated a significant decrease in muscle oxygen consumption in both men and women with increase in the thickness of adipose tissue ($r=-0.70$, $P<0.05$). These authors further showed significantly lower muscle oxygenation in women than in men during both rest and submaximal isometric contractions. Additionally, these authors found a significant but a weak correlation of 0.29 between forearm blood flow and adipose tissue thickness, suggesting an increase in blood flow with increase in the thickness of adipose tissue.

Another factor that should be considered is the role of skin blood flow in the contamination of NIRS blood volume signal. With source-to-detector separation of 40-50 mm, Hampson and Piantadosi (1988) showed that NIRS measurements were not affected by skin blood flow, and attributed such findings to a small volume of skin relative to muscle between the NIRS optodes, and the low concentration of cyctochorme oxidase in skin. Other authors also reported negligible influence of skin blood flow on NIRS signals (Mancini et al. 1994b, Piantadosi et al. 1986). Further, Feng et al. (2001) showed that for an adipose thickness of 8 mm, the optimal source-detector distance was 45 mm. These authors also identified the optimal distance of 35-40 mm for an adipose tissue thickness range of 2.5-5 mm, and 50 mm for a thickness of 17 mm.

Summary of Introduction

Since motor vehicle driving has become an integral part of life for everyone, investigating the influence of vibration dose on physiological responses in both men and women is important. Further, confounding factors such as prolonged sitting, awkward postures adopted, and frequent manual material handling associated with their job, makes whole-body vibration one of the major questionable risk factors for low-back disorders. Additionally, repetitive pushing and pulling is also considered to be one of the causal factors for work-related musculoskeletal disorders affecting both the low-back and upper extremities. It is still common practice in occupational fitness screening programs to use standardized aerobic protocols that might not be a true representative of the specific job assigned. Thus, this doctoral research investigates the physiological responses during these two low-back intensive occupational tasks in a simulated laboratory setting. Open circuit spirometry was utilized to evaluate the whole body physiological responses while Near Infra-red Spectroscopy was applied simultaneously to examine the peripheral responses in a non-invasive manner.

Objectives:

Much of the scientific research reported in the physiological capacity of human performance during exposure to whole-body vibration and manual material handling (repetitive pushing-pulling) has concentrated more on measurements such as whole-body oxygen consumption, heart rate, ventilation volume and surface EMG studies. Investigations of central and peripheral limitations have been conducted but have not been extensively researched during either of these activities. This thesis consists of two main studies. Study #1 evaluates the whole-body physiological, tissue oxygenation and blood volume responses during seated whole-body vibration. Study # 2 compares the cardiorespiratory, local muscle oxygenation and blood volume responses during standardized arm cranking and task-specific repetitive pushing-pulling protocols.

Specific objectives of Study # 1 are to:

1. evaluate the effects of whole-body vibration on the central (cardiac output, stroke volume, and heart rate) and peripheral (arterio-venous oxygen difference, change in muscle and cerebral oxygenation and blood volume) physiological responses in healthy males and females performing rhythmic handgrip exercise in different postures,
2. determine the relationship between vibration dose and the above physiological responses, and
3. investigate the role of physical fitness on the responses to whole-body vibration.

The results of this study are presented as three independent papers which are outlined below.

Paper 1 Cerebral Oxygenation and Blood Volume Responses during Exposure to Seated Whole-body Vibration

The purposes of this study were to examine the:

(1) effects of 3 Hz, 4.5 Hz, and 6 Hz WBV doses on the relative changes in oxygenation and blood volume of the prefrontal cortex region in healthy men and women;

(2) alterations in these responses during exposure to whole-body vibration 'With' and 'Without' a backrest;

(3) addition of rhythmic handgrip contractions on these responses during whole-body vibration; and

(4) differences in these responses between genders.

Paper 2 Lumbar Erector Spinae Oxygenation and Blood Volume Responses during Exposure to Seated Whole-body Vibration

The purposes of this study were to examine the:

(1) effects of 3 Hz, 4.5 Hz, and 6 Hz vibration dose on the relative changes in oxygenation and blood volume in the lumbar erector spinae muscle in healthy men and women;

(2) differences in these trends 'With' and 'Without' a backrest exposure to WBV;

(3) alterations in these responses with the addition of rhythmic handgrip contractions during WBV; and

(4) differences in these responses between genders.

Paper 3 Acute Whole-body Physiological Responses during Exposure to Seated Whole-body Vibration

The purposes of this study were to examine the effects of 3 Hz, 4.5 Hz, and 6 Hz vibration doses on the:

(1) acute physiological responses in young healthy men and women;

(2) changes in these physiological responses during exposure to WBV 'With' and 'Without' backrest;

(3) alterations in these responses with addition of maximal rhythmic handgrip contractions during WBV; and

(4) differences in these responses between genders.

Specific objectives Study #2 are to:

1. evaluate the cardiorespiratory, muscle oxygenation and blood volume responses during standardized arm cranking and task-specific repetitive pushing and pulling,
2. examine the inter-relationship amongst these variables during the two protocols; and
3. to identify the gender differences during these two aerobic protocols.

The results of this study are presented as two independent papers which are outlined below.

Paper 4 Cardiorespiratory and Biceps Brachii Oxygenation and Blood Volume Comparisons during Arm Cranking and Task-specific Pushing-Pulling

The purposes of this study were to compare the:

(1) whole-body physiological responses during incremental pushing-pulling (with feet stationary) and incremental arm cranking till volitional exhaustion;

(2) oxygenation and blood volume responses of the biceps brachii muscle during both these protocols; and

(3) differences in these responses between genders.

Paper 5 Lumbar Erector Spinae Oxygenation and Blood Volume Comparisons during Arm Cranking and Task-specific Pushing-Pulling

The purposes of this study were to compare the:

(1) lumbar erector spinae oxygenation and blood volume trends during incremental pushing-pulling (with feet stationary) and incremental arm cranking till volitional exhaustion; and

(2) differences in these responses between genders.

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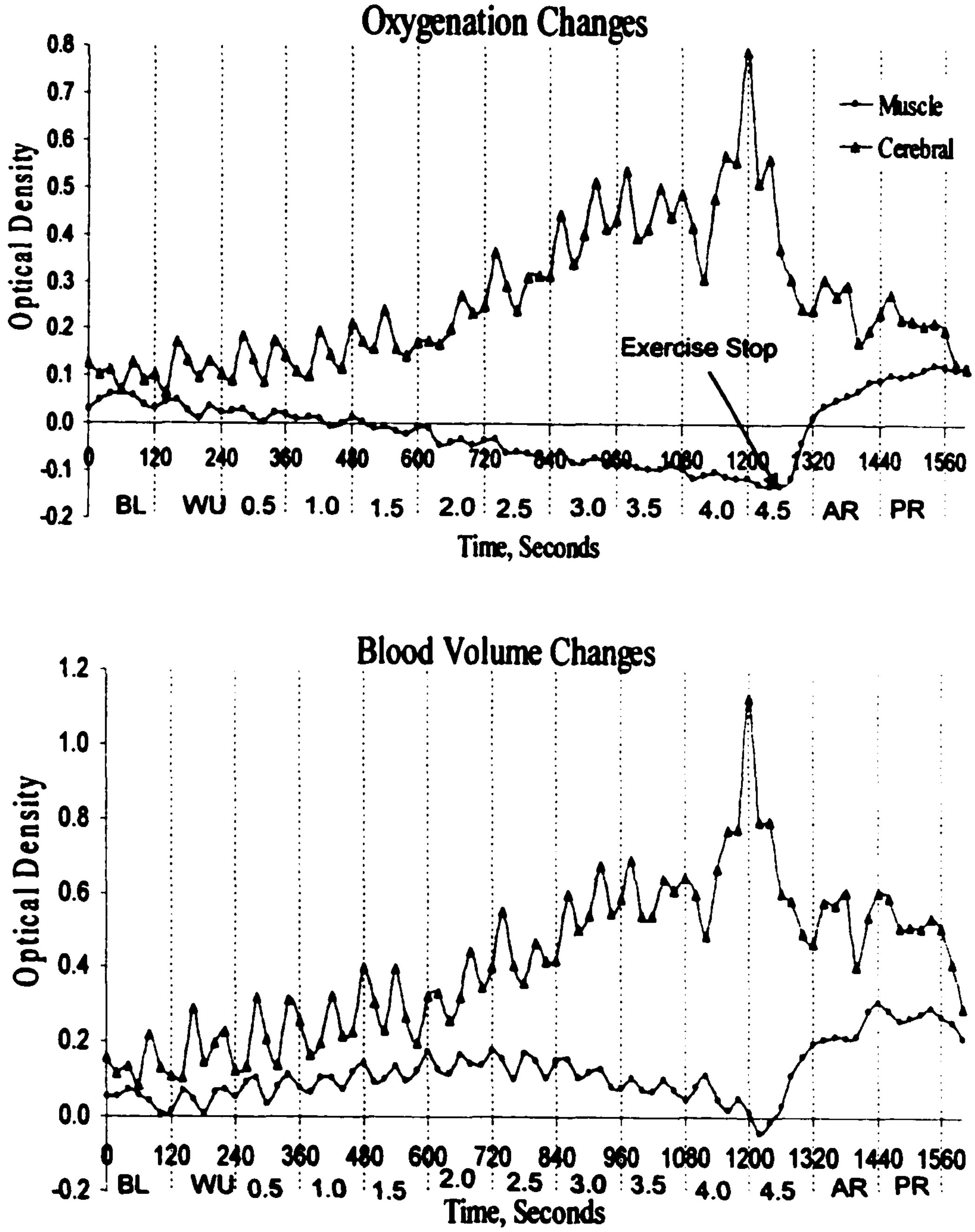
Figure 1.1 Simulaneous Cerebral and Muscle Oxygen and Blood Volume Trends in a Typical Subject (Bhambhani et al. 2000a)



BL - Baseline Rest for 2 minutes **AR - Active Recovery of 2 minutes**
WU - Warm Up at No Load for 2 minutes **PR - Passive Recovery of 4 minutes**

Load Increments 0.5 Kg every 2 minutes

Figure 1.2 Cuff Ischemia Protocol for Biceps Brachii Oxygenation Changes (Maikala and Bhambhani 1999a)

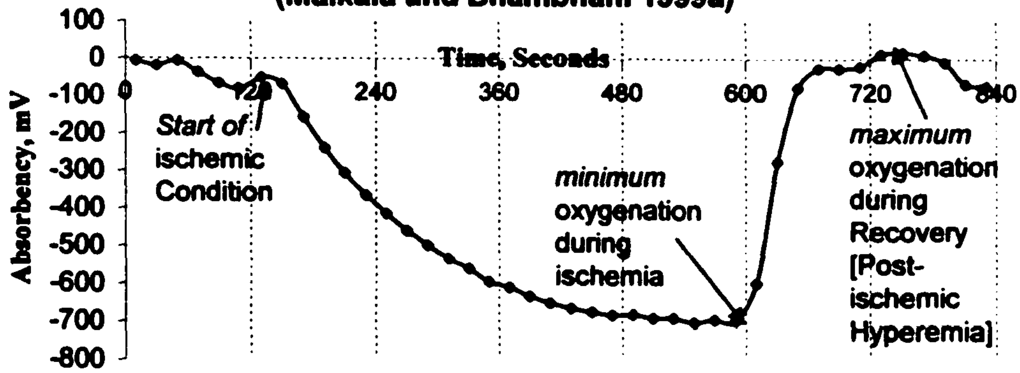


Figure 1.3 Maximal Isometric Extension for Erector Spinae Muscle Oxygenation Changes (Maikala et al. 2000)

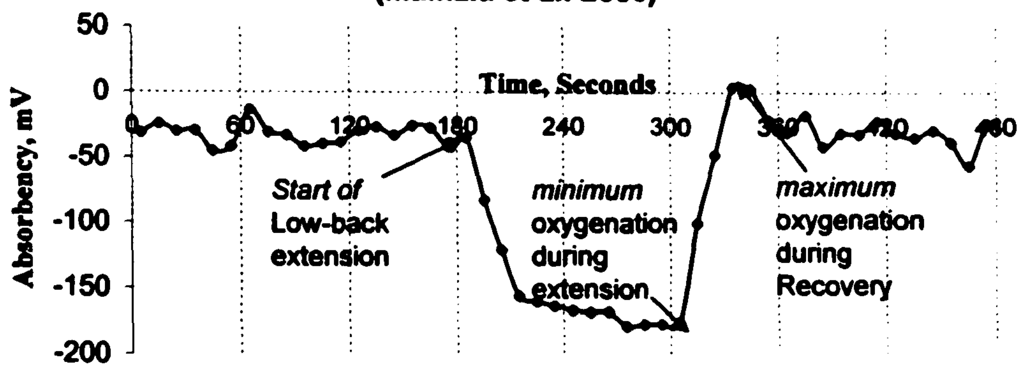
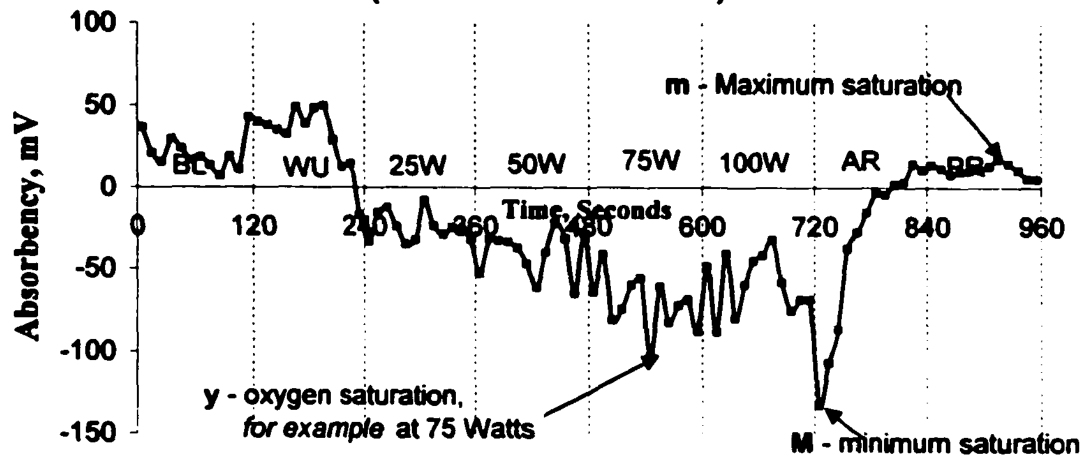


Figure 1.4 Application of the Belardinelli Equation during an Incremental Arm Cranking Exercise (Bhambhani et al. 1998a)



BL - Baseline Rest for 2 minutes
WU - Warmup at No Load for 2 minutes
AR - Active Recovery for 2 minutes
PR - Passive Recovery for 2 minutes
Load Increments 25 Watts every 2 minutes

<u>For example, based on the above figure:</u>
y = oxygen saturation at 75 Watts of workload = -100 mV
M = minimum saturation or maximum deoxygenation at the final workload = -130 mV
m = maximum saturation during recovery = 10 mV

Percent muscle oxygenation at 75 Watts of workload

$$= (y - M)/(m - M)$$
$$= [(-100) - (-130)]/[10 - (-130)]$$
$$= 21\%$$

CHAPTER 2

Cerebral Oxygenation and Blood Volume Responses during Exposure to Seated Whole-body Vibration

Whole-body vibration (WBV) is vibration transmitted to the entire human body from a vibrating surface such as the seat in a heavy equipment vehicle, truck, bus or aircraft. Thus, humans are exposed to WBV in a variety of occupations. The human response to WBV depends on the source (vibrating base, vehicle dynamics), interface (such as a seat cushion) and the characteristics of the individual. The most dominant frequency dose identified in the motorized vehicles ranges from 3 to 6 Hz (Wilder et al. 1982), with the transfer of maximum mechanical energy to the spine resulting at about 4.5 to 5 Hz (Panjabi et al. 1986, Pope et al. 1998, Wilder et al. 1982).

It has been demonstrated that the transmissibility of vibration from the buttocks to the head in a seated posture increases in an exponential manner (Wilder et al. 1982). Minor variations in the orientation of the lower back and the angle of the head can cause substantial changes in vibration transmitted though the spine to the head (Griffin 1990). Vertical transmission to the head is slightly greater in women than in men at frequencies > 5 Hz with the trend being reversed at frequencies < 5 Hz (Griffin et al. 1982). Also, leaning against a backrest ['With' Backrest] increases the transmission of vibration to the head when compared to the response 'Without' a backrest support (Boff and Lincoln 1988, Magnusson et al. 1992, Paddan and Griffin 1988a).

Compared to exposure to WBV alone, physical factors such as handling controls, static work, prolonged sitting, attention, mental stress, in association with environmental factors such as noise, light, temperature, etc. might have additive or variable effects on WBV exposed populations (Manninen 1988, Seidel et al. 1988). However, the role of physical work (e.g., handgrip) on cerebral activity during WBV, and its influence on human performance has not been investigated. Hence, it is necessary to study regional cerebral oxygenation and blood volume responses due to rhythmic handgrip contractions during exposure to WBV to more accurately simulate the occupational conditions. According to Bovenzi (1996), comparison studies on vibration exposure and physiological responses during seated WBV between genders are limited. Additionally, Boff and Lincoln (1988) and Griffin (1990) suggested that physical fitness may play an important role in minimizing the effects of the WBV on human performance. However, to date, no studies have objectively tested this hypothesis.

Near infra-red spectroscopy (NIRS) is a non-invasive optical technique capable of measuring changes in oxygenation and blood volume in the brain (Chance et al. 1988, Colier et al. 1999, Fallgatter and Strik 1998, Ide and Secher 2000, Villringer et al. 1994). Light in the near infra-red region is differentially absorbed by the oxygenated and deoxygenated forms of hemoglobin in the tissue. NIRS identifies tissue oxygenation and blood volume changes continuously in real-time during rest and work. Tissue oxygenation, defined as the relative saturation of oxyhemoglobin, depends on the balance between oxygen delivery and localized metabolic rate (Simonson and Piantadosi 1996). NIRS indicates the relative change in tissue oxygenation within the illuminated area by measuring the difference in tissue absorbency between the oxygenated and deoxygenated states of hemoglobin in the near infra-red range (700 to 1000nM). Sum of these two states of hemoglobin reflects the changes in the cerebral blood volume of the illuminated region of the tissue.

Most NIRS instrumentation uses a continuous wave technique to evaluate relative changes in tissue oxygenation and blood volume. Absolute changes in tissue oxygenation and blood volume cannot be quantified using continuous wave NIRS because the optical path length of the photons is difficult to determine. The validity of NIRS in evaluating changes in cerebral oxygenation and blood volume has been well established in humans (Holzschuch et al. 1997, Pollard et al. 1996, Punwani et al. 1998, Quaresima et al. 2000). Correlation of brain tissue oxygen pressure (measured in the frontal white matter with a Clark-type electrode) and hemoglobin oxygenation (on the forehead using NIRS) were studied in severe head injury patients (Holzschuch et al. 1997). These authors showed that under the conditions of a stable NIRS signal and a diffuse brain lesion, changes of oxygen pressure were significantly correlated with NIRS (r > 0.7). Cerebral oxygen saturation was also validated against jugular venous saturation (r=0.88-0.99) in healthy volunteers during hypoxia (Pollard et al. 1996).

Measured tissue oxygenation and calculated cerebral venous oxygen saturation were compared in healthy volunteers during partial venous occlusion (Quaresima et al. 2000). They showed that oxygen saturation measured at the right and left forehead using the spatial NIRS technique reflects mainly the intracranial venous compartment saturation (r=0.76). The reliability of this technique in evaluating cerebral oxygenation and blood volume during rhythmic handgrip exercise has been recently reported (Bhambhani et al. 2000). To date, cerebral functional activity research using NIRS has been limited to cognitive demand, motor activation, and visual stimulation studies (Colier et al. 1999, Fallgatter and Strik 1998, Hock et al. 1997, Hoshi and Tamura, 1993, Obrig et al. 1996, Obrig and Villringer 1997, Villringer et al. 1994). Nakamura et al. (1988) studied the effect of WBV on cerebral metabolites in rats and demonstrated that vibration activates the pituitary adrenal system, thus causing an imbalance in the homeostasis of the organism. However, research pertaining to changes in cerebral oxygenation and blood volume during WBV in humans has not been conducted.

The purposes of this study were to examine the effects of discrete 3 Hz, 4.5 Hz, and 6 Hz vibration doses on the: (1) accelerations at the sixth cervical region, 'With' and 'Without' a backrest in healthy young men and women; and (2) relative changes in oxygenation and blood volume of the prefrontal cortex region under the above conditions with and without the addition of rhythmic handgrip contractions. It was hypothesized that cerebral oxygenation and blood volume responses will be similar in both men and women 'With' and 'Without' backrest, and will not be influenced by the exposure to increase in vibration dose from 3 to 6 Hz during rhythmic handgrip contractions. Similarly, it was hypothesized that during exposure to vibration doses within the range of 3 to 6 Hz, accelerations generated at the cervical region will be similar in both men and women 'With' and 'Without' backrest.

MATERIALS AND METHODS

Subjects

Written informed consent was obtained from thirteen healthy men (age 24.7 ± 3.9 yrs, mass 70.8 ± 12.1 kg, height 171 ± 7 cm) and fourteen healthy women (age 23.9 ± 3.51 yrs, mass 60.3 ± 9.0 kg, height 164 ± 10 cm). Subjects were undergraduate and graduate students recruited from the university population (Table 1). They all completed the Revised Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology, 1994) to identify contraindications for exercise. All subjects were right hand dominant. The test protocols utilized were approved by the Human Ethics Review Board at this institution (APPENDIX A.1).

Vibrating Base

A steel vibrating base that housed an electro-mechanical motor connected to a cam mechanism (Advanced Therapy Products, Inc., VA, USA) was modified with an external DC speed control device. Varying the speed of this motor from 0 to 100% corresponded to vibrating frequencies of 0 Hz to 6.2 Hz. These frequencies were verified with an oscilloscope (Hitachi Digital Oscilloscope VC-6050, JAPAN). The vibrating base (Figures 2.1A and 2.1B) was also attached with a displacement transducer (Intertechnology, Inc., ON, CANADA) to measure the cam linear displacement during vibration. The average linear displacement with a subject sitting on the base during vibration was 6.1 mm at 3 Hz, 6.4 mm at 4.5 Hz and 6.6 mm at 6 Hz. The vibrating base was fitted with a seat that had an internal spring-suspension system with a weight-adjustable knob. This seat was adjustable to accommodate a maximum sitting weight capacity of 300 lbs. The backrest was adjustable to three seating positions: upright, 3° and 6°.

Placement and Calibration of Accelerometers

Two tri-axial silicon micro-machined accelerometers (Crossbow, Inc., CA, USA) were used to measure the acceleration during vibration: one was glued on to the vibrating base, and the second one was attached on the subject's neck at the level of the sixth cervical vertebrae (C6). These accelerometers were interfaced with an analog/digital board and customized software was used to convert the acceleration from volts to 'g' units. Accelerations values were then transformed into units of m/sec^2 ($1g = 9.81\ m/sec^2$) at each interface (base and C6), and were converted into root mean square values over the total vibration period.

Each accelerometer (for each axis) was placed on a horizontal surface that corresponded to +1g to obtain a more positive reading on a voltmeter (FLUKE, USA) than the zero-g voltage. It was then rotated by 180° so as to correspond to –1g resulting in a more negative reading on the voltmeter than the zero-g voltage. The regression equations between voltage output and 'g' units in the Z-axis for the two accelerometer positions were as follows: (1) Head accelerometer = 1.998 volts/g * (output voltage –2.492); and (2) Base accelerometer = 2.004 volts/g * (output voltage –2.544).

Test Protocols

Each subject completed an arm cranking exercise test in the first session to determine peak aerobic capacity, followed by three WBV tests with each dose (3 Hz, 4.5 Hz, and 6 Hz) on a separate day in a randomized order.

(1) Assessment of the Peak Oxygen Uptake

In the first testing session, the subjects completed an aerobic fitness test on an arm cranking ergometer (Cybex, MET 300, USA). The test was initiated with a two-minute rest period. It was followed by two minutes of arm cranking at no load and subsequent increments of 25 watts every 2 minutes until voluntary exhaustion, or attainment of two or more of the following end points suggested by the American College of Sports Medicine (1993): (1) leveling off in the oxygen consumption (increase of $\leq$ 100 $ml.min^{-1}$) with increasing load, (2) age predicted maximal heart rate, equated to 220-age (in years), (3) respiratory exchange ratio of $\geq$1.10, and (4) rate of perceived exertion $\geq$ 18 (Borg, 1982).

(2) Vibration Tests

The test protocol on each day lasted 30 minutes, and included initial six-minute rest without vibration, eight-minute vibration 'With' (or 'Without') a backrest, four-minute recovery, eight-minute vibration 'Without' (or 'With') a backrest, and four-minute recovery. The subject was randomly assigned to a posture 'With' or 'Without' a backrest (Figures 2.4A and 2.5), and was instructed to adopt a comfortable posture when tested 'Without' a backrest. Throughout the test, subjects sat in the vibrating chair with the eyes open. A footrest was provided for subjects to place their feet at a comfortable level. During sitting 'With' and 'Without' a backrest, angles at the knee joint and low-back were measured by a goniometer (JAMAR, Clifton, NJ, USA).

(3) Rhythmic Handgrip Measurements

Before the vibration session, right hand grip size was adjusted on the dynamometer (JAMAR, CA, USA) to a position that was comfortable for each subject. During the fifth minute of each vibration condition, the subject performed rhythmic maximal contractions for one minute at a contraction rate of one every five seconds. Contractions were performed with the right hand with the forearm in a horizontal position and the elbow at an angle of 180° (Figures 2.4B). Similar to a method suggested by Schmidt and Toews (1970), throughout the study the dynamometer was calibrated with known weights to check its accuracy identified through the dial reading on the dynamometer.

(4) Oxygenation and Blood Volume Measurements

A continuous dual wave NIRS unit (MicroRunman, NIM Inc., PA, USA) was used to evaluate relative changes in cerebral oxygenation and blood volume during the vibration tests. This unit consists of: a superficial probe consisting of a tungsten lamp placed at a distance of 4 cm from two silicone diodes which absorb light at 760nm and 850 nm; a display unit that amplifies the absorbency signal generated (Figure 2.2). Before calibration, the sensor was placed on the anterior right frontal lobe approximately 2-4 cm from the mid-line of the forehead and 2 cm above the supra-orbital ridge (Fallgatter and Strik 1998, Obrig et al. 1996). Using a linear scale, the probe placement on each subject was measured and was used for all the vibration sessions (Figure 2.3A). A piece of clear plastic was wrapped around the sensor to prevent sweat from distorting the absorbency signal. Further, a dark elastic bandage was wrapped around the sensor to secure it in place and minimize any loss of light (Figure2.3B).

As per the manufacturer's specifications, the sensor was calibrated at 760 nm and 850 nm wavelengths before the test for each subject. The vertical penetration depth of light was set to 4 cm. The difference in absorbency between these two wavelengths indicated the change in oxygenation saturation and the sum of these absorbencies indicated the change in total blood volume. Both oxygenation and blood volume were measured in terms of optical density (OD) which is defined as the logarithmic ratio of intensity of light calibrated at each wavelength to the intensity of measured light at the same wavelength (MicroRunman User Manual, NIM Inc., PA, USA, 1999). Real time data were recorded using the NIRCOM software provided by the manufacturer.

(5) NIRS Data Analysis

The real time NIRS values were averaged every 20 seconds using a customized Microsoft Excel software program specially designed for this study. Baseline oxygenation and blood volume values were monitored during initial rest or recovery from each vibration dose. Maximum values were identified for each dose during vibration with and without rhythmic handgrip contractions, and 'With' and 'Without' a backrest. The change (delta) in oxygenation and blood volume for each condition of vibration dose (3Hz, 4.5 Hz, and 6 Hz), backrest ('With' and 'Without' a backrest), workload (vibration alone and vibration combined with rhythmic handgrip contractions), was calculated as the difference between the maximum and baseline values identified for each phase of the test session. Oxygenation and blood volume responses 30 seconds before the beginning of each WBV session were identified as baseline values, and were used to calculate delta values. All statistical analyses were performed using the delta values calculated for each phase of the study.

Statistical Analysis

Two separate four-way analysis of variance (ANOVA), with gender as a between-subjects factor, and (1) three within-subject factors (dose, backrest, and acceleration) as repeated measures with a fully crossed design was used to evaluate the differences in acceleration measured at the base and C6 in m/sec^2; and (2) three within-subject factors (dose, backrest, and angle) as repeated measures with a fully crossed design was used to evaluate the differences in knee and low-back angles that were measured in degrees, respectively. A four-way analysis of covariance (ANCOVA), using the peak oxygen uptake as the covariate, gender as a between-subjects factor, and three repeated measures factors (dose, backrest, and workload) with a fully crossed design was used to evaluate the differences in the oxygenation and blood volume responses (measured in OD units). Since peak oxygen uptake is considered to be one of the best indicators of aerobic fitness, it will be used to examine whether the fitness level of the subjects has any influence on the cerebral oxygenation and blood volume responses.

To minimize the violation of the assumption of homogeneity of variance, the 'Greenhouse-Geiser' adjustment was used. Since multiple comparisons were made for each dependent variable in the present study, the Bonferroni adjustment for a P value of 0.05 was applied to minimize Type 1 error. The Bonferroni adjustment was calculated as the ratio of 0.05 and number of statistical comparisons (APPENDIX B.1). Thus, statistical significance was considered at $P < 0.01$. Significant F ratios were further analyzed with the Scheffe post hoc multiple comparison test. Pearson product moment correlations were used to examine the relationship between low-back angles and acceleration at C6. Also, the relationship between selected anthropometric variables and oxygenation and blood volume responses were evaluated using Pearson product moment correlations. The Statistical Package for Social Sciences SPSS (version 10) was used for all statistical analyses (SPSS Inc., Chicago, USA).

RESULTS

Biodynamic and Postural Differences

Effects of WBV on acceleration values at the base and C6 levels are summarized in Table 2.2. No significant four-way or three-way interactions were obtained in the acceleration values. This implies that in both genders, the changes observed in the acceleration values at different WBV doses were similar 'With' and 'Without' a backrest. However, significant two-way interactions were observed for interface and dose; interface and backrest; and interface and gender. It should be noted that comparisons of these interactions were based on the pooled mean values of other remaining independent variables.

Significant differences were observed in the acceleration values at C6 only between 4.5 Hz and 6 Hz (9.40 ± 1.45 $m.sec^{-2}_{r.m.s}$ Vs 8.60 ± 1.24 $m.sec^{-2}_{r.m.s}$, P=0.003), but not at 3 Hz and 4.5 Hz (8.75 ± 1.04 $m.sec^{-2}_{r.m.s}$ Vs 9.40 ± 1.45 $m.sec^{-2}_{r.m.s}$, P=0.059) and 3 Hz and 6 Hz (8.75 ± 1.04 $m.sec^{-2}_{r.m.s}$ Vs 8.60 ± 1.24 $m.sec^{-2}_{r.m.s}$, P=0.072). Acceleration values at the base for all doses were not significant (P>0.05). Further, acceleration values at C6 'With' backrest were significantly higher than those 'Without' backrest ('With' backrest: 9.04 ± 1.25 $m.sec^{-2}_{r.m.s}$ Vs 8.77 ± 1.33 $m.sec^{-2}_{r.m.s}$, P=0.000), but there was no difference observed at the base ('With' backrest: 9.00 ± 0.09 $m.sec^{-2}_{r.m.s}$ Vs 9.00 ± 0.08 $m.sec^{-2}_{r.m.s}$, P=0.381). At C6, men had significantly higher accelerations than women (men: 9.36 ± 1.27 $m.sec^{-2}_{r.m.s}$ Vs 8.48 ± 1.18 $m.sec^{-2}_{r.m.s}$, P=0.015), but there was no gender difference observed at the base (men: 9.03 ± 0.09 $m.sec^{-2}_{r.m.s}$ Vs 9.01 ± 0.08 $m.sec^{-2}_{r.m.s}$, P=0.640).

The postural differences during the WBV experimental conditions in both genders are presented in Table 2.2. No significant four-way or three-way interactions were obtained in the postural values. This implies that in both genders during 'With' and 'Without' a backrest, the changes in low-back and knee angles were similar across all three vibration doses. A significant interaction was found between backrest and angle. However, knee angles were not significantly different between 'With' and 'Without' a backrest conditions (99.6° ± 7.5° Vs 99.2° ± 6.4°, p=0.488), and low-back angles were significantly higher during 'With' and 'Without' a backrest conditions (107.6° ± 7.1° Vs 95.2° ± 5.9°, p=0.000). It should be noted that comparisons of the significant two-way interaction were based on the pooled mean values at the three different doses and both genders.

Cerebral Oxygenation and Blood Volume Trends in Men and Women

A typical profile of the cerebral oxygenation and blood volume trends at 4.5 Hz, 'With' and 'Without' a backrest in a male and female subject is shown in Figures 2.6A and 2.6B respectively. It is evident from both figures that as soon as the vibration started 'Without' a backrest, oxygenation and blood volume responses increased from the baseline (resting) value during the four-minute period. During vibration combined with rhythmic handgrip contractions for one minute, oxygenation values increased to a higher level than vibration alone. As soon as the rhythmic handgrip contractions stopped, oxygenation (Figure 2.6A) and blood volume (Figure 2.6B) trends dropped to the initial vibration level. In the recovery from vibration exposure phase, the trends dropped further toward baseline values (recovery 1). Similar trends were observed in the oxygenation and blood volume responses 'With' a backrest, however with the values increasing to higher levels than that of 'Without' a backrest.

The cerebral oxygenation and blood volume differences during the WBV experimental conditions in both genders are presented in Table 2.3. Statistical analysis of cerebral oxygenation and blood volume values for each dose during the different experimental conditions in both men and women revealed: (1) the covariate, namely, peak oxygen uptake, had no significant influence on the cerebral oxygenation and blood volume responses, (2) the four-way and three-way interactions were not significant, implying that both genders responded similarly to the three doses of WBV during 'With' and 'Without' a backrest, and with and without the rhythmic handgrip contractions, (3) the interaction between gender and workload was significant for the oxygenation and blood volume responses, and (4) the main effects of dose and workload were significant. It should be noted that the comparisons of the significant two-way interaction were based on the pooled mean values at the three different doses and both genders. Similarly comparison of the main effects was also based on the pooled mean values of the remaining three independent variables in the experimental design. The results of these significant main effects and interaction are presented below.

Comparison Between Doses

Significant differences were observed in the mean values of the mean oxygenation between 3 Hz and 4.5 Hz (-0.009 ± 0.07 OD Vs 0.050 ± 0.17 OD, P=0.010) and 3 Hz and 6 Hz (-0.009 ± 0.07 OD Vs 0.054 ± 0.09 OD, P=0.017). Corresponding comparisons for the blood volume changes were also significant: between 3 Hz and 4.5 Hz (0.028 OD ± 0.12 Vs 0.114 ± 0.10 OD, P=0.000) and 3 Hz and 6 Hz (0.028 ± 0.12 OD Vs 0.117 ± 0.20 OD, P=0.012). However, no significant difference was observed in oxygenation (P=0.975) and blood volume (P=0.945) mean values between 4.5 Hz and 6 Hz.

Comparison 'With' and 'Without' a Backrest Support

No statistical differences were found in the values of mean oxygenation and blood volume between conditions 'With' and 'Without' a backrest. 'With' backrest mean delta values for oxygenation were higher but not significant compared to 'Without' backrest condition (0.0326 ± 0.12 OD Vs 0.0311 ± 0.13 OD, P=0.419). Further, mean delta values for blood volume were also higher 'With' backrest but not significant compared to 'Without' a backrest condition (0.092 ± 0.16 OD Vs 0.080 ± 0.15 OD, P=0.055).

Comparison Between Vibration Alone and Vibration Combined with Rhythmic Handgrip Contractions

Significant differences in mean oxygenation and blood volume responses were observed between vibration alone and vibration combined with rhythmic handgrip contractions. Mean oxygenation values were significantly higher during vibration combined with rhythmic handgrip contractions than vibration alone (0.054 ± 0.14 OD Vs 0.010 ± 0.09 OD, P=0.000). Also, mean blood volume values were significantly higher during vibration combined with rhythmic handgrip contractions than vibration alone (0.116 ± 0.17 OD Vs 0.057 ± 0.13 OD, P=0.000). Significant interaction was obtained between workload and gender, suggesting effect of gender on work performance (Figures 2.7A and 2.7B). During vibration alone, men showed less mean oxygenation changes than women (0.0005 ± 0.11 OD Vs 0.019 ± 0.07 OD, P=0.036). However, during vibration with rhythmic handgrip contractions, this trend was reversed (0.070 ± 0.19 OD Vs 0.042 ± 0.07 OD, P=0.036). During vibration alone, men showed more mean blood volume changes than women (0.066 ± 0.17 OD Vs 0.05 ± 0.06 OD, P=0.001). A similar trend was observed during vibration with rhythmic handgrip contractions (0.160 ± 0.20 OD Vs 0.08 ± 0.12 OD, P=0.001).

Comparison Between Genders

No significant differences in oxygenation and blood volume were found between men and women for all conditions of dose, workload and backrest. In men, mean delta values for oxygenation were not significantly different from women (0.033 ± 0.16 OD Vs 0.030 ± 0.07 OD, P=0.894). Blood volume values were higher in men but not significantly different from women (0.111 ± 0.20 OD Vs 0.063 ± 0.10 OD, P=0.068). Further, no significant interaction between gender and dose was observed in both oxygenation and blood volume responses (Figures 2.8A and 2.8B).

Correlations between Selected Variables and Oxygenation and Blood Volume

Pearson correlations obtained between angles measured during sitting and accelerations at C6 were not significant (P>0.05), suggesting that greater accelerations reported 'With' backrest were not influenced by the greater angles measured at either low-back or knee during sitting 'With' backrest (Table 2.4). Further, acceleration at C6 and angles measured at the low-back during 'With' and 'Without' backrest did not correlate (P>0.05) with cerebral oxygenation and blood volume responses (Table 2.5). Anthropometric variables such as diameter at C6, neck length measured from C6 to the occipital region were also not significantly correlated with cerebral oxygenation and blood volume responses (Table 2.5).

Pearson correlations were also calculated between the maximal handgrip contractions performed during WBV and changes in oxygenation and blood volume responses, however, gender differences in the right handgrip strength did not influence the increase observed in oxygenation and blood volume responses (Table 2.6). Additionally, relationship between the relative peak aerobic power during arm cranking and changes in oxygenation and blood volume responses were also not significantly correlated (Table 2.7) (P>0.05).

DISCUSSION

Biodynamic and Postural Differences during Sitting

In the current investigation, acceleration values measured at C6 in both genders was significantly highest at 4.5 Hz compared to the other doses. However, Griffin et al. (1982) found highest transmissibility in women above 5 Hz. Skin-mounted placement of the accelerometer, and anatomical region selected (C6) in the current study might have contributed to this discrepancy. Pope et al. (1986) reported a significant artifact due to surface- or skin-mounted accelerometers, and Magnusson et al. (1992) recommended a pin-mounted method for the best results. Further, optimal measurement of acceleration and transmissibility at the head can be obtained by a bite-bar method (Pope et al. 1989, Griffin 1990).

Men showed 9.4% higher acceleration values at C6 than women, suggesting gender influence in acceleration responses at the head. Such response might be due to the greater girth of neck in men measured at C6 and Occipital regions (Table 2.1B). Griffin (1990) and Paddan and Griffin (1988a,b) found that transmission of vertical vibration to seated subjects depends on the vibration of the backrest. However, acceleration of the backrest attached to the vibration shaker was not measured in the current investigation. On the contrary, Magnusson et al. (1992) found use of a backrest and its inclination had minor effects on the attenuations of WBV. Thus, they concluded that a backrest does not necessarily reduce the effect of vibration on spinal loading. They also did not report the acceleration values of the backrest in their study. In the present study, use of a backrest played a small but significant role in acceleration measured at C6, with acceleration during vibration 'With' backrest being 3% higher than 'Without' backrest (P=0.003).

Furthermore, vibration accelerations reported in the present study are within the range of 1g reported by Wilder et al. (1982). Human tolerance limits for WBV between 4 and 8 Hz was also reported in the ranges of 1.5g to 2.0g r.m.s (Magid et al. 1960). Similar to the present study, Hoover and Ashe (1962) and Gaeuman et al. (1962) used an electromechanical vibration shaker, and reported different displacements and accelerations at the vibration base with increases in the vibration dose. Thus, higher accelerations of up to 1g at the vibration base and C6 in the present study might be due to the type of vibration base used as well. Therefore, accelerometer placements and the type of vibration shaker used in the current study may limit comparison to other mentioned studies using different methodology.

In the present study, knee and low-back angles were greater while using a backrest (Table 2.2). In this posture, subjects tend to transfer most of their body weight to the backrest, thus reducing load on the low-back caused by the upper body weight (Andersson et al. 1991). However, based on the non-significant correlation values reported in the Table 2.4, postural adjustment might not have resulted in greater transmission of vibration to the C6 region.

Cerebral Oxygenation and Blood volume Responses during Whole-Body Vibration

To the best of our knowledge, no studies to date have examined cerebral oxygenation and blood volume responses during WBV in any species. Schoenberger (1972) defined vibration as a diffuse stimulus that can stimulate various kinds of neural receptors that include touch, pressure, vision, body position and spatial orientation, and pain receptors. The response of a particular receptor on the human body depends on the type and degree of vibration exposed. Cortical activation is possible with different stimuli to these receptors in the body (Landstrom and Lundstrom 1985). Based on strength and explosive power-training studies, Bosco et al. (1998) suggested that exposure to WBV may result in increased neural potentiation either via spinal or cortical reflexes. In another investigation (Bosco et al. 2000), these researchers demonstrated an increase in plasma concentrations of testosterone and growth hormone, and a decrease in cortisol as a result of 10 min exposure to WBV.

The typical NIRS response over an activated cortical area during a motor task results in an increase in oxyhemoglobin and total hemoglobin (cerebral blood volume), with a simultaneous decrease in deoxyhemoglobin (Obrig et al. 1996). These authors, with a hand tapping activity demonstrated that cerebral oxygenation exceeds the increase in oxygen demand during motor stimulation. In the present study, vibration as a stimulus increased the frontal cortical oxygenated signal (850 nm signal) with a concomitant but smaller decrease in the deoxygenated signal (760 nm signal), thereby resulting in an increase in total blood volume (Figure 2.6B). Regional brain activity induces a local arteriolar vasodilation, resulting in an increase in blood volume and blood flow (Villringer and Chance 1997). In the present study, blood volume trends (Figure 2.6B) were almost parallel and showed greater increase than that of oxygenation trends

(Figure 2.6A), suggesting a close coupling between oxygenation and blood volume responses during exposure to WBV.

Based on animal studies, Nakamura et al. (1994) suggested that pain transmitters such as hippocampal vasoactive intestinal polypeptides might play a significant physiological role in regulating cerebral blood flow during WBV. They also found a decrease in vasoactive intestinal polypeptide like immunoreactivity in the frontal cortex after exposure to WBV. However, they did not observe a significant difference in the frontal cortex values during control and WBV conditions. Weinstein et al. (1988) studied the effects of WBV on neuropeptides, substance P (pain mediator) and vasoactive intestinal polypeptide neuropeptides in rabbits' dorsal root ganglion, a major output structure of the frontal cortex (Goldman-Rakic 1984). Weinstein et al. (1988) demonstrated a localized decrease in substance P and an increase in vasoactive intestinal polypeptide following low-frequency vibration, suggesting an increase in axonal transport due to direct stimulation of the brain similar to the mechanism occurring during peripheral nerve injury. Even though the present study did not study these pain transmitters, the current evidence from exposure to WBV in different experimental conditions suggest that, increased neuronal activity subsequently results in increased perfusion to the pre-frontal cortex.

Increases in oxygenation and blood volume immediately at the end of vibration exposure for a brief period were observed in most of the subjects (Figures 2.6A and 2.6B). Such a response may be due to the sudden 'stop' of vibration exposure, thus increase in oxygenation and blood volume changes. Additionally, in the present study the exact percentage of hemoglobin in the cortical size of the frontotemporalis region investigated was not determined. Also, results from the present study were based on a single cortical volume (in specific, a sample optical volume from the right side of the forehead), hence these values were representative of regional differences in that a specific cerebral region was monitored rather than the global cerebral area. With these limitations in mind, one has to be cautious in relating the results obtained in the blood flow studies reported to blood volume interpretations.

Role of Whole-Body Vibration Dose

Griffin et al. (1982) reported that vertical vibration transmission to the head was greater in men at frequencies below 5 Hz but greater in women at frequencies above 5 Hz. The present study demonstrated a similar trend in terms of cerebral oxygenation and blood volume changes, however they were not statistically significant. Men demonstrated highest cerebral oxygenation and blood volume values at 4.5 Hz ($P>0.05$) while women peaked at 6 Hz ($P>0.05$) [Figure 2.8A and 2.8B]. Such stimulus frequency-dependent changes in cerebral blood flow responses during a variety of cortical non-WBV activities have been previously reported using positron emission tomography (PET) (Fox and Raichle 1984, Sadato et al. 1996, Vafaee et al. 1999).

Fox and Raichle (1984) studied changes in blood flow responses in human striate cortex as a function of visual stimulus rate and found that maximal responses occurred at 7.8 Hz with a subsequent drop in blood flow as the frequency further increased. Overall, they observed a non-linear relationship between blood flow and stimulus rate. They indicated that this pattern of response may be due to the region being monitored and the subsequent neuronal demand resulting from its activation, and "the methodological necessity of accumulating tissue counts over an interval of time". Sadato et al. (1996) also showed a non-linear increase in regional blood flow in humans as a function of repetitive flexion movement of the right index finger against the thumb. They found a greater increase in regional blood flow between the slow (0.75 and 1 Hz) and fast movement repetitive rates (2 and 2.5 Hz), with flow saturation occurring at the very fast rates (3 and 4 Hz). Vafaee et al. (1999) also found that cerebral metabolic rate of oxygen in human striate cortex increased with increase in frequency of visual stimulus and peaked at 4 Hz (for both genders) and dropped considerably as the frequency increased from 4 Hz. They treated frequency as an indicator of neuronal activity and regional cerebral metabolic rate as an indicator of neuronal metabolism.

Even though none of the studies cited above pertain to WBV, the current NIRS observations of pre-frontal cortex oxygenation and blood volume trends suggest that these responses are dependent upon the vibration dose as well. Even though not statistically significant, the decrease in cerebral oxygenation and blood volume responses in men after 4.5 Hz, and a further increase in women at 6 Hz of vibration in the present study supports the non-linear observations of Vafaee et al. (1999). These researchers concluded that the non-linear frequency-dependent cerebral oxygen metabolic responses could be due to two possible limitations.

A physiological limitation known as finite oxygen diffusibility in the brain, resulting from limited oxygen transfer across the cerebral capillaries. This phenomenon can be overcome by an increase in blood flow such that it can elevate the average oxygen tension in capillary blood, thus increasing oxygen delivery to the tissue. However, this limitation does not seem to always increase the oxygen consumption to the region monitored, thus leading to a secondary limitation known as enzymatic mechanism (Vafaee et al. 1999). This mechanism causes the brain not to fully sustain the increase in cerebral metabolic rate that was possible by an increase in blood flow. This secondary limitation can be overcome by increasing the stimulus load (in the present study – may be the dose and its intensity). From these limitations, they hypothesized that once the frequency is increased beyond 4 Hz, neuronal work no longer requires the metabolic rate to rise. They concluded that the "stimulus load imposed on the brain tissue must exceed a certain threshold before glycolysis is augmented by increased oxidative metabolism" (Vafaee et al. 1999).

It is hypothesized that a similar limitation might have occurred in the present study, in light of the fact that beyond 4.5 Hz neuronal work did not require cerebral oxygenation (and blood volume) to rise in men, whereas women demonstrated linear increases with the increasing dose. However, these conclusions should be interpreted cautiously, as Vafaee et al. (1999) exposed their subjects to increasing doses of visual stimuli in the same session, whereas in the present study the subjects were exposed to three different WBV doses on three separate days. Also, the cerebral regions monitored in the studies reported

(Fox and Raichle 1984, Sadato et al. 1996, Vafaee et al. 1999) were entirely different from the present study.

Role of Sitting 'With' and 'Without' a Backrest during Whole-Body Vibration

Griffin (1990) summarized the results of various studies pertaining to the effect of backrest during vibration and concluded that leaning against the backrest, in general, increases the vibration transmission to the head. Oxygenation and blood volume values obtained in this present study during 'With' backrest were 5% and 14% higher than during 'Without' backrest condition (P>0.05). Griffin (1990) also reported that postural variations at the low back and head would substantially change the vibration transmission. In the present study, leaning against the backrest resulted in back angles that were significantly higher (11.5%) 'With' backrest compared to 'Without' backrest condition (Table 2.2). Also, in the present study accelerations obtained at the C6 during 'With' backrest were 3% higher than 'Without' backrest. However, the differences reported at the low-back angles and acceleration at C6 were not significantly correlated to the oxygenation and blood volume values (Table 2.5).

Mehagnoul-Schipper et al. (2000) demonstrated that the change of posture from supine to standing resulted in a decrease in cerebral oxygenation and blood volume changes in elderly subjects but not in young men and women. Moraine et al. (2000) reported that as the head elevates from 0 to 45°, cerebral blood flow decreases in a gradual manner in comatose patients. They concluded that arterio-venous pressure gradient was the major determinant for regional cerebral blood flow in postural variations. However, in the present study posture of the head during WBV was not measured.

Role of Workload during Whole-Body Vibration

Significant differences in oxygenation and blood volume were observed during vibration alone and during vibration combined with rhythmic handgrip contractions. As the exposure to dose varied from 3 to 6 Hz, oxygenation and blood volume values during vibration alone increased. However, during vibration combined with rhythmic handgrip contractions, maximum delta values were attained at 4.5 Hz. During vibration combined with rhythmic handgrip contractions, delta oxygenation and blood volume values were 81% and 51% higher than that of vibration alone, respectively.

In elite cyclists, Pott et al. (1996) showed that during rhythmic handgrip contractions, mean cerebral blood volume (obtained with transcranial Doppler technique) increased by 21% over resting conditions. Additionally, Friedman et al. (1992) suggested that blood flow changes in the cortical regions (during dynamic right hand contractions before and after right side axillary blockade) monitored were an indirect measure of neuronal activity within these regions, and thus neuronal feedback was essential for the changes observed. Using single photon computer tomography, these authors demonstrated that smaller afferents (Groups III and IV) were mainly responsible for the feedback signals that were essential for an increase in motor sensory regional blood flow. Also, a reduction in motor strength during anesthesia correlated with the decrease in motor sensory regional blood flow, thus demonstrating group I and II fibers might also influence the afferent process (Friedman et al. 1992).

Williamson et al. (1996) showed that regional blood flow to the motor sensory areas during left hand dynamic contraction was not influenced by the afferent stimulation of the Group Ia or III and IV metabolically sensitive fibers. However, these authors postulated that this type of contraction might have resulted in cerebral activation either due to the combination of increase in central command and muscle afferent input or due to activation of Group IIIa muscle mechanosensitive fibers or Ib Golgi tendon organs. Nowak et al. (1999) also studied regional cerebral blood flow during handgrip squeezing of a force transducer before and after axillary blockade to investigate if activated areas were responsible for the increase in cardiovascular variables. They concluded that cortical activation in the sensory motor area after regional anaesthesia was not indicative of central command that influenced the cardiovascular variables such as heart rate and blood pressure.

The oxygenation and blood volume results of the present study are based on rhythmic maximum voluntary contractions over a period of one minute. Also, in the present study NIRS trends during rhythmic handgrip contractions without vibration were not evaluated. However, it can be hypothesized that the increased oxygenation and blood volume changes during vibration combined with rhythmic handgrip contractions observed in the present study will be greater than that obtained while performing rhythmic handgrip contractions without vibration. Also, Uzuner et al. (2000) pointed out that investigating the stimulated motor cortex area during "just thinking of gripping one's hands" rather than "actual gripping activity" may also give different but lower responses.

Drivers and pilots often have to spend their workday not only in prolonged sitting postures but also simultaneously operating manual controls. This necessitates isometric work of the forearm muscles at varying percentages of maximal voluntary contraction. The present study has shown that cerebral responses during prolonged sitting (without WBV) are much less than the values observed during WBV alone. However, delta values observed during WBV combined with rhythmic handgrip contractions showed the greatest demand of oxygenation and blood volume changes than any other condition of the study. Thus, the present study demonstrates the importance of investigating the combined effects of physical factors during WBV.

Role of Gender

Resonance frequencies associated with WBV in the Z-axis (foot-to-head) for humans range from doses of 4 to 8 Hz (International Organization for Standardization 1997). Interestingly, in the present study women showed a systematic increase in oxygenation and blood volume measurements with increases in vibration dose up to 6 Hz ($P>0.05$), while the responses in men peaked at 4.5 Hz ($P>0.05$). Even though gender differences in the current study were statistically not significant, men demonstrated higher oxygenation and blood volume delta values than women. However, accelerations measured at C6 were significantly different between men and women, with men's accelerations 9.4%

times higher than women's. At this point, this discrepancy between difference in acceleration values at the C6 and their non-significant oxygenation and blood volume values at the cerebral region are not clear.

Additionally, even though statistically not significant, interaction of dose and gender suggests that both men and women respond differently below and within the resonance frequency range (Figures 2.8A and 2.8B). Gender played a significant role in work performance as well. During vibration alone, women showed higher values in oxygenation and blood volume responses than men. However, during vibration combined with rhythmic handgrip contractions, men showed higher values than women (Figure 2.7A and 2.7B). This phenomenon suggests that, men show greater cerebral oxygenation and blood volume responses than women during motor simulation when being exposed to WBV. In other words, men demand more oxygen (hence greater blood flow to the cerebral region) during rhythmic handgrip contractions compared to women. Maximal grip strength of men are greater than women (Table 2.1), however, non-significant correlations reported between grip strength values during WBV and cerebral oxygenation and blood volume changes (Table 2.6), implies that men's greater strength did not influence the observed differences.

Bilateral hand gripping in both men and women showed a significant blood flow velocity increase in bilateral middle cerebral arteries compared to rest condition (Uzuner et al. 2000). These authors used transcranial Doppler sonography in studying the blood flow velocity and reported no significant differences between genders. Mehagnoul-Schipper et al. (2000) demonstrated that cerebral oxyhemoglobin changes were smaller in women than in men during postural variations, however, there were no significant gender differences in oxygenation and blood volume measurements. Levin et al. (1988) used functional magnetic resonance imaging to demonstrate significant sex differences in blood-oxygen-level-dependent signals when subjects were exposed to photic stimulation. The values were 38% lower in women than men, and the researchers attributed this to the type of stimulus adopted. Since hemoglobin was shown as a contrast in the magnetic resonance signal and its concentration is generally lower in women compared to men, it was postulated that this could be a reason for this gender difference.

Rodriguez et al. (1988) reported that the regional blood flow in the frontal cortex was higher in women compared to men during resting. However, hemispheric comparisons indicated no significant differences in women, but significantly higher values in the right compared to the left hemisphere in men. They speculated that this difference between men and women might be due to differences in functional organization of the cerebral cortex or gender related differences in the functional state of brain during the testing sessions. During resting and seated conditions, Misra et al. (1998) showed sex, age, height, weight, and skin colour did not influence regional cerebral oxygen saturation. Using a blood-oxygen-level-dependent technique, Kastrup et al. (1999) showed higher signals in women than men in the visual cortex during sustained checkerboard stimulation. The researchers suggested that this gender difference in the vascular response to focal neuronal activation may be due to differences in visual physiology. With an isotope clearance technique, Gur et al. (1982) showed a higher rate of blood flow per unit weight of brain in women than in men during resting and cognitive activities. It should be noted that, none of the studies cited were related to WBV, thereby making it difficult to compare and interpret the present gender differences.

Role of Fitness

In the present study, the level of aerobic fitness in the subjects did not influence the oxygenation and blood volume responses during WBV (Table 2.7). Using the peak oxygen uptake obtained from incremental arm cranking test till exhaustion as a covariate (Table 2.1A), the results suggested that cerebral oxygenation and blood volume responses in men and women were not dependent upon the level of aerobic fitness in the subjects of the present study. These results are in contradiction to the hypothesis of Boff and Lincoln (1988) and Griffin (1990) who suggested that fitness might influence the subjects exposed to WBV. However, their assumption might be based on the whole-body cardiorespiratory responses.

Dustman et al. (1990) showed that men of high fitness perform better in neurocognitive tasks, and have a greater visual sensitivity than low fit men. These authors divided the subjects into high and low fit groups based on their maximal oxygen uptake values obtained during an incremental treadmill exercise test till exhaustion. Based on the results, they hypothesized that oxygen availability for cerebral metabolism was greater in high fit groups. Even though Dustman et al. (1990)'s study is not related to WBV, their approach towards combined psychological demand and exercise can be related to occupational performance of transit drivers or aviation pilots who perform various cognitive and motor functions in addition to just driving (Johanning et al. 1991, Hankins and Wilson 1998).

CONCLUSION

In the present study, the role of vibration dose, backrest support, workload, and gender on cerebral oxygenation and blood volume responses during seated WBV were investigated. Compared to sitting without WBV, an increase in cerebral activity (implied through an increase in both blood volume and oxygenation trends) was observed in both men and women during WBV when exposed to discrete doses of 3 Hz, 4.5 Hz, and 6 Hz. Vibration alone showed a much lower increase in oxygenation (and blood volume) changes than vibration combined with rhythmic handgrip contractions, suggesting variable physiological effects during man-environment interactions with WBV. During vibration alone, women had higher values for mean oxygenation and blood volume responses than men. However, during vibration combined with rhythmic handgrip contractions, men demonstrated higher values than women. These responses were not significantly correlated to greater maximal grip strength of men. This suggests that, men demand greater cerebral oxygenation and blood volume responses than women during work performance when being exposed to WBV.

Based on the vibration dose range of 3-6 Hz tested, men demonstrated the highest oxygenation and blood volume responses at 4.5 Hz and women peaked at 6 Hz. However, these results were not statistically significant. Subjects sitting 'With' and 'Without' a backrest showed similar cerebral responses, indicating the presence of a backrest support may not influence cerebral oxygenation and blood volume responses. The level of aerobic fitness in the subjects investigated did not influence the cerebral responses for both genders.

Significant secondary findings in biodynamics and postures during sitting were also observed. Accelerations at C6 were higher in men than women, with highest accelerations being observed at 4.5 Hz than any other dose. Greater girth of neck in men measured at C6 and Occipital regions might be the reasons for such a gender difference. Further, accelerations obtained at C6 during 'With' backrest were significantly higher than 'Without' backrest for all doses. Such significantly higher values during 'With' backrest may suggest the role of backrest vibration during WBV. Considering postural differences during seated vibration, angles adopted during 'With' backrest were higher than 'Without' backrest values, with low-back angles during 'With' backrest showed to be higher than 'Without' backrest values.

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Table 2.1A: Demographics of subjects (Mean ± SD)

Gender	Age	Body Mass	Sitting Height	Standing Height	Body Mass Index Standing
	Yrs	Kgs	m	m	$Kg. m^{-2}$
Men N=13	24.7 ± 3.9	70.8 ± 12.1[a]	0.86 ± 0.05	1.71 ± 0.07[a]	24.0 ± 3.2
Women N=14	23.9 ± 3.5	60.3 ± 9.0	0.84 ± 0.08	1.63 ± 0.10	23.0 ± 3.7

[a] – significant difference between Men and Women ($p < 0.05$)

Table 2.1B: Demographics of subjects (Mean ± SD)

Gender	Neck Dimension			Maximal Right Hand Grip Strength	Peak Oxygen Uptake Arm Cranking
	Length	C6[Ψ]	Occipital[Ψ]		
	Cm	Cm	Cm	Kgs	$mL.Kg^{-1}.min^{-1}$
Men N=13	12.6 ± 1.4	37.8 ± 3.2[a]	37.5 ± 2.8[a]	34.2 ± 9.1[a]	24.5 ± 6.6
Women N=14	12.3 ± 1.5	32.4 ± 1.7	31.5 ± 1.8	22.5 ± 3.6	21.4 ± 4.6

[Ψ] Diameter measured at the placement of accelerometer at C6 and at Occipital regions

[a] – significant difference between Men and Women ($p < 0.05$)

Table 2.2: Postural and acceleration differences during WBV at different doses in healthy men and women (Mean ±SD)

GENDER	BACKREST	DOSE	LOW-BACK ANGLE	KNEE ANGLE	Acceleration at C6	Acceleration at BASE
		Hz	Degrees	Degrees	$m.sec^{-2}$ r.m.s	$m.sec^{-2}$ r.m.s
Men	ON	3	106.2 ± 5.6[a]	100.7 ± 9.4	9.26 ± 1.16[bd]	8.94 ± 0.1
	OFF	3	93.4 ± 5.2	99.5 ± 6.0	8.99 ± 1.33	
	ON	4.5	106.2 ± 7.2[a]	100.2 ± 6.1	9.86 ± 1.34[bcd]	8.99 ± 0.1
	OFF	4.5	94.7 ± 4.6	100.2 ± 7.0	9.69 ± 1.49	
	ON	6	107.2 ± 7.8[a]	99.5 ± 7.1	9.29 ± 1.03[bd]	9.11 ± 0.1
	OFF	6	94.1 ± 7.2	101.1 ± 6.8	9.06 ± 1.19	
Women	ON	3	106.6 ± 5.6[a]	99.3 ± 6.3	8.62 ± 0.57[b]	8.94 ± 0.1
	OFF	3	95.6 ± 6.2	97.4 ± 5.2	8.22 ± 0.75	
	ON	4.5	106.1 ± 6.7[a]	99.1 ± 7.2	9.24 ± 1.43[bc]	8.99 ± 0.1
	OFF	4.5	97.4 ± 6.4	99.7 ± 6.2	8.85 ± 1.46	
	ON	6	106.6 ± 9.4[a]	98.8 ± 9.3	8.06 ± 1.18[b]	9.11 ± 0.1
	OFF	6	96.0 ± 5.6	97.2 ± 7.1	7.93 ± 1.06	

[a] - significant difference between back-on and back-off for the low-back angle at the same dose ($P<0.01$)
[b] - significant difference between back-on and back-off for acceleration at the C6 at the same dose ($P<0.01$)
[c] - significant difference between 4.5 Hz and 6 Hz for acceleration at the C6 ($P<0.01$)
[d] – significant difference between men and women for acceleration at the C6 ($P<0.01$)

Table 2.3: Cerebral Oxygenation and Blood Volume differences in Optical Density units (Mean ± SD) in healthy men and women during WBV at three different doses

GENDER	BACKREST	DOSE	Δ Oxygenation $^{\Psi}$		Δ Blood volume $^{\Psi}$	
		Frequency in Hz	WBV Without Grip	WBV With Grip	WBV Without Grip	WBV With Grip
Men	ON	3	-0.034 ± 0.11^{abcd}	0.007 ± 0.09^{abd}	0.046± 0.10^{abcd}	0.124 ± 0.13^{abd}
	OFF	3	-0.044 ± 0.07^{abcd}	-0.005 ± 0.08^{abd}	-0.04 ± 0.11^{abcd}	0.028 ± 0.14^{abd}
	ON	4.5	0.029 ± 0.18^{cd}	0.114 ± 0.27^{ad}	0.111 ± 0.09^{cd}	0.197 ± 0.08^{ad}
	OFF	4.5	0.020 ± 0.11^{cd}	0.138 ± 0.34^{ad}	0.123 ± 0.13^{cd}	0.207 ± 0.13^{ad}
	ON	6	0.018 ± 0.09^{cd}	0.072 ± 0.10^{bd}	0.071 ± 0.32^{cd}	0.189 ± 0.35^{bd}
	OFF	6	0.015 ± 0.11^{cd}	0.068 ± 0.12^{bd}	0.083 ± 0.16^{cd}	0.193 ± 0.21^{bd}
Women	ON	3	-0.004 ± 0.05^{abc}	0.015 ± 0.06^{ab}	0.016 ± 0.03^{abc}	0.045 ± 0.05^{ab}
	OFF	3	-0.013 ± 0.02^{abc}	0.003 ± 0.03^{ab}	0.016 ± 0.03^{abc}	-0.008 ± 0.23^{ab}
	ON	4.5	0.022 ± 0.06^{c}	0.043 ± 0.07^{a}	0.051 ± 0.06^{c}	0.096 ± 0.06^{a}
	OFF	4.5	0.008 ± 0.04^{c}	0.033 ± 0.04^{a}	0.050 ± 0.05^{c}	0.088 ± 0.05^{a}
	ON	6	0.044 ± 0.10^{c}	0.065 ± 0.09	0.061 ± 0.1^{c}	0.114 ± 0.1
	OFF	6	0.056 ± 0.10^{c}	0.095 ± 0.07	0.094 ± 0.07^{c}	0.135 ± 0.08

$^{\Psi}$ Δ is defined as the difference between 'maximum optical density' [during seated WBV with or without rhythmic handgrip contraction] and 'minimum optical density' [during initial rest without WBV or after recovery from WBV session with a backrest condition (recovery 1)].

NOTE: All subjects were exposed to 3, 4.5 and 6 Hz doses.

a – significant difference between doses 3 Hz and 4.5 Hz ($p < 0.01$)

b - significant difference between doses 3 Hz and 6 Hz ($p < 0.01$)

c – significant difference between vibration alone and vibration combined with rhythmic handgrip ($p < 0.05$)

d – significant interaction between work and gender (for oxygenation – $p < 0.05$); for blood volume – $p < 0.01$)

Table 2.4: Pearson Correlations between Angles measured during Sitting and Acceleration at C6

DOSE	BACKREST	MEN		WOMEN	
Frequency in Hz		Low-back	Knee	Low-back	Knee
3	WITH	0.56	-0.16	0.33	-0.36
	WITHOUT	0.06	-0.42	-0.07	-0.27
4.5	WITH	-0.54	-0.32	-0.01	-0.35
	WITHOUT	-0.19	-0.39	-0.12	-0.15
6	WITH	0.14	0.38	-0.41	0.04
	WITHOUT	0.46	0.51	-0.10	-0.24

Table 2.5: Pearson Correlations between Cerebral [Oxygenation and Blood Volume] responses and Selected Variables during Sitting 'With' Backrest

GENDER	DOSE	Selected Variables	Oxygenation		Blood volume	
	Frequency in Hz		WBV Without Grip	WBV With Grip	WBV Without Grip	WBV With Grip
Men	3	Acceleration at C6	0.49	0.15	-0.04	-0.11
		Diameter at C6	0.05	-0.06	-0.28	-0.19
		Neck Length	-0.06	-0.20	0.22	0.02
		Low-back Angle	0.33	0.11	-0.04	0.01
	4.5	Acceleration at C6	-0.15	-0.37	-0.05	0.09
		Diameter at C6	-0.30	0.04	0.01	0.04
		Neck Length	0.02	-0.14	0.49	0.52
		Low-back Angle	-0.11	0.01	0.37	0.32
	6	Acceleration at C6	0.13	0.31	-0.34	-0.36
		Diameter at C6	0.16	0.29	0.37	0.40
		Neck Length	-0.03	0.30	-0.03	-0.09
		Low-back Angle	-0.03	0.32	0.18	-0.03
Women	3	Acceleration at C6	0.19	0.16	-0.13	-0.17
		Diameter at C6	0.07	-0.05	-0.15	-0.25
		Neck Length	-0.06	-0.13	-0.16	-0.19
		Low-back Angle	-0.01	0.16	0.33	0.03
	4.5	Acceleration at C6	-0.07	-0.11	0.25	0.15
		Diameter at C6	-0.25	-0.18	-0.37	-0.33
		Neck Length	-0.34	-0.24	-0.52	-0.24
		Low-back Angle	-0.08	-0.25	0.23	0.21
	6	Acceleration at C6	0.15	-0.01	0.10	-0.04
		Diameter at C6	0.49	0.51	0.48	0.44
		Neck Length	-0.11	-0.15	-0.25	-0.28
		Low-back Angle	0.19	0.25	-0.09	-0.02

Table 2.6: Pearson Correlations between Maximal Rhythmic Handgrip Contractions and Cerebral [Oxygenation and Blood Volume] responses

DOSE	BACKREST	MEN		WOMEN	
Frequency in Hz		Oxygenation	Blood Volume	Oxygenation	Blood Volume
3	WITH	-0.46	0.03	-0.33	0.15
	WITHOUT	0.55	0.13	0.32	0.45
4.5	WITH	0.02	-0.01	0.21	0.43
	WITHOUT	-0.55	-0.10	0.25	-0.16
6	WITH	0.15	0.52	-0.27	-0.34
	WITHOUT	0.24	-0.04	-0.47	-0.11

Table 2.7: Pearson Correlations between Cerebral [Oxygenation and Blood Volume] responses and Relative Peak Aerobic Power

GENDER	BACKREST	DOSE	Oxygenation		Blood Volume	
		Frequency in Hz	WBV Without Grip	WBV With Grip	WBV Without Grip	WBV With Grip
Men	WITH	3	0.22	-0.01	0.48	0.51
	WITHOUT	3	0.14	0.20	-0.24	-0.26
	WITH	4.5	0.41	0.22	-0.21	-0.08
	WITHOUT	4.5	-0.38	-0.45	-0.10	0.10
	WITH	6	-0.33	0.14	0.31	0.44
	WITHOUT	6	0.04	0.10	0.01	0.06
Women	WITH	3	-0.12	-0.05	-0.11	-0.06
	WITHOUT	3	-0.25	-0.01	-0.09	-0.17
	WITH	4.5	-0.06	-0.06	0.14	0.13
	WITHOUT	4.5	0.14	0.27	-0.07	-0.05
	WITH	6	-0.46	-0.52	-0.57	-0.52
	WITHOUT	6	-0.44	-0.47	-0.41	-0.48

Figure 2.1A Vibration Simulator

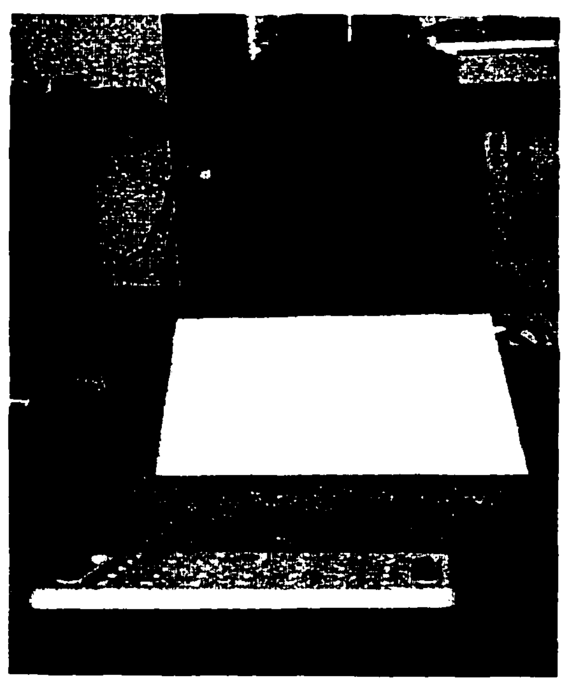

Figure 2.1B Vibration Simulator

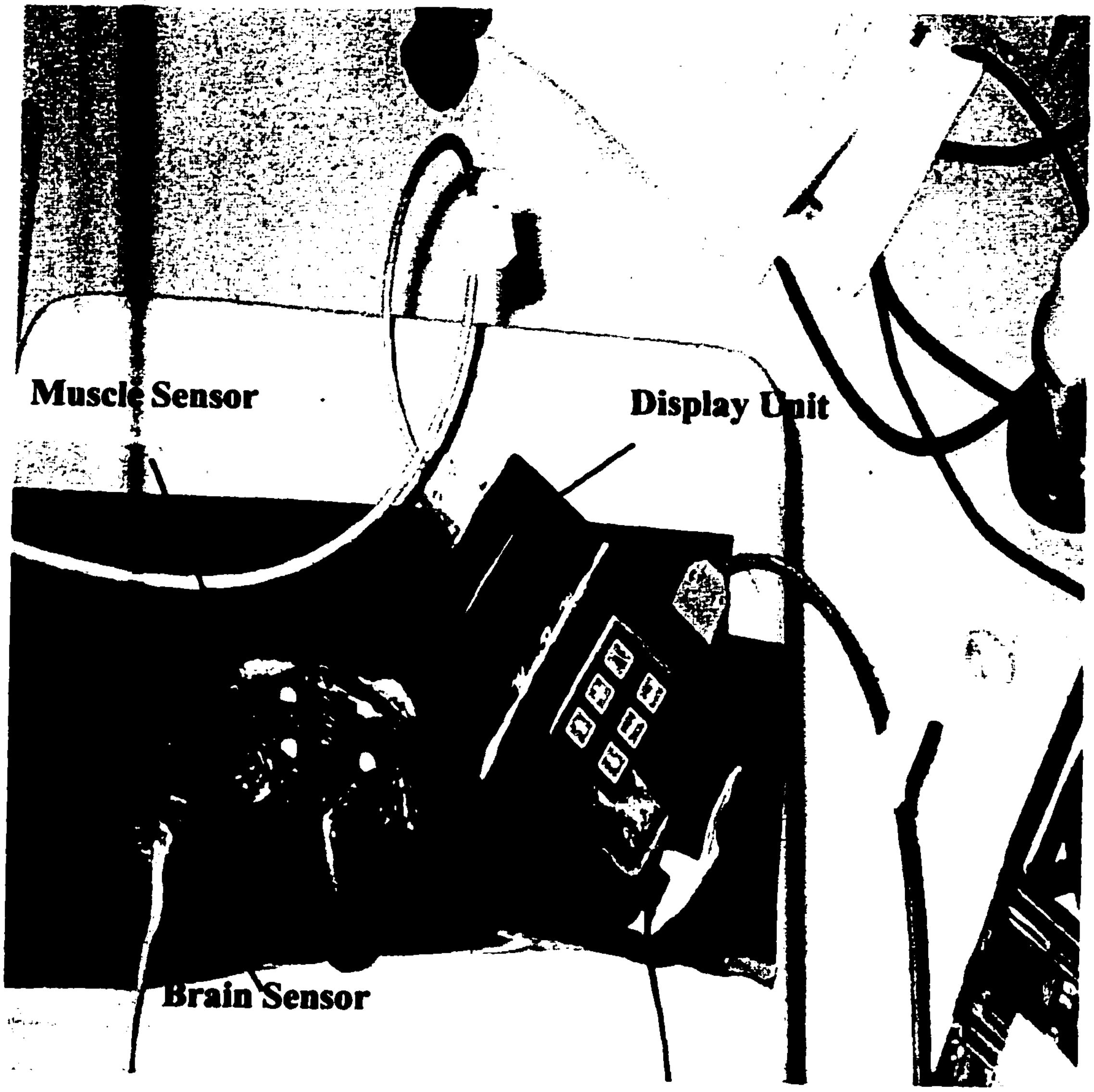

Figure 2.2 Near Infra-red Spectroscopy Unit

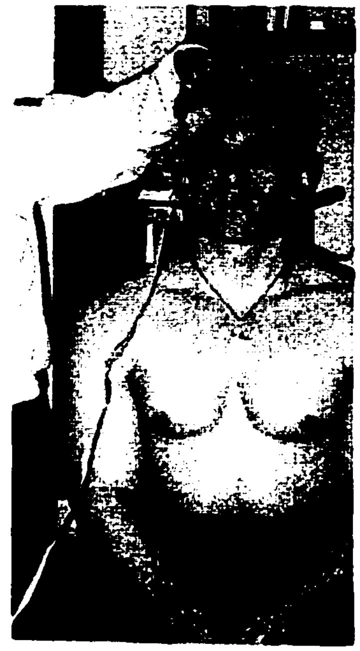

Figure 2.3A NIRS Sensor Placement on the Right Forehead
(The sensor was positioned approximately 3 cm from midline and 1 cm above supraorbital ridge)

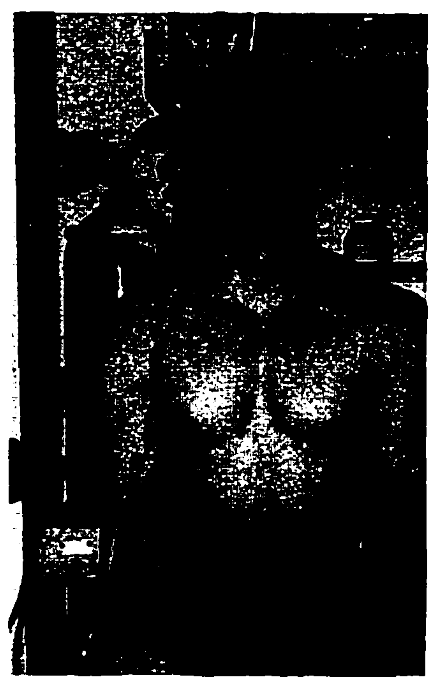

Figure 2.3B Tensor Bandage on the Head

Figure 2.4A Subject Sitting 'Without' Backrest

Figure 2.4B Subject Sitting 'Without' Backrest Combined with Handgrip Contractions

Figure 2.5 Subject Setup during Sitting 'With' Backrest

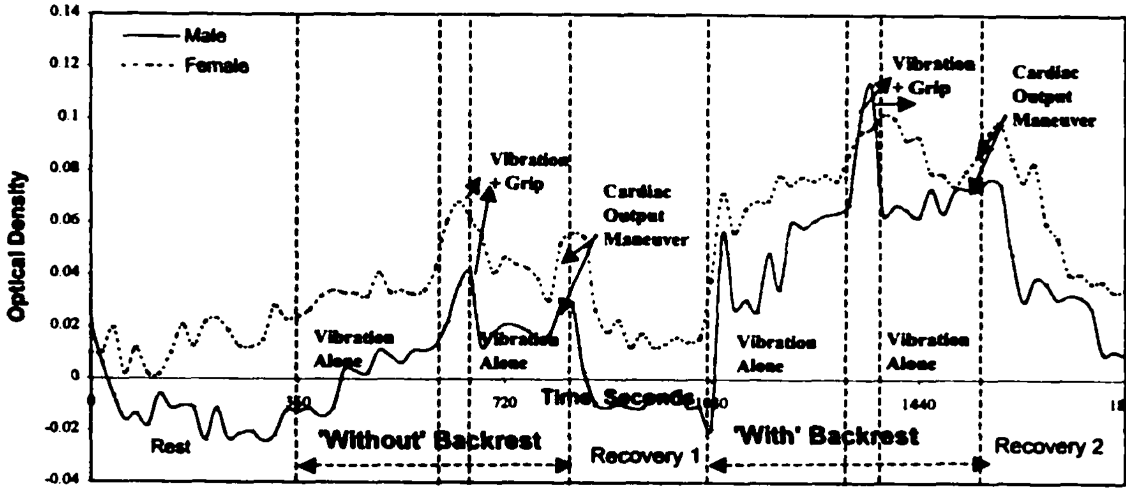

Figure 2.6A. Cerebral Oxygenation Trends

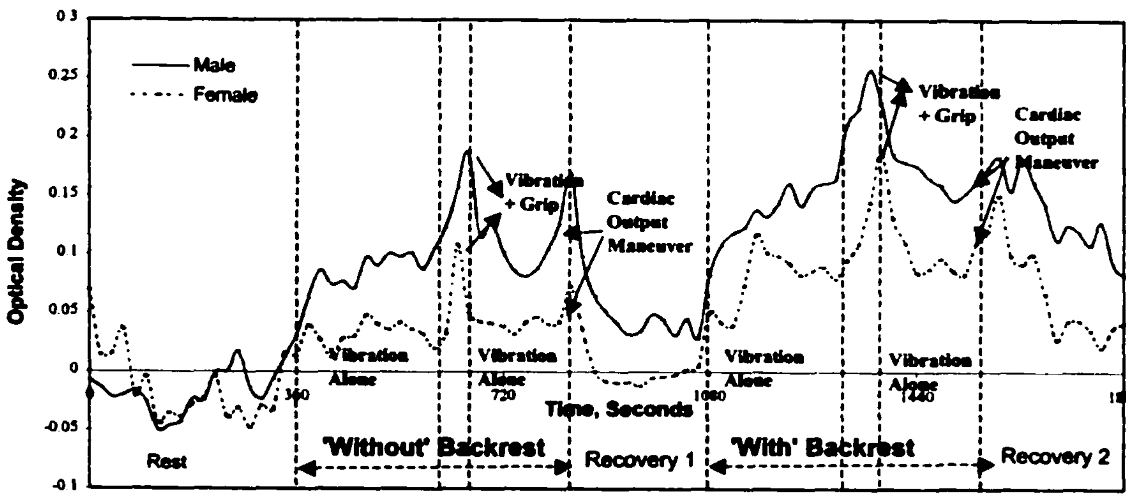

Figure 2.6B. Cerebral Blood Volume Trends

Cerebral oxygenation (top panel) and blood volume (bottom panel) trends in a typical male and female subject during exposure to seated whole-body vibration with and without handgrip exercise

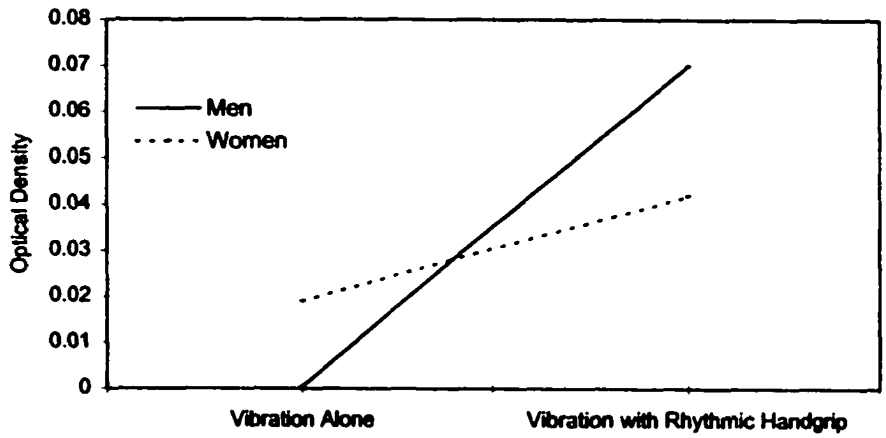

Figure 2.7A. Interaction between Gender and Work Mean Oxygenation Changes (P<0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Backrest).

3. Graph suggests that during Vibration Alone condition, women demonstrated greater oxygenation changes than men. However, men demonstrated greater oxygenation changes during Vibration with Rhythmic Handgrip contractions.

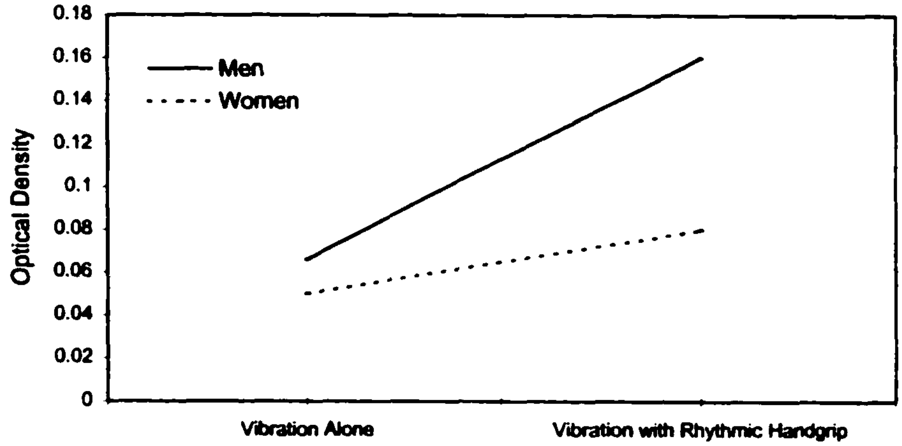

Figure 2.7B. Interaction between Gender and Work Mean Blood Volume Changes (P<0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Backrest).

3. Graph suggests that during both conditions of Vibration Alone and Vibration with Rhythmic Handgrip contractions, men demonstrated greater blood volume changes than women.

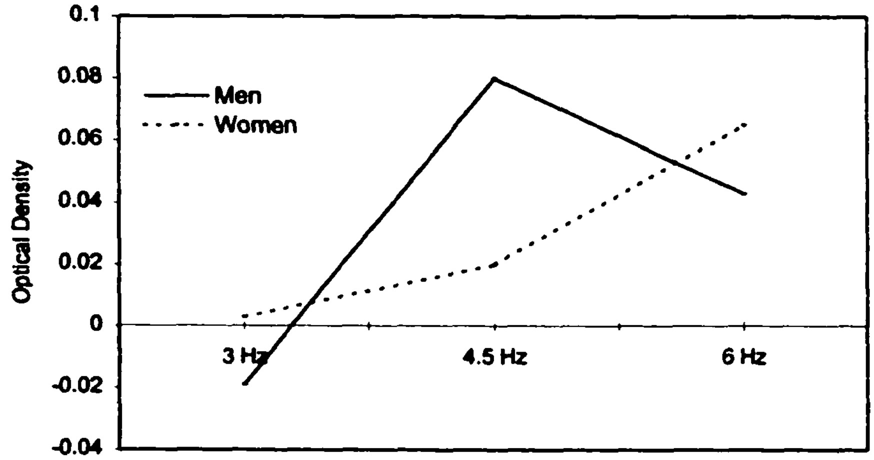

Figure 2.8A. Interaction between Gender and Dose Mean Oxygenation Changes (P>0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Backrest and Work).

3. It appears from the above graph that men and women demonstrate distinct patterns of oxygenation changes. However, because of greater varaince obtained, Dose did not influnce the results.

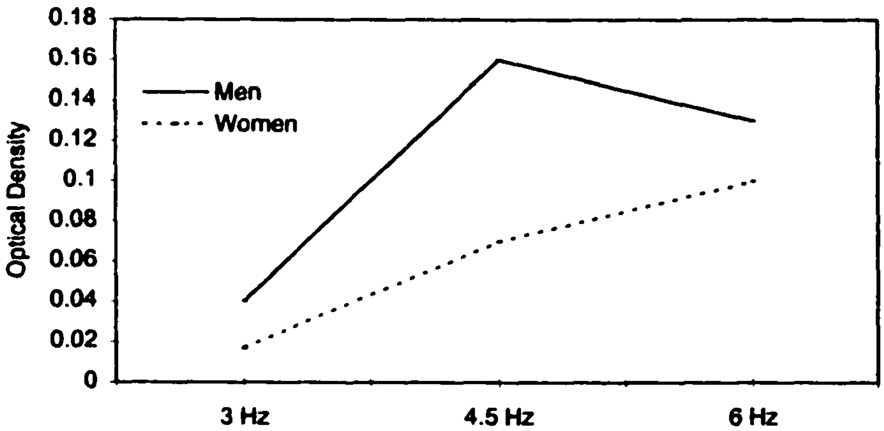

Figure 2.8B. Interaction between Gender and Dose Mean Blood Volume Changes (P>0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Backrest and Work).

3. It appears from the above graph that men and women demonstrate distinct patterns of blood volume changes. However, because of greater varaince obtained, Dose did not influnce the results.

CHAPTER 3

Lumbar Erector Spinae Oxygenation and Blood Volume Responses during Exposure to Seated Whole-body Vibration

According to Guinard (1985), vibration is defined as any continuous or intermittent oscillating mechanical force or motion that affects humans at work through the mediation of anatomical structures and sensory receptors other than the organ of hearing. Whole-body vibration (WBV) is transmitted to the entire body through a supporting structure such as a vehicle seat in a car, tractor, ship, aircraft, and snowmobile or through lifts, escalators in buildings, and from the shop floor. Extensive literature indicates that human exposure to WBV is a risk factor for the development of low-back pain (Bovenzi 1996, Dupuis and Zerlett 1986, Hulshof and van Zanten 1987, Pope 1989, Seidel and Heide 1986). Aircrew and helicopter pilots (Simon-Arndt et al. 1997) and drivers of earth-moving vehicles (Miyashita et al. 1992), agricultural tractor drivers (Boshuizen et al. 1990, Bovenzi and Betta 1994), and buses and transit drivers (Bongers et al. 1988) are some of the occupational groups who are at a greater risk for low-back complaints than the control groups unexposed to WBV.

Establishing dose-response relationships of WBV in humans is important, as driving has become an integral part of life for everybody including the specific occupational groups mentioned above. However, the majority of research has not established a quantitative relationship between exposure (dose) and effects (physiological responses). Some of the reasons include inadequate controls of concomitant exposures to potentially confounding factors, such as prolonged sitting, awkward postures adopted, frequent twisting of the spine during work, handling various controls, and frequent heavy manual material handling.

Primary factors that influence human response to WBV are: the source (vibrating base, vehicle dynamics), interface such as a seat cushion and the host (humans). The host's physical characteristics (e.g. body dynamics, gender, age, weight) and physiological differences (e.g. fitness) also may influence human performance and responses during exposure to WBV (Boff and Lincoln 1988, Griffin 1990). The most dominant frequency dose identified in vehicles ranges from 3 to 6 Hz (Wilder et al. 1982), with the transfer of maximum mechanical energy to the spine resulting at about 4.5 to 5 Hz (Panjabi et al. 1986, Pope et al. 1998, Wilder et al. 1982).

Electromyographic WBV studies of the paraspinal muscles in the low-back demonstrated the development of localized muscular fatigue in a variety of postural positions and vibration doses (Hansson et al. 1991, Pope et al. 1998, Wilder et al. 1982). It was suggested that this localized fatigue could be due to compromised blood flow, resulting in reduced oxygenation and availability of nutrients to these muscles (Hansson et al. 1991, Pope et al. 1990; Zimmerman et al. 1993). This hypothesis, however, has yet to be objectively tested. Using a backrest during driving is common. Several authors have suggested that vibration of a backrest during driving may amplify the vibration transmission to the human body (Cho and Yoon 2001, Griffin 1990, Magnusson et al. 1992, Paddan and Griffin (1988a,b). This raises an important question. Physiologically, does the presence of a backrest increase or decrease lumbar erector spinae muscle oxygenation and blood volume responses? Those employed in occupations with WBV, often work not only in prolonged sitting but also operating manual controls. This demands isometric work of the forearm muscles at varying percentages of maximal voluntary contraction. Hence, it is necessary to understand physiological responses due to rhythmic handgrip during exposure to WBV. Palmer et al. (2000) demonstrated that in general occupational exposure to WBV in men over a one-week period is approximately four times greater than in women. However, research pertaining to differences between genders with respect to physiological responses during exposure to WBV is limited (Bovenzi 1996). Also, the role of physical fitness on responses to WBV has not been studied to date.

Near infra-red spectroscopy (NIRS) is a non-invasive optical technique that has been used to measure relative changes in oxygenation and blood volume levels in skeletal muscle continuously in real-time during rest and work (Bhambhani et al. 1998, Boushel et al. 1998, Chance et al. 1992, Mancini et al.

1994, Murthy et al. 1997). Muscle oxygenation, defined as the relative saturation of oxyhemoglobin and oxymyoglobin, depends on the balance between oxygen delivery and oxygen utilization (Mancini et al. 1994). Blood volume is defined as the sum of oxygenated and deoxygenated states of hemoglobin and myoglobin in the illuminated region of the muscle. Detailed description of the NIRS theory, its validation with various established optical and magnetic techniques are provided in Chapter 1. The reliability of NIRS in the upper and lower extremity human skeletal muscles has been reported in the Chapter 1 as well. In establishing the reliability of NIRS in the erector spine muscle during maximal back extension, Maikala et al. (2000) reported significant intra-class correlation coefficients of 0.83 and 0.84 for minimum oxygenation during sitting and standing respectively, and 0.99 for the minimum blood volume during both postures. To date, erector spinae oxygenation and blood volume changes using NIRS have been limited to sub-maximal and maximal isometric contractions (Jensen et al. 1999, McGill et al. 2000, Maikala et al. 2000, Maikala and Bhambhani 1999, Maronitis et al. 2000, Yoshitake et al. 2001). No studies have evaluated the oxygenation and blood volume trends of any skeletal muscle group during exposure to WBV.

The purposes of this study were to examine: (1) the effects of 3 Hz, 4.5 Hz, and 6 Hz vibration dose on the relative changes in oxygenation and blood volume measured by NIRS in the lumbar erector spinae muscle in healthy men and women; (2) the differences in these trends 'With' and 'Without' a backrest exposure to WBV; (3) alterations in these responses with the addition of rhythmic handgrip contractions during WBV, and (4) differences in these responses between genders. It was hypothesized that erector spinae oxygenation and blood volume responses will be similar in both men and women 'With' and 'Without' backrest, and will not be influenced by the exposure to vibration dose within the range of 3 to 6 Hz while performing rhythmic handgrip contractions.

MATERIALS AND METHODS

Subjects

Written informed consent was obtained from 13 healthy men (mean ± SD: age 24.7 ± 3.9 yrs, mass 70.8 ± 12.1 kg, height 171 ± 7 cm) and 14 healthy women (age 23.9 ± 3.51 yrs, mass 60.3 ± 9.0 kg, height 164 ± 10 cm). Subjects were undergraduate and graduate students recruited from the university population (Table 3.1). They all completed the Revised Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology, 1994) to identify contraindications for exercise. All subjects were right hand dominant. The test protocols utilized were approved by the Health Ethics Research Board at this institution (APPENDIX A.1).

Vibrating Base

A steel vibrating base that housed an electro-mechanical motor connected to a cam mechanism (Advanced Therapy Products, Inc., VA, USA) was modified with an external DC speed control device (Figures 2.1A and 2.1B). Varying the speed of this motor from 0 to 100% corresponded to vibrating frequencies of 0 Hz to 6.2 Hz. Detailed description of the vibrating base, placement and calibration of accelerometers were described in the Chapter 2. Average vertical accelerations (in root mean square values [r.m.s]) generated at different doses are also provided in the Chapter 2.

Test Protocols

Each subject completed an arm cranking exercise test in the first session, followed by three WBV tests on separate days (3 Hz, 4.5 Hz, and 6 Hz) in a randomized order.

(1) Assessment of the Peak Oxygen Uptake

In the first testing session, the subject completed an aerobic fitness test on an arm cranking ergometer (Cybex, MET 300, USA). Details of the peak oxygen uptake measurements and the exercise termination criteria are explained in the Chapter 2.

(2) Vibration Tests

The test protocol on each day lasted 30 minutes, and included initial six-minute rest without vibration, eight-minute vibration 'With' (or 'Without') a backrest, four-minute recovery, eight-minute vibration 'Without' (or 'With') a backrest, and four-minute recovery. Subjects were randomly assigned to a posture 'With' or 'Without' a backrest. They were instructed to adopt a comfortable posture when tested 'Without' a backrest (Figures 2.4A and 2.5). Throughout the test, subjects sat in the vibrating chair with the eyes open. A footrest was provided for subjects to place their feet at a comfortable level. During sitting 'With' and 'Without' a backrest, angles at the knee joint and low-back were measured by a goniometer (JAMAR, Clifton, NJ, USA).

(3) Rhythmic Handgrip Measurements

Before the vibration session, right hand grip size was adjusted on the dynamometer (JAMAR, CA, USA) to a position that was comfortable for each subject. During the fifth minute of each vibration condition, the subject performed rhythmic maximal contractions for one minute at a contraction rate of one every five seconds (Figure 2.4B). Contractions were performed with the right hand with the forearm in a horizontal position and the elbow at an angle of 180°. Similar to a method suggested by Schmidt and Toews (1970), throughout the study the dynamometer was calibrated with known weights to check its accuracy identified through the dial reading on the dynamometer.

(4) Oxygenation and blood volume measurements

A continuous dual wave NIRS unit (MicroRunman, NIM Inc., PA, USA) was used to evaluate relative changes in the lumbar erector spinae oxygenation and blood volume during the vibration tests (Figure 2.2). This unit consists of: a superficial near infra-red sensor fitted with six light emitting tungsten lamps placed 2 cm, 3 cm, and 4 cm part; two photo-diode detectors that absorb light in the near infra-red range between 760 nm and 850 nm; and a display unit that amplifies and displays the absorbency signal generated. Sensor was placed on the erector spinae muscle at 3 cm from the middle of spine to the right side on the third lumbar region [Figure 3.1A] (Maikala et al. 2000). A dark elastic bandage was wrapped around the sensor to secure it in place and minimize any loss of light (Figure 3.1B). A piece of clear plastic was wrapped around the sensor to prevent sweat from distorting the absorbency signal. Erector spinae muscle skinfold thickness at the sensor location was measured twice using a skinfold caliper (Cambridge Scientific Industries, Inc. Maryland, USA) before placing the NIRS sensor on that muscle belly. Then adipose tissue thickness (a sum of fat and skin layer) at the sensor site was calculated as a half of the skinfold thickness. Position of the NIRS sensor at the 3rd Lumbar region from the mid line of the spine was noted to the nearest millimeter, thus ensuring the correct placement of NIRS sensor on each subject for all the testing sessions.

As per the manufacturer's specifications, the sensor was calibrated at 760 nm and 850 nm wavelengths before the test for each subject. The vertical penetration depth of light was set to 4 cm. The difference in absorbency between these two wavelengths indicated the change in oxygenation saturation and the sum of these absorbencies indicated the change in total blood volume. Both oxygenation and blood volume were measured in terms of optical density (OD) that is defined as the logarithmic ratio of intensity of light calibrated at each wavelength to the intensity of measured light at the same wavelength (MicroRunman User Manual, NIM Inc., PA, USA, 1999). Real time data were recorded using the NIRCOM software provided by the manufacturer.

NIRS Data Analysis

The real time NIRS values were averaged every 20 seconds using a customized Microsoft Excel software program specially designed for this study. Baseline oxygenation and blood volume values were recorded during initial rest or recovery from each vibration dose. Minimum values were recorded for each dose during vibration with and without rhythmic handgrip, and 'With' and 'Without' a backrest. The change (delta value) in oxygenation and blood volume for each condition [dose (3Hz, 4.5 Hz and 6 Hz), backrest (With' and 'Without' a backrest), workload (vibration alone and vibration combined with rhythmic handgrip contraction)] was calculated as the difference between the baseline and minimum values for each phase of the test session. *It should be noted that the greater the delta values the greater the decrease in oxygenation and blood volume changes.* Oxygenation and blood volume values 30 seconds before the beginning of each WBV session were identified as baseline values, and were used to calculate delta values. All statistical analyses were performed using the delta values calculated for each phase of the study.

Statistical Analysis

A four-way analysis of covariance (ANCOVA), using the peak oxygen uptake as the covariate, gender as a between-subjects factor, and three repeated measures factors (dose, backrest, and workload) with a fully crossed design was used to evaluate the differences in the oxygenation and blood volume responses (measured in OD units). Since peak oxygen uptake is considered to be one of the best indicators of aerobic fitness, it will be used to examine whether the fitness level of the subjects has any influence on the lumbar erector spinae oxygenation and blood volume responses.

To minimize the violation of the assumption of homogeneity of variance, the 'Greenhouse-Geiser' adjustment was used. Since multiple comparisons were made for each dependent variable in the present study, the Bonferroni adjustment for a P value of 0.05 was applied to minimize Type 1 error. The Bonferroni adjustment was calculated as the ratio of 0.05 and number of statistical comparisons (APPENDIX B.2). Thus, statistical significance was considered at $P < 0.01$. Significant F ratios were further analyzed with the Scheffe post hoc multiple comparison test. Also, the relationship between maximal rhythmic handgrip contractions and changes in oxygenation and blood volume responses were evaluated using Pearson product moment correlations. A

Spearman correlation test was used to examine the relationship between logarithmic value of adipose tissue thickness and [minimum and maximum] oxygenation and blood volume responses for the three protocols. Since the adipose tissue thickness of the subjects in the present study was normally distributed, a nonlinear correlation test was used to examine its role on the NIRS measurements. The Statistical Package for Social Sciences SPSS (version 10) was used for all statistical analyses (SPSS Inc., Chicago, USA).

RESULTS

Lumbar Erector Spinae Oxygenation and Blood Volume Trends in Men and Women

A typical profile of the lumbar erector spinae oxygenation and blood volume trends at 4.5 Hz, 'With' and 'Without' a backrest in a male and female subject is shown in Figures 3.2A and 3.2B respectively. It is evident from both figures that as soon as the vibration started 'Without' a backrest, oxygenation and blood volume responses increased for about 20-30 seconds, and then decreased from the baseline (resting) value during the four-minute period. During vibration combined with rhythmic handgrip contractions, oxygenation values decreased to a lower level than vibration alone. As soon as the rhythmic handgrip contractions stopped during vibration, oxygenation (Figure 3.2A) and blood volume (Figure 3.2B) trends returned to the initial vibration level. In the recovery phase, oxygenation and blood volume responses increased towards the baseline values (recovery 1). In the subsequent 'With' backrest condition of vibration period without rhythmic handgrip contractions, similar trends were observed in the oxygenation and blood volume responses with the values less decreasing than those observed during 'Without' a backrest condition.

The lumbar erector spinae oxygenation and blood volume differences during the WBV experimental conditions in both genders are presented in Table 3.2. Statistical analysis of lumbar erector spinae oxygenation and blood volume values for each dose during the different experimental conditions in both men and women revealed: (1) the covariate, namely, peak oxygen uptake, had no significant influence on the erector spinae oxygenation and blood volume responses, (2) the four-way and three-way interactions were not significant implying that both genders responded similarly to the three doses of WBV 'With' and 'Without backrest, and with and without the rhythmic handgrip contractions, (3) the interaction between gender and workload was significant for only oxygenation but not blood volume responses, (4) the interaction between gender and backrest was significant for only blood volume responses but not oxygenation, (5) the main effects of dose and gender were not significant for both oxygenation and blood volume responses, (6) the main effects of workload were significant for both oxygenation and blood volume responses, and (7) the main effects of backrest were significant only for blood volume responses.

It should be noted that the comparisons of the significant two-way interaction were based on the pooled mean values at the three different doses and both genders. Similarly comparison of the main effects was also based on the pooled mean values of the remaining three independent variables in the experimental design. The results of these significant main effects and interactions are presented below.

Comparison between Doses

No significant differences were observed in mean oxygenation and blood volume values for all doses (3Hz: 0.018 ± 0.06 OD, 4.5 Hz: 0.037 ± 0.13 OD, 6Hz, 0.025 ± 0.08 OD, P=0.636). Corresponding comparisons for the blood volume changes (P=0.405) were: 0.005 ± 0.13 OD (3Hz), 0.032 ± 0.14 OD (4.5 Hz), 0.006 ± 0.12 OD (6Hz).

Comparison between 'With' and "without' a Backrest Support

No statistical differences were found in the values of mean oxygenation between 'With' and 'Without' backrest conditions. There was no significant difference in the mean oxygenation responses 'With' and 'Without' backrest conditions (0.029 ± 0.11 OD Vs 0.024 ± 0.08 OD, P=0.271). Interestingly, mean values for blood volume 'Without' a backrest were significantly higher than that of 'With' backrest condition (0.056 ± 0.15 OD Vs –0.028 ± 0.09 OD, P=0.000).

Comparison between Vibration Alone and Vibration Combined with Rhythmic Handgrip Contractions

Significant differences in mean oxygenation and blood volume responses were observed between vibration alone and vibration combined with rhythmic handgrip contractions. Mean oxygenation values were significantly higher during vibration combined with rhythmic handgrip contractions than vibration alone (0.034 ± 0.10 OD Vs 0.019 ± 0.09 OD, P=0.000). Also, mean blood volume values were significantly higher during vibration combined with rhythmic handgrip contractions than vibration alone (0.020 ± 0.13 OD Vs 0.008 ± 0.13 OD, P=0.009). Significant interaction was obtained between workload and gender for only oxygenation values (Figure 3.3A). During both conditions of workload, men showed greater mean oxygenation changes (Vibration alone: 0.024 ± 0.12 OD; Vibration combined with handgrip: 048 ± 0.13 OD) than women (Vibration alone: 0.015 ± 0.06 OD; Vibration combined with handgrip: 0.021 ± 0.06 OD, P=0.020). Even though statistically not significant, during vibration alone men demonstrated less mean blood volume changes than women (0.006 ± 0.17 OD Vs 0.010 ± 0.08 OD, P=0.264). Also, during vibration combined with rhythmic handgrip contractions, men did not show significant difference in mean blood volume changes from women (0.023 ± 0.16 OD Vs 0.017 ± 0.08 OD, P=0.264) (Figure 3.3B).

Comparison between Genders

No significant differences in oxygenation and blood volume were found between men and women for all conditions of dose, workload and backrest. However, there was a tendency for the mean oxygenation and blood volume responses to be consistently higher in men. In men, mean values for oxygenation were higher than that of women (0.036 ± 0.12 OD Vs 0.018 ± 0.06 OD, P=0.164). Blood volume values were also higher in men compared to women (0.015 ± 0.17

OD Vs 0.014 ± 0.08 OD, P=0.952). No significant interaction between gender and dose was observed in both oxygenation and blood volume responses. However, men showed greatest values at 4.5 Hz (P>0.05) and women peaked at 6 Hz (P>0.05) (Figures 3.4A and 3.4B). Interestingly, significant interaction between gender and backrest was observed in blood volume responses only, with greater values reported 'Without' backrest condition for both genders (Fig 3.5A and 3.5B).

Correlations between Selected Variables and Oxygenation and Blood Volume

Pearson correlations obtained between maximal rhythmic handgrip contractions and changes in oxygenation and blood volume responses were not significant (P>0.05), suggesting maximal effort did not influence the muscle NIRS measurements (Table 3.3). Further, adipose tissue thickness calculated from erector spinae skinfolds for men and women (mean ± SD) are: 5.7 ± 2.5 mm, and 5.8 ± 2.2 mm, respectively. They were not significantly different from each other (P>0.05). Spearman correlations between adipose tissue thickness and mean changes in oxygenation and blood volume data for both men and women during three protocols are shown in Table 3.4. No significant correlations (P>0.05) were found between adipose tissue thickness at the lumbar erector spinae muscle and oxygenation and blood volume responses.

DISCUSSION

Lumbar Erector Spinae Oxygenation and Blood Volume Trends during Whole-Body vibration

There has been, no studies to date that have examined the lumbar erector spinae oxygenation and blood volume responses during WBV in any species. Hence it is difficult to compare current results with the existing vibration literature. Using photon diffusion principle, NIRS can detect oxygenation and blood volume of skeletal muscle during any state, and in the present study decrease in muscle blood volume and oxygenation during various WBV conditions demonstrates that a reduction in erector spinae oxygen saturation is possible during exposure to WBV (Figures. 3.2A and 3.2B). Such a decrease in oxygenation may also be due to an increase in intramuscular pressure above perfusion pressure, thus limiting blood flow to the working muscle (Rundell et al. 1996).

NIRS signal is treated primarily as a representative of capillary and venous HbO_2 saturation (Mancini et al. 1994a). Since NIRS monitors oxygen saturation at the levels of smaller blood vessels, a decrease in oxygenation and blood volume trends during WBV confirmed deficiency in the vascular supply to the low-back muscles during WBV. During recovery, blood supply (in terms of increase in 'optical' blood volume, thus blood flow) and reoxygenation to these paraspinal muscles returned closer to the baseline. Such an increase in local muscle blood volume can be due to larger capillary volume through local metabolic vasodilation.

Repeated contraction of lumbar erector spinae muscle during WBV in addition to static sitting, might have resulted from vasoconstriction of venous blood, and increase in venous return, thus reflecting a reduction in blood volume. Yoshitake et al. (2001) hypothesized a similar decrease in both oxygenation and blood volume responses observed during maximal back extension in a prone position might be due to ischemic muscle activity in the low-back region, specifically in the muscles that contain fast twitch fibers. Also, Maikala et al. (2000) showed a similar decrease in both oxygenation and blood volume in the right side of lumbar erector spinae muscles during maximal back extension in both sitting and standing postures. McGill et al. (2000) hypothesized a few mechanisms for such a decrease in oxygenation: compromised blood flow in these smaller blood vessels (due to intramuscluar pressure exceeding intravascular pressure), thus reducing blood volume; reduced perfusion and increase in oxygen extraction from the muscle; or skin blood flow. However, NIRS signal primarily monitors muscle not skin oxygenation (Mancini et al. 1994). Also, an imbalance between oxygen supply and uptake may lead to a greater deoxygenation in the muscle, thus reducing muscle oxygen saturation.

However, in the present study, some of the subjects did not show any steep decrease, and few in fact demonstrated an increase in blood volume changes during WBV combined with rhythmic handgrip contractions. This may be due to the diffusion limitation between the capillaries and erector spinae muscle. Boushel et al. (1998) suggested a similar hypothesis during rhythmic handgrip exercise. They found oxygen saturation of venous blood (collected from antecubital space) remained the same (after 15% to 30% contractions) even though a decrease in pH was found. They speculated this unchanged value may also be due to contribution of blood from less active tissues, and flow impeded by the mechanical forces generated during muscle contraction.

Jorgensen (1997) reported that "paravertebral muscles are dominated by slow twitch fibers, with small fiber areas and well-developed capillary network." Junghanns (1990) suggested the relation between the spinal movements and diffusion of nutrition to the intervetebral discs, and attributed exposure to WBV and prolonged sitting (without movement) may lead to muscle fatigue in the low-back. Seroussi et al. (1989) compared muscle fatigue during static sitting and WBV, and concluded that fatigue observed in the lumbar erector spinae muscles after exposure to WBV may affect the load-bearing capacity of the trunk muscles. Several researchers have hypothesized that low-back muscle fatigue might be due to the prolonged cyclic firing of these paraspinal muscles during WBV (Pope et al. 1992, Pope et al. 1998, Pope and DeVocht 1999, Seroussi et al. 1989, Wilder et al. 1982, Zimmerman et al. 1993).

Role of Whole-Body vibration Dose:

Since the mechanical resonance range of the human spine for the seated operator is between 4-8 Hz (International Organization for Standardization 2631/part1 1997), it is evident from the current investigation that dose responses below resonance are different from the responses in the range of human resonance. As the dose increased from 3 to 6 Hz, men showed greatest lumbar erector spinae oxygenation and blood volume values at 4.5 Hz ($P>0.05$) while women demonstrated greatest values at 6 Hz ($P>0.05$) (Figures 3.4A and 3.4B).

Several authors suggested the frequency shift from a higher to a lower level in the EMG profile during WBV as an indication of low-back muscle fatigue (Hansson et al. 1991, Pope et al. 1998, Seidel and Heide 1986, Wilder et al. 1982). Based on EMG findings, Hansson et al. (1991) hypothesized that exposure to WBV would result in a reduced arterial supply to the back muscles. The present study confirmed a reduction in both blood volume and oxygenation in the lumbar erector spinae muscles during exposure to WBV (Figures 3.1A and 3.1B), thus suggesting WBV might disturb the blood supply to the erector spinae muscles in the lumbar region.

Seroussi et al. (1989) showed peak-to-peak torque generated at L3 of the erector spinae muscles during vibration was maximum at 4 Hz, and decreased as the frequency increased. These authors also demonstrated that mean and peak-to-peak torque generated during WBV was also significantly higher than static sitting. Hansson et al. (1991) studied the EMG activity of erector spinae muscles in subjects during sitting (at L3 and seventh thoracic) for a period of 5 min with and without WBV at 5 Hz, and demonstrated that vibration increases both the speed and the magnitude of the development of muscle fatigue.

In the present investigation, even though exposure to dose below (3 Hz) and in the human spinal resonance range (4.5 and 6 Hz) did not influence significant difference in oxygenation and blood volume responses. However, the decrease in trend in these local physiological responses compared to sitting without WBV shows the role of prolonged exposure of WBV in muscle desaturation of the human back in both men and women.

Role of Sitting 'With' and 'Without' a Backrest Support:

Mean oxygenation and blood volume values obtained in the present study 'Without' backrest were 20% ($P>0.05$) and 150% ($P<0.05$) higher compared to 'With' backrest values. During sitting 'Without' a backrest, it has been speculated that sustained isometric contraction of the paravertebral muscles in maintaining this erect posture for a prolonged period will slow down the pumping mechanism, thus disturbing the nutritional diffusion (Junghanns 1990). This would result in decrease in blood flow (represented by reduction in blood volume changes as shown in Fig. 3.2B), resulting in deprivation of oxygenation availability to these postural muscles. However, non-significant responses in mean oxygenation values during 'With' and 'Without' a backrest may suggest that oxygen availability and utilization were equally balanced in these two conditions, with blood flow compromised to a greater extent during sitting 'Without' backrest as compared to 'With' backrest.

During exposure to WBV for 30 min, Wilder et al. (1982) did not find any statistically significant changes in the EMG activity in both right erector spinae and external oblique muscles at the L3 level due to postural variations (neutral posture, neutral and valsalva position, forward flexion (5°), extension (5°), left and right lateral bend (5°), and maximal left/right axial rotation). In a real driving task on the road, Hosea et al. (1986) evaluated the responses of EMG activities of 12 paraspinal muscles with respect to backrest inclination and lumbar support during a 3.5 h period of car driving. These authors did not find any EMG evidence of fatigue (measured by decrease in mean power frequency and increase in amplitude for equal function) to the duration of WBV exposure. However, minimum EMG activity was reported at 130° inclination of the backrest, 13.5°-18.5° of the seat angle, and 5 cm of the lumbar support.

During 2 min of vertical vibration at 4.5 Hz, the EMG magnitude in the erector spinae muscles was greater for the anterior and neutral postures, with anterior posture being recorded highest than for the posterior lean posture (Zimmerman et al. 1993). These authors demonstrated greater cyclic compression of the spine during anterior lean posture, and hypothesized that during prolonged periods in this position such cyclic compression may result in decreased nutrient diffusion, thus leading to earlier onset of erector spinae muscle fatigue. In a simulated truck driving, Wilder et al. (1994) vibrated subjects for a period of 10 min (1-20 Hz), and based on the surface EMG results demonstrated that upright sitting causes more fatigue than during any other posture. However, seat suspension did not affect the EMG responses, and these authors suggested that such results might be reflective of monitoring for only short-duration. Sitting posture in most of the above EMG studies has used either a slightly flexed posture or subjects were loaded with a small weight so as to register erector spinae activity. Since NIRS identifies oxygenation and blood volume changes in any postural variation during rest and work, we believe it is not necessary to load the subjects with any weights during sitting.

Studies pertaining to muscle oxygenation and blood volume of postural variations during WBV have not been reported to date. However, few studies have reported influence of posture on other skeletal muscle oxygenation and blood volume responses in other activities. Rundell et al. (1996) demonstrated that deoxygenation was greater during low-skating position compared to upright position. These authors also reported lower blood volume changes during low-skating position suggesting that this posture might compromise blood flow to the working muscles, thus limiting oxygen delivery. Binzoni et al. (1997) and Ferrari et al. (1997) demonstrated that changes in calf muscle deoxyhemoglobin and blood volume increased as the bed angle increased, and returned to base line when the bed position was reset, thus suggesting that NIRS was sensitive enough to monitor postural changes. Even though none of the NIRS studies cited above were related to WBV, it can be concluded that posture adopted 'With' and 'Without' a backrest plays a role in determining the changes in oxygenation and blood volume responses, in particular mean blood volume response during WBV.

Role of Workload during Whole-Body Vibration:

During vibration combined with rhythmic handgrip contractions, mean oxygenation and blood volume were 43.3% and 60% respectively higher than vibration alone, suggesting a greater decrease in skeletal muscle oxygenation and blood volume responses when subjects perform physical activity combined with exposure to WBV. From figures 3.2A and 3.2B, it is obvious that oxygenation and blood volume responses decreased from baseline during vibration alone, and continued to decline during vibration combined with work.

Mester et al. (1999) reported that people involved in sports such as sailing, surfing, alpine skiing, horse-back riding, etc., experience considerable vibration. Their group (Hoffmann et al. 1999) studied the role of isometric contraction during with and without vibration on muscular energy metabolism. Subjects did isometric plantar flexion against a vibrating force generator (at 4 and 8 Hz) in a 4.7 Telsa Magnet. These authors showed that phosphocreatine decreased rapidly by 50% during vibration exposure compared to no exposure, suggesting an increased rate of adenosine triphosphate hydrolysis. Further, they suggested that the minimal level of relative phosphocreatine obtained might depend on both isometric contraction force and vibration frequency, and emphasized the importance of relating this phenomenon to isometric contractions applied during activities such as alpine skiing. Also, Andersson et al. (1974) observed an increase in myoelectric activity in the lumbar muscles with shifting gears during driving. In the current study, a significant deoxygenation in the right side of erector spinae muscle during WBV alone, and during WBV combined with rhythmic handgrip contractions was observed, supporting the similar findings cited above.

In the present study, valsalva maneuver occurred during maximal rhythmic handgrip contractions. This may result in increased intrathoracic pressure subsequently reducing venous return of the blood to the heart (McArdle et al. 1996). However, reduction in blood volume (Fig. 3.2A) and subsequently oxygenation (Fig. 3.2B) during maximal rhythmic handgrip contractions suggests that muscle co-activation is possible even at the erector spinae level when in fact primary muscles involved during such handgrip activity were forearm muscles (Kahn et al. 2000). Furthermore, the additional 'postural load' of sitting for a prolonged period of time might concomitantly affect such decrease in oxygenation and blood volume responses during work as well. Thus, the present study demonstrated decrease in both oxygenation and blood volume responses during rhythmic handgrip contractions combined with WBV, demonstrating the role of physical work during WBV may further burden the low-back muscles.

Role of Gender:

In the present study, gender as 'a main effect' did not influence the oxygenation and blood volume responses. Resonance frequencies associated with WBV in the Z-axis (foot-to-head) for humans range from doses of 4 to 8 Hz (International Organization for Standardization 1997). Interestingly, in the present study women showed a systematic decrease in oxygenation and blood volume responses (or greater mean values) with increases in vibration dose up to 6 Hz, while the responses in men reached nadir at 4.5 Hz (Fig 3.4A and 3.4B). Even though these results were not statistically significant, such gender differences may suggest the influence of gender in erector oxygenation and blood volume responses within the resonance frequency range.

Gender interacted with workload and showed significance in the mean oxygenation values but not in mean blood volume values. Mean changes in oxygenation values during WBV alone for men were 38.5% greater than women, and during WBV combined with rhythmic handgrip contractions, men showed 56.3% greater values than women. In the present study, since greater mean (oxygenation and blood volume) values are an indication of greater decrease in oxygenation and blood volume responses, such a decrease in phenomenon in men could be attributed to lower percentages of slow twitch (aerobic) fibers, thus having less oxidative capacity and endurance than women (Jorgensen 1997). From Table 3.1, it is evident that maximal grip strength of men are greater (by 34%) than women, suggesting that greater absolute force produced by the men might result in greater change in deoxygenation, however these responses in men were not significantly ($P>0.05$) correlated to their grip values (Table 3.3). Hence, the present study results may suggest that fatigability of low-back muscles in men is greater than women during exposure to WBV and work. Bilodeau et al. (1992) showed greater EMG responses (median frequency and mean power frequency) in men compared to women as well, and attributed these trends to the lower fast twitch fibers of women in triceps and biceps brachii. Such fiber type content was evidenced in the EMG power spectrum reported in their study. They also attributed such low EMG responses in women to the smaller diameter of fiber size recruited and higher skinfold thickness.

However, NIRS sensitivity to detect the role of slow and fast twitch fibre dominance is poor. Alfonsi et al. (1999) demonstrated that NIRS trends could not successfully distinguish slow or fast muscle fibre composition in the tibialis anterior during ischemia combined with maximal isometric work. Using time resolved spectroscopy, Kuno et al. (1997) showed a very low positive correlation ($r < 0.50$) between oxygenation in the vastus lateralis muscle and muscle fibre composition. These authors concluded that muscle fibre composition does not affect the availability of oxygen in the muscle during maximal workout. Reasons for mean blood volume values not achieving significance are not clear at present. Does this suggest mean blood volume changes (thus blood flow to these back muscles) will not be affected by both conditions of work even if there exists an imbalance between oxygen delivery and oxygen uptake? Is it due to blood flow from non-exercising muscles? Such types of questions warrant further investigation.

Based on EMG median frequency slopes, Elfving et al. (2000) investigated gender differences during seated back extension. At the fifth lumbar position, men showed a steeper slope than women implying a greater fatigue, however, their results did not reach significance. In the present study, gender interacted with backrest and showed significance in mean blood volume values but not in mean oxygenation values. 'With' backrest, men showed 79% lower mean blood volume changes than women. However, 'Without' backrest, men showed 51% greater mean blood volume values than women. Such discrepancy in only mean blood volume responses between men and women is not clear at present. Similar mean oxygenation responses of men and women during both backrest conditions observed in the present study might be attributed to balance of oxygen uptake with oxygen delivery to these erector spinae muscles.

In the present study, all the subjects were right handed (however, it was not a selection criteria for the current investigation). Interestingly, few subjects demonstrated increase in oxygenation and blood volume trends during handgrip contractions, suggesting a conflicting evidence of their dominant side responses. In our unpublished observations of back muscle oxygenation and blood volume (on either side of spine) during maximal extension tests showed such variable responses as well. Hence, in both genders significant results of mean oxygenation during work, and significant results of mean blood volume responses during postural variation would have been more clear provided the present study would have monitored both sides of the low-back, thus understanding the influence of side difference and side dominance of individual subjects.

Role of Adipose Tissue Thickness on NIRS measurements

van Beekvelt et al. (2001) reported that adipose tissue metabolism is lower than muscle metabolism, and therefore, muscle oxygenation determined using NIRS is underestimated. In the current study, there was no significant difference in adipose tissue thickness at the erector spinae region between men and women (Table 3.1). Also, the adipose tissue thickness in both genders was not significantly correlated to NIRS measurements [at a source-detector separation of 4 cm] among the three vibration tests (Table 3.4). *This suggests that at the same source-detector separation of 4 cm, oxygenation and blood volume values obtained during the different experimental conditions were not influenced by adipose tissue thickness.* This is in contrast to the findings of van Beekvelt et al. (2001) who demonstrated a significant decrease in oxygenation with increase in adipose tissue thickness.

The discrepancy between these two studies could be due to the NIRS technique used (continuous wave Vs spatially resolved), exercise protocol (WBV Vs maximal rhythmic contractions of forearm flexors), and sample size (11 men and 11 women Vs 44 men and 34 women). Further, Feng et al. (2001) showed that for an adipose thickness of 8 mm, the optimal source-detector distance was 45 mm. These authors also identified the optimal distance of 35-40 mm for an adipose tissue thickness range of 2.5-5 mm and 50 mm for a thickness of 17 mm. However, in the current study, a fixed source-detector distance of 4 cm was used, irrespective of skinfold thickness which ranged from 7 to 24 mm. It is possible that this could have influenced the findings of the present study.

Role of Fitness

In the present study, level of aerobic fitness did not influence the oxygenation and blood volume responses during WBV. Using the peak oxygen uptake obtained from incremental arm cranking test till exhaustion as a covariate (Table 3.1), the results suggested that erector spinae oxygenation and blood volume responses in men and women were not dependent upon the level of their aerobic fitness. Further, correlations calculated between the relative aerobic capacity and muscle oxygenation and blood volume responses were not significant ($P>0.05$) (Table 3.5). This is in contradiction to the hypotheses of Boff and Lincoln (1988) and Griffin (1990) who suggested that the physiological responses to WBV may be influenced by the level of fitness. Since oxygenation and blood volume responses monitored in the erector spinae muscles are of 'peripheral' nature, one can also interpret these results in such a way that the level of fitness may not influence the peripheral responses to WBV but may play a role in the central physiological responses.

Conclusions

In the present study, the role of dose, backrest, workload, and gender on erector spinae oxygenation and blood volume responses during seated WBV was investigated. A decrease in vascular supply (observed through decrease in blood volume) to the back muscles was observed in both men and women during WBV compared to sitting without WBV. Similar mean oxygenation values during both backrest conditions suggest equal oxygen supply and utilization. During both vibration alone and vibration combined with rhythmic handgrip contractions, men showed greater mean oxygenation values than women, suggesting greater deprivation of oxygen occurs (without significant concomitant changes in blood volume) in these working muscles during work combined with WBV. Skinfold thickness did not influence oxygenation and blood volume responses in either gender. Also, controlling for the level of aerobic fitness showed no influence on oxygenation and blood volume responses in both genders.

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Table 3.1: Demographics of subjects

Gender	Age	Body Mass	Sitting Height	Standing Height	Body Mass Index Standing	Maximal Right Hand Grip Strength	Skinfold at Third Lumbar region	Peak Oxygen Uptake during Arm Cranking
	Yrs	Kgs	m	m	$Kg.m^{-2}$	Kgs	mm	$mL.Kg^{-1}.min^{-1}$
Men N=13	24.7 ± 3.9	70.8 ± 12.1 [a]	0.86 ± 0.05	1.71 ± 0.07 [a]	24.07 ± 3.2	34.22 ± 9.1 [a]	11.31 ± 5.09	24.5 ± 6.6
Women N=14	23.9 ± 3.5	60.26 ± 9.0	0.84 ± 0.08	1.63 ± 0.10	23.0 ± 3.7	22.49 ± 3.6	11.59 ± 4.46	21.4 ± 4.6

[a] – significant difference between men and women, $p<0.05$

Table 3.2: Erector Spinae Oxygenation and Blood Volume differences in Optical Density units (Mean ± SD) in healthy men and women during WBV at three different doses

GENDER	BACKREST	DOSE	Δ Oxygenation [Ψ]		Δ Blood volume [Ψ]	
		Frequency in Hz	WBV Without Grip	WBV With Grip	WBV Without Grip	WBV With Grip
Men	ON	3	0.020 ± 0.05[a]	0.036 ± 0.08	-0.063± 0.10[b]	-0.05 ± 0.10[b]
	OFF	3	0.031 ± 0.10[a]	0.046 ± 0.09	0.058 ± 0.22	0.058 ± 0.19
	ON	4.5	0.027 ± 0.09[a]	0.060 ± 0.13	-0.049 ± 0.10[b]	-0.029 ± 0.12[b]
	OFF	4.5	0.057 ± 0.23[a]	0.065 ± 0.24	0.14 ± 0.20	0.14 ± 0.20
	ON	6	-0.002 ± 0.05[a]	0.032 ± 0.07	-0.066 ± 0.11[b]	-0.028 ± 0.12[b]
	OFF	6	0.014 ± 0.10[a]	0.046 ± 0.11	0.018 ± 0.18	0.045 ± 0.17
Women	ON	3	-0.004 ± 0.05	0.001 ± 0.05	-0.025 ± 0.08	-0.010 ± 0.08[b]
	OFF	3	0.007 ± 0.05	0.012 ± 0.05	0.029 ± 0.07	0.038 ± 0.07
	ON	4.5	0.022 ± 0.09	0.031 ± 0.09	-0.011 ± 0.08	-0.005 ± 0.08[b]
	OFF	4.5	0.010 ± 0.02	0.025 ± 0.04	0.034 ± 0.06	0.043 ± 0.07
	ON	6	0.028 ± 0.07	0.032 ± 0.09	-0.004 ± 0.05	-0.005 ± 0.04[b]
	OFF	6	0.025 ± 0.06	0.025 ± 0.07	0.038 ± 0.10[ab]	0.043 ± 0.12

[Ψ] Δ is defined as the difference between 'maximum optical density' [during initial rest without WBV or after recovery from WBV session with a backrest condition (recovery 1)] and 'minimum optical density' during seated vibration with or without rhythmic handgrip contraction.
NOTE: All subjects were exposed to 3, 4.5 and 6 Hz doses.
a – significant interaction between work and gender ($p < 0.05$)
b – significant interaction between backrest and gender ($p < 0.05$)

Table 3.3: Pearson Correlations between Maximal Rhythmic Handgrip Contractions and Erector Spinae [Oxygenation and Blood Volume] responses

DOSE	BACKREST	MEN		WOMEN	
Frequency in Hz		Oxygenation	Blood Volume	Oxygenation	Blood Volume
3	WITH	0.24	-0.38	-0.16	-0.07
	WITHOUT	0.08	-0.02	0.35	-0.05
4.5	WITH	0.39	-0.43	0.37	-0.18
	WITHOUT	-0.05	0.11	0.22	0.23
6	WITH	0.39	0.27	0.13	-0.28
	WITHOUT	0.02	-0.02	-0.23	0.44

Table 3.4: Spearman Correlations between Erector Spinae [Oxygenation and Blood Volume Responses] and Adipose Tissue Thickness

GENDER	BACKREST	DOSE	Oxygenation		Blood Volume	
		Frequency in Hz	WBV Without Grip	WBV With Grip	WBV Without Grip	WBV With Grip
Men	WITH	3	-0.42	-0.38	0.38	0.48
	WITHOUT	3	-0.04	-0.10	0.03	0.12
	WITH	4.5	0.00	-0.39	0.15	0.17
	WITHOUT	4.5	-0.28	-0.21	-0.24	-0.16
	WITH	6	-0.004	-0.28	0.10	0.06
	WITHOUT	6	-0.30	-0.41	-0.24	-0.26
Women	WITH	3	-0.09	-0.15	0.14	-0.05
	WITHOUT	3	-0.18	-0.29	0.06	-0.04
	WITH	4.5	-0.19	-0.22	0.09	0.12
	WITHOUT	4.5	0.04	-0.10	-0.01	-0.05
	WITH	6	-0.04	-0.05	0.21	0.06
	WITHOUT	6	0.18	0.16	-0.18	-0.16

Table 3.5: Pearson Correlations between Erector Spinae [Oxygenation and Blood Volume Responses] and Relative Peak Aerobic Power

GENDER	BACKREST	DOSE	Oxygenation		Blood Volume	
		Frequency in Hz	WBV Without Grip	WBV With Grip	WBV Without Grip	WBV With Grip
Men	WITH	3	0.51	0.53	-0.46	-0.49
	WITHOUT	3	-0.01	0.19	-0.02	-0.10
	WITH	4.5	0.06	0.36	-0.18	-0.15
	WITHOUT	4.5	0.27	0.22	0.19	0.15
	WITH	6	0.10	0.35	-0.20	-0.15
	WITHOUT	6	0.12	0.17	0.10	0.14
Women	WITH	3	-0.08	-0.03	-0.52	-0.39
	WITHOUT	3	-0.08	-0.23	-0.39	-0.33
	WITH	4.5	0.08	0.15	-0.14	-0.22
	WITHOUT	4.5	0.00	0.03	-0.30	-0.16
	WITH	6	0.41	0.41	-0.36	-0.42
	WITHOUT	6	-0.37	-0.47	-0.21	-0.18

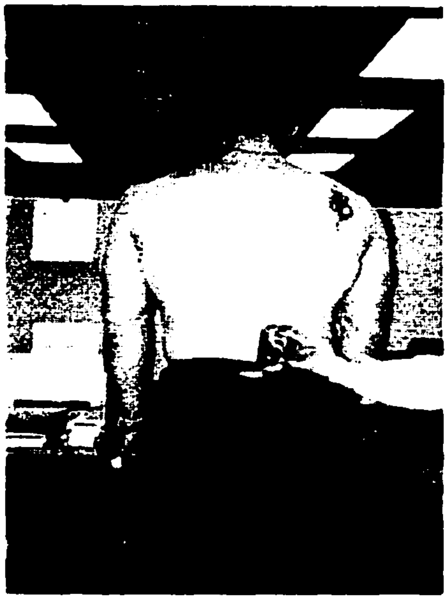

Figure 3.1A NIRS Sensor Placement on the Low-back
(The sensor was positioned right side at the level of third vertebra, approximately 3 cm from the spinal column)

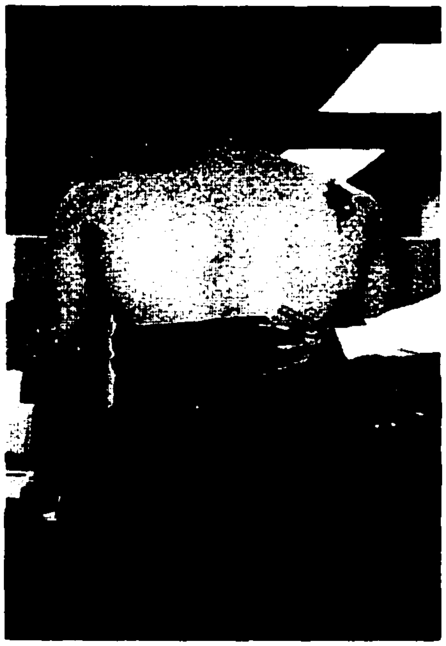

Figure 3.1B Tensor Bandage around the Low-back

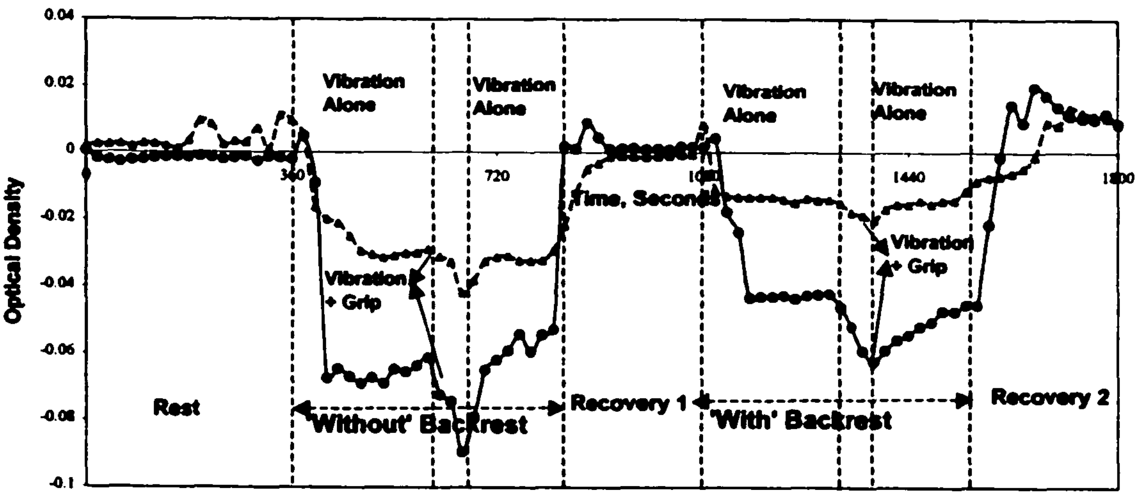

Figure 3.2A. Erector Spinae Oxygenation Trends

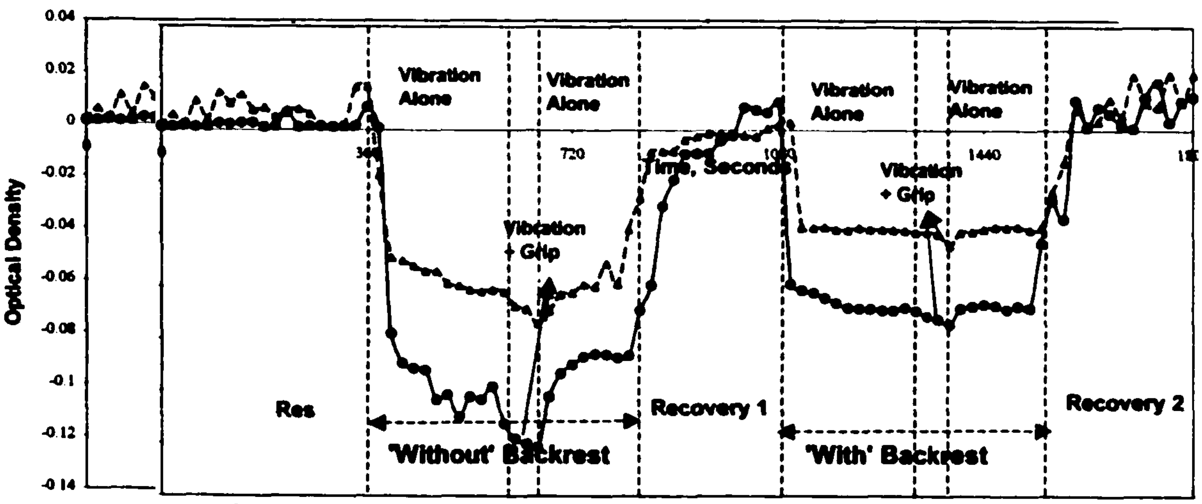

Figure 3.2B. Erector Spinae Blood Volume Trends

Erector Spinae Oxygenation (top panel) and blood volume (bottom panel) trends in a typical male [solid line] and female [dotted line] subject during exposure to seated whole-body vibration with and without handgrip exercise

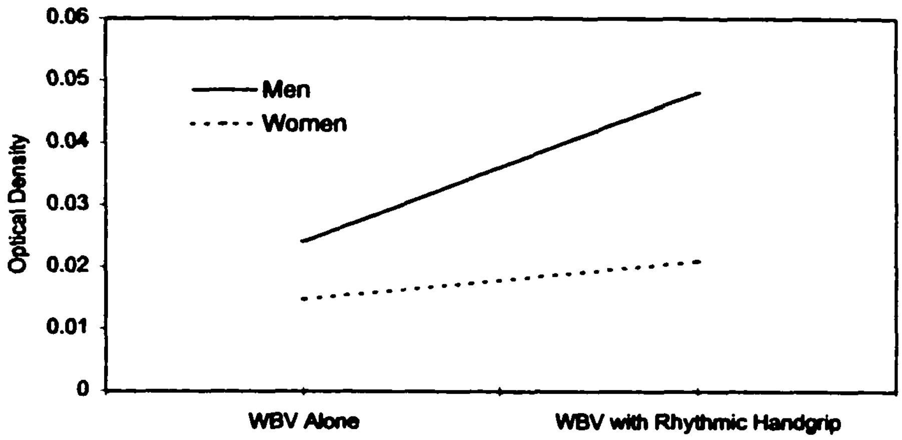

Figure 3.3A. Interaction between Gender and Work Mean Oxygenation Changes (P<0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Backrest).

3. Graph suggests that during both conditions of WBV Alone and WBV with Rhythmic Handgrip contractions, men demonstrated greater degree of deoxygenation compared to women.

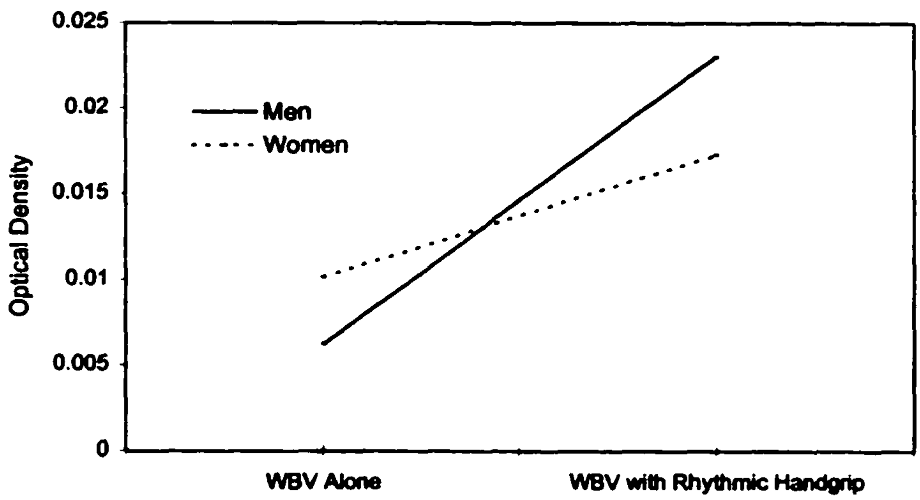

Figure 3.3B. Interaction between Gender and Work Mean Blood Volume Changes (P>0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Backrest).

3. Graph suggests that during both conditions of WBV Alone and WBV with Rhythmic Handgrip contractions, gender did not influence blood volume changes.

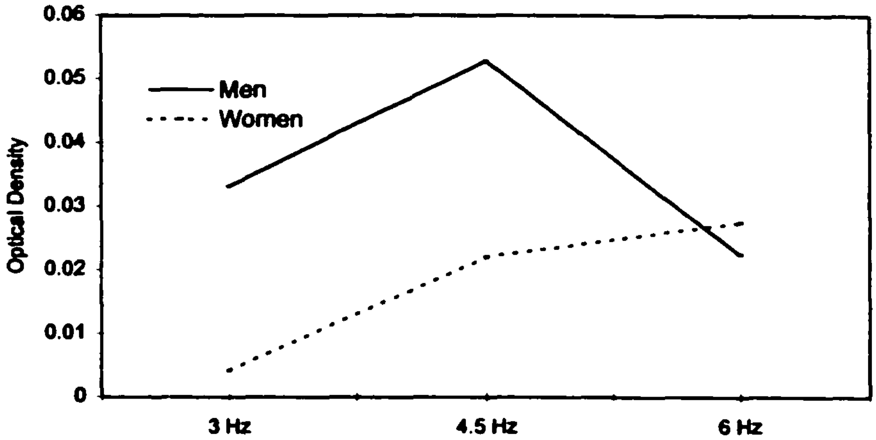

Figure 3.4A. Interaction between Gender and Dose Mean Oxygenation Changes (P>0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Work and Backrest).

3. It appears from the above graph that men and women demonstrate distinct patterns of oxygenation changes. However, because of greater variance obtained, Dose did not inlfuence the results.

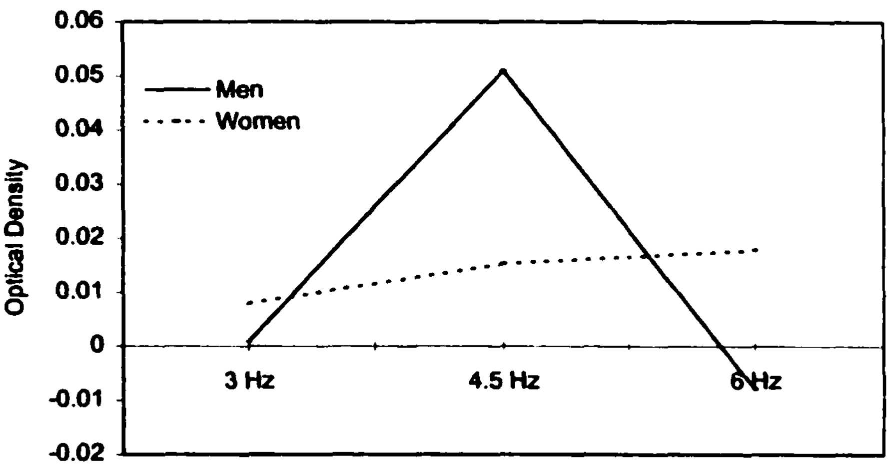

Figure 3.4B. Interaction between Gender and Dose Mean Blood Volume Changes (P>0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Work and Backrest).

3. It appears from the above graph that men and women demonstrate distinct patterns of blood volume changes. However, because of greater variance obtained, Dose did not inlfuence the results.

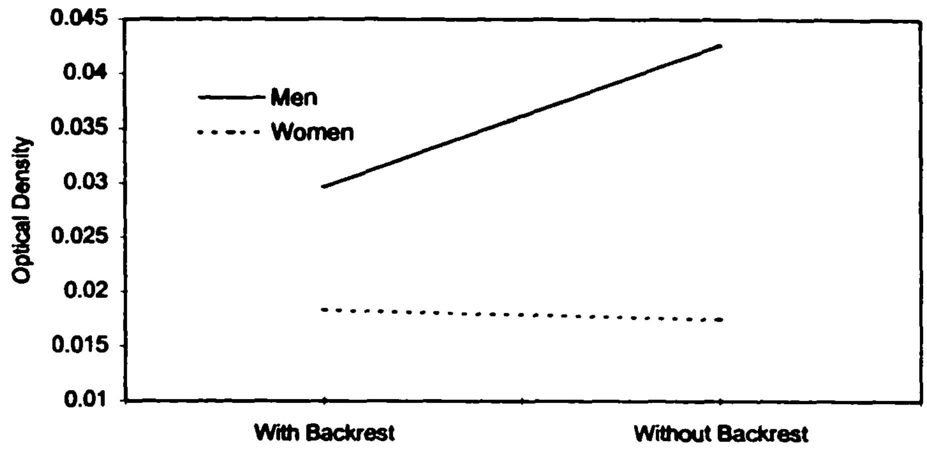

Figure 3.5A. Interaction between Gender and Backrest Mean Oxygenation Changes (P>0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Work).

3. Graph suggests that presence of Backrest did not influence oxygenation responses in the low-back.

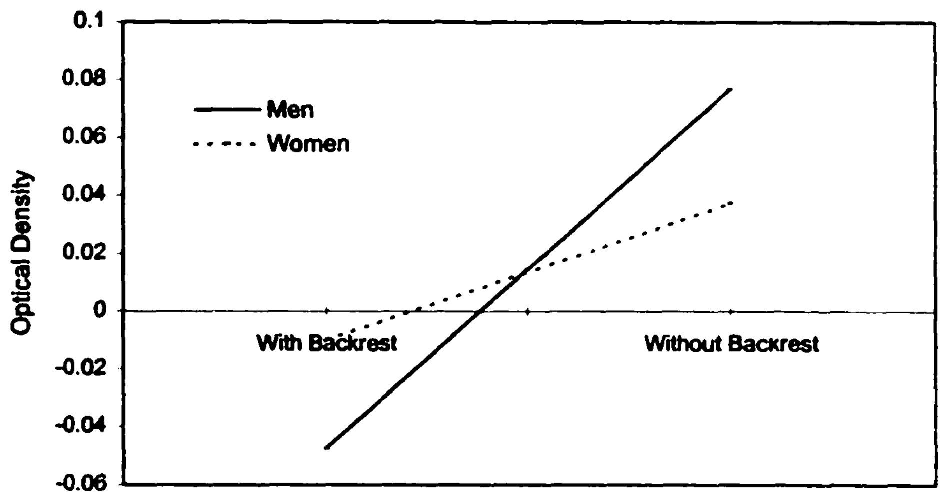

Figure 3.5B. Interaction between Gender and Backrest Mean Blood Volume Changes (P<0.01)

NOTE: 1. Due to larger coefficient of variations obtained, standard deviations are not included in the graphs shown above.

2. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Work).

3. Graph suggests that presence of Backrest demonstrated lower blood volume changes in men than women. However, men 'Without' Backrest showed greater blood volume changes than women.

CHAPTER 4

Acute Physiological Responses during Exposure to Seated Whole-body Vibration

Whole-body vibration (WBV), defined as an oscillating motion transmitting to the whole-body, depends primarily on its intensity (frequency, acceleration, amplitude, duration), type of vibration source, and direction of its input to the human body. Human factors such as demographics (height, weight, age, gender), posture adopted, fitness, personality, etc. also influence various psychophysiological, biomechanical and biodynamic responses resulting from the exposure to WBV (Griffin 1990). Several authors have demonstrated variable cardiorespiratory responses during exposure to different vibration doses (from less than 1g to greater than 1g) with a variety of WBV simulators (Bennett et al. 1977, Dupuis and Zerlett 1986, Gaeuaman et al. 1962, Guinard 1985, Hood et al. 1966, Manninen 1984, Pope et al. 1990, Thornton et al. 1984).

Low-frequency WBV exposure in the region of 2 to 20 Hz between the intensities of 0.1 to $0.5g_{r.m.s}$ elicits cardiorespiratory responses similar to moderate exercise, elevating variables such as oxygen uptake, ventilation rate, respiratory frequency, heart rate, and cardiac output (Guinard 1985). Pope et al. (1990) suggested that monitoring physiological variables such as absolute oxygen uptake during WBV is useful, and relevant to the assessment of the energy demands of populations exposed in the industries. Most of the above studies showed that monitoring the cardiorespiratory system provide useful information on the acute effects of WBV exposure. In a comprehensive epidemiological review pertaining to this topic, Seidel and Heide (1986) emphasized that WBV might pose an additional risk factor for ischemic heart disease. However, the review of Wikstrom et al. (1994) suggested that exposure to vibration doesn't significantly increase the risk of diseases in the cardiovascular system. Electromyographic activity of the paravertebral muscles demonstrated low-back muscle fatigue during exposure to WBV (Hansson et al. 1991, Pope et al. 1998, Wilder et al. 1982), subsequently leading to pain and injury of the lower back. With such mixed opinions of various authors, it is essential to evaluate both central physiological responses and peripheral limitations of the human body during exposure to WBV.

Occupational exposure to WBV usually involves concomitant physical and physiological stresses that may hinder successful human performance. For example, during hovering by helicopter pilots, Thornton et al. (1984) showed higher energy expenditure requirements. Manninen (1984) demonstrated higher heart rate during WBV combined with dynamic work. Also, Bennett et al (1977) reported increase in absolute oxygen consumption and heart rate responses during WBV combined with tracking tasks. However, research pertaining to physiological responses during WBV combined with 'simulated' manual work is still limited. Occupants' posture during prolonged sitting with and without WBV may also influence their physiological responses (Pope et al. 1990, Magnusson et al. 1987). Sitting 'With' and 'Without' backrest support might not only affect human comfort but also load the postural muscles, thus eliciting variable cardiorespiratory and muscular responses. While the number of women employed in occupations involving exposure to WBV has grown considerably in the last century, research pertaining to their physiological responses and comparison with their male counterparts is still lacking (Bovenzi 1996). It has also been suggested that fitness of the subjects plays an important role in determining the effects of WBV exposure on humans (Boff and Lincoln 1988, Griffin 1990). However, there are no studies that have objectively examined its influence on the physiological responses elicited during exposure to WBV.

The purposes of this study were to examine the effects of discrete 3 Hz, 4.5 Hz, and 6 Hz vibration doses on: (1) the acute physiological responses in young healthy men and women; (2) the changes in these physiological responses during exposure to WBV 'With' and 'Without' backrest; (3) the addition of maximal rhythmic handgrip contractions during WBV, and (4) differences in these responses between genders. It was hypothesized that the acute physiological responses will be similar in both men and women 'With' and 'Without' backrest, and will not be influenced by the exposure to vibration dose within the range of 3 to 6 Hz while performing rhythmic handgrip contractions.

METHODS

Subjects

Written informed consent was obtained from 13 healthy men (age 24.7 ± 3.9 yrs, mass 70.8 ± 12.1 kg, height 171 ± 7 cm) and 14 healthy women (age 23.9 ± 3.51 yrs, mass 60.3 ± 9.0 kg, height 164 ± 10 cm). Subjects were undergraduate and graduate students recruited from the university population (Table 4.1). All subjects were right hand dominant. They all completed the Revised Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology, 1994) to identify contraindications for exercise. The test protocols utilized were approved by the Human Research Ethics Board at this institution (APPENDIX A.1).

Vibrating Base

A steel vibrating base that housed an electro-mechanical motor connected to a cam mechanism (Advanced Therapy Products, Inc., VA, USA) was modified with an external DC speed control device (Figures 2.1A and 2.1B). Varying the speed of this motor from 0 to 100% corresponded to vibrating frequencies of 0 Hz to 6.2 Hz. Detailed description of vibrating base was provided in the Chapter 2. Average vertical accelerations (in root mean square values) generated at different doses are given in the Chapter 2 (Table 2.2) as well.

Test Protocols

Each subject completed an arm cranking exercise test to determine his/her aerobic fitness in the first session, followed by three WBV tests on separate days (3 Hz, 4.5 Hz, and 6 Hz) in a randomized order.

(1) Assessment of the Peak Oxygen Uptake

In the first testing session, the subject completed an aerobic fitness test on an arm cranking ergometer (Cybex, MET 300, USA). After preparing each subject with the mouthpiece and headgear (Figure 4.1A), the test was initiated with a two-minute rest period. It was followed by two minutes of arm cranking at no load and subsequent increments of 25 Watts every 2 minutes until voluntary exhaustion, or attainment of two or more of the following end points suggested by the American College of Sports Medicine (1993): (1) leveling off in the oxygen consumption (increase of ≤ 100 $ml.min^{-1}$) with increasing load, (2) age predicted maximal heart rate, equated to 220-age (in years), (3) respiratory exchange ratio of ≥1.10, and (4) rate of perceived exertion ≥ 18 (Borg, 1982).

(2) Vibration Tests

The test protocol on each day lasted 30 minutes, and included initial six-minute rest without vibration, eight-minute vibration 'With' (or 'Without') a backrest, four-minute recovery, eight-minute vibration 'Without' (or 'With') a backrest, and four-minute recovery. Subjects were randomly assigned to a posture 'With' or 'Without' a backrest (Figures 2.4A and 2.5), and were instructed to adopt a comfortable posture when tested 'Without' a backrest. Throughout the test, subjects sat in the vibrating chair with the eyes open. A footrest was provided for subjects to place their feet at a comfortable level. During sitting 'With' and 'Without' a backrest, angles at the knee joint and low-back were measured by a goniometer (JAMAR, Clifton, NJ, USA).

(3) Rhythmic Handgrip Measurements

Before the vibration session, right hand grip size was adjusted on the dynamometer (JAMAR, CA, USA) to a position that was comfortable for each subject. During the fifth minute of each vibration condition, the subject performed rhythmic maximal contractions for one minute at a contraction rate of one every five seconds (Figures 2.4B). Contractions were performed with the right hand with the forearm in a horizontal position and the elbow at an angle of 180°. Similar to a method suggested by Schmidt and Toews (1970), throughout the study the dynamometer was calibrated with known weights to check its accuracy identified through the dial reading on the dynamometer.

(4) Whole-body Physiological Measurements

For all the tests, gas exchange measurements were continuously monitored with an automated metabolic measurement cart (MMC 2900, Sensormedics Corporation, Yorba Linda, CA). The oxygen (O_2) and carbon dioxide (CO_2) analyzers of the cart were calibrated before each test with commercially available precision gases (16% O_2, 4% CO_2, balance Nitrogen; 26% O_2, balance Nitrogen). The pneumotach was calibrated for volume using a 3 liter syringe, as recommended by the manufacturer. Heart rate was recorded using a polar heart rate monitor (Polar Accurex Plus, Finland). Metabolic data were recorded in the mixing chamber mode and averaged over 20 second intervals for further analysis. Oxygen pulse was calculated as the ratio of absolute oxygen uptake and heart rate. Tidal volume was calculated as the ratio of ventilation volume and respiratory frequency.

(5) Measurement of Cardiac Output by CO_2 Rebreathing

According to the indirect Fick equation, cardiac output is determined by the ratio of carbon dioxide produced (VCO_2) to the difference in CO_2 concentration between the mixed venous and arterial blood ($C_{v\text{-}a}CO_2$). In a validation study for Q, Marks et al. (1985) showed a significant correlation of 0.82 between the direct Fick method and CO_2 rebreathing technique. Further, Bhambhani et al. (1994) showed a test-retest reliability of 0.89 for the rebreathing technique in males exercising at 60% of their maximal aerobic capacity. The rebreathing maneuver and the calculations to obtain $VCO_2/C_{v\text{-}a}CO_2$ in the above equation are explained below.

During the fourth minute of initial rest without WBV, and during the WBV sessions 'With' and 'Without' backrest, each subject inhaled a mixture of CO_2 and O_2 from a 5 liter anesthesia bag under steady state conditions. During the rest period, the rebreathing mixture consisted of 8% CO_2 and balance O_2 for all the subjects. During exposure to WBV, the rebreathing mixture consisted of 11%-12% CO_2 and balance O_2. The concentration of CO_2 utilized for rebreathing was determined by the VO_2 during vibration (Jones 1986). Steady state conditions were ascertained by monitoring the values of absolute oxygen uptake, ventilation rate, heart rate and end tidal CO_2 ($P_{ET}CO_2$) by switching the metabolic cart from the mixing chamber to the breath-by-breath mode prior to the initiation of the rebreathing maneuver.

The subject hyperventilated for approximately 15 sec so as to establish an equilibrium between the CO_2 in the bag mixture and in the lungs (Figure 4.1B). A difference of less than 1 Torr pressure during the first 6-8 sec of the rebreathing maneuver was considered to be indicative of an equilibrium in the CO_2 concentration between the mixed venous blood and alveolar gas. A downstream correction factor (Jones 1986) was applied to this measurement to obtain a more accurate estimate of venous CO_2. The steady state $P_{ET}CO_2$ obtained prior to the rebreathing maneuver was considered to be indicative of the arterial CO_2 level. A hemoglobin concentration of $15.8 gm.100ml^{-1}$ of blood for men and $13.9 gm.100ml^{-1}$ of blood for women was assumed for the conversion of CO_2 tension into content (Jones 1986). All of these measurements and calculations (including mixed arterio-venous oxygen difference) were performed using the software available with the metabolic measurement cart (MMC 2900, Sensormedics Corporation, Yorba Linda, CA). Stroke volume was calculated as the ratio of cardiac output and heart rate for each condition (initial rest without WBV, 'With' backrest during WBV, and 'Without' backrest during WBV).

Statistical Analysis

Independent 't' tests were used to compare the physical characteristics of the men and women (Table 4.1). A four-way analysis of covariance (ANCOVA), using the peak oxygen uptake as the covariate, gender as a between-subjects factor, and three repeated measure factors (dose [3 Hz, 4.5 Hz, and 6 Hz], backrest ['With' and 'Without' backrest], and workload [WBV alone and WBV combined with maximal rhythmic handgrip contractions]) with a fully crossed design was used to evaluate the differences in the metabolic responses. A three-way ANCOVA, using the peak oxygen uptake as the covariate, gender as a between-subjects factor, and two repeated measures factors (dose and condition [initial rest without WBV, 'With' backrest during WBV, and 'Without' backrest during WBV]) with a fully crossed design was used to evaluate the differences in the cardiovascular responses.

To minimize the violation of the assumption of homogeneity of variance, the 'Greenhouse-Geiser' adjustment was used. Since multiple comparisons were made for each dependent variable in the present study, the Bonferroni adjustment for a P value of 0.05 was applied to minimize Type 1 error. The Bonferroni adjustment was calculated as the ratio of 0.05 and number of statistical comparisons (APPENDIX B.3). Thus, statistical significance was considered at $P < 0.01$. Significant F ratios were further analyzed with the Scheffe post hoc multiple comparison test. The relationship between maximal rhythmic handgrip contractions and changes in selected physiological responses during WBV were evaluated using the Pearson product moment correlations. Also, relationship between the changes in selected physiological responses during WBV and peak oxygen uptake measured during arm cranking was evaluated using the Pearson correlations. The Statistical Package for Social Sciences SPSS (version 10) was used for all statistical analyses (SPSS Inc., Chicago, USA).

RESULTS

Metabolic and Respiratory Responses

The metabolic and cardiorespiratory responses (mean ± SD) in men and women, 'With' and 'Without' backrest, during the different doses of WBV are summarized in Table 4.2. No significant four-way and three-way interactions were obtained in these responses. This implies that in both genders, the changes observed in these responses at different WBV doses were similar 'With' and 'Without' backrest support. No significant two-way interactions between gender and dose, and dose and workload were obtained for any of these responses. However, the interaction between workload and gender showed significance only for the absolute and relative oxygen uptake, and oxygen pulse. No significant interactions between workload and gender were obtained for the heart rate, ventilation rate, respiratory frequency and tidal volume. It should be noted that comparisons of these significant interactions between these independent variables were based on the pooled mean values of other remaining factors (i.e., WBV dose and Backrest conditions).

Further, when these physiological responses were controlled for the level of aerobic fitness of the subjects (as a covariate), the effect of aerobic fitness was evident in absolute oxygen uptake (P=0.005), relative oxygen uptake responses (P=0.008), and oxygen pulse (P=0.010) during workload. Pearson correlations between metabolic responses and the peak aerobic capacity during WBV 'With' and 'Without' a backrest support are shown in the Tables 4.5a, 4.5 b and 4.5c.

Comparison between Doses

All subjects showed similar absolute oxygen uptake ($L.min^{-1}$) responses during the three doses of WBV (3 Hz: 0.289 ± 0.012, 4.5 Hz: 0.303 ± 0.012, and 6 Hz: 0.306 ± 0.012, P=0.331). Also, when oxygen uptake was expressed relative to their body mass ($mL.kg.^{-1}.min^{-1}$), no significant difference was observed among the doses (3 Hz: 4.48 ± 1.75, 4.5 Hz: 4.65 ± 1.66, and 6 Hz: 4.77 ± 1.84, P=0.285). The heart rate ($beats.min^{-1}$) was also unaffected by the dose (3 Hz: 85 ± 13, 4.5 Hz: 88 ± 12, and 6 Hz: 88 ± 11, P=0.269). Oxygen pulse ($mL.beat^{-1}$), defined as the ratio between the absolute oxygen uptake and the heart rate, was similar among all the doses (3 Hz: 3.4 ± 1.3, 4.5 Hz: 3.4 ± 1.1, and 6 Hz: 3.5 ± 1.2, P=0.884).

Ventilation rate ($L.min^{-1}$) showed significant differences only between 3 Hz and 6 Hz (11.3 ± 5.5 Vs 12.8 ± 6.2, P=0.005). However, no significant differences were observed in the ventilation rate between 3 Hz and 4.5 Hz (12.5 ± 9.6, P=0.260), and 4.5 Hz and 6 Hz (P=0.692). Respiratory frequency ($breaths.min^{-1}$) showed no significant differences among the doses (3 Hz: 23 ± 7, 4.5 Hz: 22 ± 7, and 6 Hz: 23 ± 6, P=0.827). Similar to ventilation rate, a significant difference in tidal volume ($L.breath^{-1}$) was observed only between 3 Hz and 6 Hz (0.53 ±

0.26 Vs 0.59 ± 0.29, P=0.010). However, no significant differences in tidal volume were observed between 3 Hz and 4.5 Hz (0.62 ± 0.64, P=0.140), and 4.5 Hz and 6 Hz (P=0.692).

Comparison between Sitting 'With' and 'Without' Backrest during Whole-Body Vibration

The following physiological responses were significantly higher during exposure to WBV 'Without' backest: (1) absolute oxygen uptake (0.283 ± 0.018 $L.min^{-1}$ Vs 0.317 ± 0.012 $L.min^{-1}$, P=0.000); relative oxygen uptake (4.88 ± 1.77 $mL.kg.^{-1}.min^{-1}$ Vs 4.37 ± 1.71 $mL.kg.^{-1}.min^{-1}$, P=0.000); (3) heart rate (89 ± 11 $beats.min^{-1}$ Vs 85 ± 11 $beats.min^{-1}$, P=0.000); (4) oxygen pulse (3.53 ± 1.23 $mL.beat^{-1}$ Vs 3.30 ± 1.16 $mL.beat^{-1}$, P=0.000); and (5) ventilation rate (12.9 ± 8.5 $L.min^{-1}$ Vs 11.5 ± 5.8 $L.min^{-1}$, P=0.010). However, respiratory frequency (22 ± 7 $breaths.min^{-1}$ Vs 23 ± 7 $breaths.min^{-1}$, P=0.409), and tidal volume (0.55 ± 0.3 $L.breath^{-1}$ Vs 0.61 ± 0.5 $L.breath^{-1}$, P=0.086) were similar between these conditions.

Comparison between WBV Alone and WBV Combined with Maximal Rhythmic Handgrip Contractions

When subjects performed maximal rhythmic handgrip contractions during WBV, absolute oxygen uptake increased significantly from the WBV alone conditions (0.365 ± 0.013 $L.min^{-1}$ Vs 0.234 ± 0.065 $L.min^{-1}$, P=0.000). Similarly, relative oxygen uptake also increased during WBV combined with isometric work (5.64 ± 1.8 $mL.kg.^{-1}.min^{-1}$ Vs 3.62 ± 0.9 $mL.kg.^{-1}.min^{-1}$, P=0.000). During WBV combined with maximal rhythmic handgrip contractions, heart rate values were significantly higher than WBV alone values (95 ± 10 $beats.min^{-1}$ Vs 80 ± 8 $beats.min^{-1}$, P=0.000). Oxygen pulse values were significantly higher during maximal rhythmic handgrip contractions as well (3.88 ± 1.3 $mL.beat^{-1}$ Vs 2.96 ± 0.8 $mL.beat^{-1}$, P=0.000). Isometric work performed during WBV also resulted in a significant increase in ventilation rate (14.95 ± 9.3 $L.min^{-1}$ Vs 9.41 ± 2.6 $L.min^{-1}$, P=0.000). Respiratory frequencies were not significantly different between the two conditions (23 ± 6 breaths.min^{-1} Vs 22 ± 6 breaths.min^{-1}, P=0.488). However, similar to ventilation rate, tidal volume responses showed significantly higher values during maximal rhythmic handgrip contractions (0.72 ± 0.56 L.breath^{-1} Vs 0.44 ± 0.16 L.breath^{-1}, P=0.000).

Comparison between Genders

Significant interaction between workload and gender was observed for the: absolute and relative oxygen uptake, and oxygen pulse. During WBV alone, men consumed more oxygen than women (0.256 ± 0.074 L.min^{-1} Vs 0.216 ± 0.051 L.min^{-1}, P=0.008). This gender difference was negated when oxygen uptake was expressed relative to body mass (3.60 ± 0.86 mL.kg.$^{-1}$.min^{-1} Vs 3.63 ± 0.96 mL.kg.$^{-1}$.min^{-1}, P=0.047). During WBV combined with maximal rhythmic handgrip contractions, men showed significantly higher values for both absolute oxygen uptake (0.426 ± 0.015 L.min^{-1} Vs 0.309 ± 0.078 L.min^{-1}, P=0.008) and relative oxygen uptake values (6.10 ± 1.95 mL.kg.$^{-1}$.min^{-1} Vs 5.24 ± 1.60 mL.kg.$^{-1}$.min^{-1}, P=0.001), respectively.

Heart rate responses were similar in both men and women (88 ± 13 beats.min^{-1} Vs 86 ± 10 beats.min^{-1}, P=0.495), with no significant interaction being observed in heart rate between gender and workload (P=0.666). However, gender showed a significant interaction with workload for the oxygen pulse responses. Similar to absolute oxygen uptake, men utilized greater amount of oxygen per heartbeat during WBV alone compared to women (3.2 ± 1.0 mL.beat^{-1} Vs 2.7 ± 0.7 mL.beat^{-1}, P=0.005). A similar trend was observed in both genders during WBV combined with maximal rhythmic handgrip contractions (4.5 ± 1.5 Vs 3.3 ± 0.8, P=0.005).

Ventilation rate was not significantly different between men and women (13.20 ± 6.8 L.min^{-1} Vs 11.23 ± 7.7 L.min^{-1}, P=0.176), and no significant interaction was observed between gender and workload (P=0.292). Respiratory frequency was similar in both genders (21 ± 6 breaths.min^{-1} Vs 24 ± 7 breaths.min^{-1}, P=0.103) under both conditions of work (P=0.762). No significant differences in tidal volume were observed between men and women (0.66 ± 0.34 L.breath^{-1} Vs 0.50 ± 0.5 L.breath^{-1}, P=0.047), and no significant interaction was observed between gender and workload as well (P=0.400).

Cardiovascular Responses at Three Conditions

Effect of WBV on the cardiovascular responses in men and women at the three doses and during the three conditions (initial rest with no WBV, 'With' backrest during WBV, and 'Without' backrest during WBV) are summarized in Table 3. No significant three-way or two-way interactions were obtained for the cardiac output (L.min^{-1}), heart rate (beats.min^{-1}), stroke volume (mL.beat^{-1}), and mixed arterio-venous oxygen difference (mL%) responses. This implies that in both genders, the changes observed in these responses at different WBV doses were similar during rest, 'With' and 'Without' backrest. The results of the significant main effects are explained below. It should be noted that comparisons of these significant effects were based on the pooled mean values of the remaining factors (gender and backrest conditions).

Comparison between Doses

All the cardiovascular responses were similar during exposure to the three doses of WBV: cardiac output (3 Hz: 6.0 ± 1.1 L.min^{-1}, 4.5 Hz: 5.9 ± 1.3 L.min^{-1}, and 6 Hz: 6.2 ± 1.5 L.min^{-1}, P=0.393); heart rate (3 Hz: 78 ± 1 beats.min^{-1}, 4.5 Hz: 77 ± 2 beats.min^{-1}, and 6 Hz: 78 ± 1 beats.min^{-1}, P=0.234); stroke volume (3 Hz: 79 ± 19 mL.beat^{-1}, 4.5 Hz: 77 ± 17 mL.beat^{-1} and 6 Hz: 81 ± 20 mL.beat^{-1}, P=0.462); and mixed arterio-venous oxygen difference (3 Hz: 6.3 ± 1.2 mL%, 4.5 Hz: 6.4 ± 1.1 mL% and 6 Hz: 6.4 ± 1.0 mL%, P=0.842).

Comparison among Three Conditions

Significant difference in cardiac output was obtained between sitting 'With' and 'Without' backrest during WBV (5.8 ± 1.4 L.min^{-1} Vs 6.3 ± 1.3 L.min^{-1}, P=0.000). However, no significant difference was observed between: either rest (6.0 ± 1.2 L.min^{-1}, P=0.312) and 'With' backrest conditions; or rest and 'Without' backrest conditions (P=0.104). Heart rate responses showed significant differences among all conditions (P=0.000). During sitting 'Without' backrest, heart rate values were higher (84 ± 1 beats.min^{-1}) than both sitting 'With' backrest (78 ± 1 beats.min^{-1}) and rest 'Without' WBV conditions (71 ± 1 beats.min^{-1}). Stroke volume responses showed significant differences between sitting 'With' and 'Without' backrest conditions (73 ± 18 mL.beat^{-1} Vs 78 ± 16 mL.beat^{-1}, P=0.006). These values were also significantly higher during rest (85 ± 19 mL.beat^{-1}) than both 'With' backrest (P=0.000), and 'Without' backrest conditions (P=0.012). However, mixed arterio-venous oxygen difference showed no significant difference among these three conditions (rest: 6.36 ± 0.16 mL%, 'With' backrest: 6.37 ± 0.15 mL%, and 'Without' backrest: 6.41 ± 0.15 mL%, P=0.633).

Comparison between Genders

Cardiac output was significantly higher in men than women (6.7 ± 1.4 L.min^{-1} Vs 5.4 ± 0.9 L.min^{-1}, P=0.000). However, gender did not influence heart rate responses (men: 78 ± 2 beats.min^{-1} Vs women: 77 ± 2 beats.min^{-1}, P=0.956). Stroke volume responses in men were significantly higher than women (82 ± 19 mL.beat^{-1} Vs 71 ± 13 mL.beat^{-1}, P=0.000). Mixed arterio-venous oxygen difference also showed significant difference between men and women (men: 6.8 ± 1.1 mL% Vs women: 6.0 ± 1.0 mL%, P=0.010).

Correlations between Selected Variables and Physiological Responses

Correlation coefficients between maximal handgrip contractions and metabolic responses are summarized in Table 4.4. Majority of the responses correlated with handgrip contractions were absolute and relative oxygen uptake, oxygen pulse, ventilation rate, and tidal volume (P<0.05). However, these correlations were not consistent between genders among three vibration tests.

DISCUSSION

Whole-body Physiological responses

In general, the metabolic and respiratory responses observed during WBV alone were greater than those observed during initial rest before WBV or recovery after each WBV exposure. During WBV combined with maximal rhythmic handgrip contractions, these responses were greater than that observed during WBV alone (Table 4.2). However, as soon as the WBV stopped, all the metabolic and respiratory responses reached baseline in less than a minute. In a majority of the subjects, cardiac output and stroke volume responses were lowest during sitting 'With' backrest. Mixed arterio-venous oxygen differences were not consistent during a variety of WBV conditions. However, heart rate responses during sitting 'Without' backrest were greater than both 'With' backrest during WBV and initial rest without WBV (Table 4.3).

Role of WBV Dose

In the present study, the effects of dose on physiological responses obtained (Table 4.2 and Table 4.3) were in accordance with those reported in the literature (Gaeuman et al. 1962, Hood et al. 1966, Hoover and Ashe 1962, Pope et al. 1990). However, only two physiological responses (ventilation rate and tidal volume) were significantly affected by the dose in the present study. Ventilation rate was 12% greater during 6 Hz than that obtained at 3 Hz. Since respiratory frequency was similar for all the doses, and tidal volume was significantly high during 6 Hz than at 3 Hz, increases in ventilation rate were attributed to changes in tidal volume only (Hoover and Ashe 1962, Gaeuman et al. 1962).

During exposure to doses of 2, 4, 6, 8, and 11 Hz (at accelerations of 0.03 and 2.88g, and amplitudes of 1.6 mm and 3.2 mm), Hoover and Ashe (1962) reported respiratory responses similar to the present study (Table 4.2). In their subjects, ventilation rate ranged from 7 to 13 $L.min^{-1}$, tidal volume from 0.44 to 0.84 $liters.breath^{-1}$, and respiratory frequency from 16 to 20 $breaths.min^{-1}$. Furthermore, they reported significant differences in respiratory responses at only 6 Hz (at 3.2

mm vibration amplitude). They concluded that changes in tidal volume resulted in an increase in ventilation rate and the changes observed are similar to those seen in hyperventilation. In another study, Gaeuman et al. (1962) exposed their subjects to a variety of doses and accelerations (at a fixed amplitude of 6.4 mm) and also concluded that exposure to WBV induces hyperventilation. They suggested that if subjects were unrestrained in their sitting posture, they were able to adjust or position their body with respect to different WBV conditions through voluntary and involuntary muscle guarding, thus damping the WBV, and subsequently reducing its transmission to human body parts. These authors hypothesized that such postural adjustments during WBV may eventually result in an increase in metabolic activity, which if continued for extended periods at higher doses (6-15 Hz), could lead to fatigue. However, in the present study metabolic responses during exposure to the three doses were identical (Table 4.2). The subjects were unrestrained during the WBV exposures as well. Also, vibration amplitude was almost double (6.1mm – 6.6 mm) to that of cited in Hoover and Ashe (1962), and were similar to that of Gaeuman et al. (1962). Furthermore, accelerations obtained (Chapter 2, Table 2.2) were approximately less than half of the values reported by Hoover and Ashe (1962).

Similar to the studies reported above, Hood et al. (1966) also demonstrated an increase in ventilation rate during WBV. Their findings supported the hypothesis that the physiological changes observed were due to maximal stretching of muscle spindles and reflex muscular contractions under optimal vibratory conditions. They emphasized that greater mechanical movements of the human body during WBV, specifically of the extremities, may result "in a mild circulatory stress, suggesting patients with severe cardiovascular disease should avoid rough means of transportation".

The oxygen uptake responses reported in the present study (Table 4.2) are also in accordance with the 'light physical activity' values reported in the literature (McArdle et al. 1996, Pope et al. 1990). Pope et al. (1990) exposed seated subjects to intermittent (at 5 Hz) and continuous (0, 2.5, 5, and 8 Hz) WBV, and studied the effect of posture (relaxed and erect) on absolute oxygen uptake responses. Similar to the present study, their results showed an increase in oxygen uptake during WBV (0.24 $L.min^{-1}$ to 0.29 $L.min^{-1}$) when compared to sitting rest without WBV. Also, similar to the present study, they did not observe any significant increase in oxygen uptake with the increase in WBV dose. Based on the low oxygen uptake responses, these authors concluded that changes observed in physiological responses during WBV resembled light machining work.

During exposure to WBV in a semi supine restrained position (with doses of 2 to 12 Hz in steps of 2 Hz increments; and accelerations of 0.6g and 1.2g), Hood et al. (1966) demonstrated significant cardiorespiratory changes in the range of 8 - 10 Hz (at 1.2g). Such changes were accompanied by increased mixed arterial-venous oxygen difference, decreased peripheral vascular resistance index, and a slight increase in stroke index, suggesting physiological responses were similar to a typical semi-supine 'exercise' pattern. At 0.6g and at frequencies above and below 8-10 Hz range, these authors attributed the small increase in cardiac index (without increased heart rate or oxygen consumption) to the mechanism of overperfusion relative to the recovery values. This suggested that at lower intensities of WBV a venous pump mechanism is usually activated. However, unlike the significant differences obtained in cardiovascular responses in Hood et al. (1966), the cardiovascular responses such as cardiac output, stroke volume, and mixed arterio-venous oxygen difference obtained in the present study (Table 4.3) were unchanged during exposure to 3 Hz, 4.5 Hz, and 6 Hz. This discrepancy between the two studies may be due to the different dose and intensity combinations of WBV, and the postures adopted during exposure to WBV.

Role of Sitting 'With' and 'Without' a Backrest during WBV

When leaning against the backrest, subjects tend to transfer most of their body weight to the backrest, thus reducing the load on the low-back imposed by the upper body weight (Andersson et al. 1991). During WBV 'Without' backrest, absolute and relative oxygen uptake significantly increased by 11% and 12%, respectively than 'With' backrest condition. Further, a small but significant increase of 4.5% was observed in the heart rate during sitting 'Without' backrest condition. Since oxygen pulse is calculated as the ratio of oxygen uptake and heart rate, this value was 7% higher during WBV 'Without' backrest. Ventilation rate was 11% higher 'Without' backrest than 'With' backrest as well. Interestingly, neither respiratory frequency nor tidal volume influenced the increase in ventilation rate.

Few authors have reported similar oxygen uptake and heart rate responses during postural variation in the absence of WBV (Sato and Tanaka 1973), and during WBV (Magnusson et al. 1987, Pope et al. 1990). As the posture becomes more upright, venous return to the heart will decrease due to an increase in gravitational force, thereby lowering cardiac output (Sato and Tanaka 1973). Consequently there would be an increase in the heart rate to maintain cardiac output (mediated through baroreceptor mechanism, with changes being observed in distribution of blood and peripheral resistance). However, in the present study, cardiac output during sitting without backrest (in an erect posture) was 8% greater than sitting with backrest, suggesting that 'WBV' might have stimulated such a reverse response. An increase in cardiac output might have also been facilitated by an increase in both the heart rate and stroke volume responses. Further, Sato and Tanaka (1973) attributed the increase in heart rate during upright posture to the static muscle contractions necessary to sustain the adopted posture. This would increase the intramuscular tension leading to an inefficient venous pumping mechanism, subsequently resulting in reduced venous return to the heart. They reported a correlation coefficient of 0.81 between relative oxygen uptake and heart rate responses during various postures.

Magnusson et al. (1987) monitored oxygen uptake in subjects 'Without' backrest support during: a) sitting (without WBV) in a relaxed symmetric posture; b) sitting erect without WBV; c) axial trunk rotation to the left without WBV; and d) WBV plus axial rotation, respectively. Their results indicated that axial rotation and WBV exposure (to a constant frequency of 5 Hz and acceleration 2.0 m/sec^2) increases the oxygen uptake by 32% compared to non-vibration and non-twisted tests. During exposure to intermittent (at 5 Hz) and continuous WBV

(0, 2.5, 5, and 8 Hz), Pope et al. (1990) found an increase in oxygen uptake in the erect posture compared to the relaxed posture. These results essentially suggest more energy is expended in maintaining an erect posture during sitting 'Without' backrest condition. Based on these findings, Pope et al. (1990) postulated that muscle contraction to maintain a posture leads to muscle fatigue, resulting in shifting loads on to ligaments and discs.

Role of Workload during Whole-Body Vibration

The responses observed in the present study during WBV combined with maximal rhythmic handgrip contractions can be related to WBV studies that combined physical and psychological work during WBV (Bennett et al. 1977, Grether et al. 1971 and 1972, Manninen 1984, 1985, and 1988, Thornton et al. 1984, Webb et al. 1981). In the present study, both absolute and relative oxygen uptake responses showed approximately 36% increase during WBV combined with maximal rhythmic handgrip contractions (Table 4.2). Further, heart rate and oxygen pulse values were 16% and 24% higher during WBV combined with maximal rhythmic handgrip contractions, respectively. The increase in ventilation rate (37%) paralleled the increase in oxygen uptake values. However, respiratory frequencies were similar during both conditions, suggesting that the increase in ventilation rate was primarily due to an increase in tidal volume (39%).

Bennett et al. (1977) demonstrated that performance of a motor task (tracking) during WBV might be affected by the physiological cost (heart rate and oxygen consumption). They showed an increase in oxygen consumption (0.31 $L.min^{-1}$ to 0.42 $L.min^{-1}$) with WBV exposure, and suggested that a combination of WBV and tracking tasks may lead to a higher metabolic cost. Additionally, they also classified subjects into internal and external 'personality' types and showed that internal subjects, who believed in themselves and were more successful in performing any type of task, demonstrated less performance decrements accompanied by greater physiological cost. Thus, internal subjects showed greater heart rate responses than external subjects during a motor task combined with WBV.

Webb et al. (1981) also studied the role of personality type in performance and physiological cost during WBV. 'Internal' subjects who assume their effort in a given task as a personal challenge, showed less performance decrements (indicated by less tracking errors) and greater physiological cost (measured by heart rate responses) than 'external' subjects. They attributed the significant results of internal subjects' responses to higher level of job satisfaction, suggesting "..conditions which foster higher job satisfaction may cause people to have greater confidence in their own influence over events". These authors also hypothesized that internal subjects show similar characteristics of type A behavior pattern (greater competitiveness and enthusiasm to control the environment), and are often linked with coronary heart disease, thus suggesting long-term effects may be psychosomatic.

Grether et al. (1971 and 1972) studied the effect of environmental stressors namely heat, noise, and WBV (of 5 Hz at peak 0.5g), individually and/or in combination, on psychological (tracking, choice reaction time, voice communication, mental arithmetic, visual acuity, and subjective severity ratings on a 7 point scale), and physiological responses (body temperature, heart rate, weight loss, and biochemical urine analysis). Interestingly, with the exception of mental arithmetic tests and subjective ratings, their results showed lower values in physiological and performance measurements during exposure to combined stressors. They concluded that additive or synergistic interactions among the three stressors were absent. However, subjective stress severity ratings increased with the number of stressor combinations. Moreover, Thornton et al. (1984) showed that handling controls during hovering required the greatest energy expenditure. The oxygen uptake for aviation pilots during level flight was almost 50% higher than that of sitting at rest. Even though the mental demand during flying at low levels was greater, they did not find significant differences in energy expenditure between flying at cruising altitude and flying at low level.

Manninen (1984) exposed subjects to WBV alone, noise alone or a combination of these two during dynamic work. Subjects intermittently pulled a handle attached to a pneumatic piston-cylinder mechanism with one hand. The workload was adjusted to correspond to 2, 4, and 8 Watts. The author demonstrated an increase in heart rate values during all exposures and in all exposure combinations when compared to the control values, suggesting that the change in heart rate was not only accomplished with the dynamic work but also with the quality of noise and WBV exposure. Consistent with the findings of Bennett et al. (1977) and Webb et al. (1981), Manninen (1985) showed that mental load caused by 'competition' increased the temporary hearing threshold, the heart rate, and systolic blood pressure when subjects were simultaneously exposed to noise or a combination of noise and WBV. In a related study, Manninen (1988) showed that duration of exposure and temperature differences in the environment enhanced the changes induced by shorter exposure periods and smaller differences in temperature. A rise in the hearing threshold values was very strongly correlated with a rise in the heart rate, systolic blood pressure and hemodynamic index values (a product of heart rate and systolic blood pressure divided by one thousand), especially when the subjects were sitting and performing light, self paced work while exposed to WBV and noise.

Thus from the above studies, it is quite evident that combined stressors such as noise, light, temperature, physical work, and psychological load combined with WBV, elicit variable physiological responses in humans. As Bennett et al. (1977) stated "..cognitive factors in personality are involved in attempts to maintain performance during vibration stress and that the level of performance achieved may be associated with the physiological cost incurred".

Role of Gender

During WBV alone and WBV combined with maximal rhythmic handgrip contractions, men showed 15% and 27% higher absolute oxygen uptake values than women, respectively (Figure 4.2A). When oxygen uptake was normalized relative to body mass, gender differences were absent during the WBV alone condition (Figure 4.2B). However, during WBV combined with maximal rhythmic handgrip contractions, men showed a 14% higher relative oxygen uptake value than women (Figure 4.2B). Since heart rate values were not significantly different between genders, the difference in oxygen pulse obtained during both conditions of workload were attributed to oxygen uptake responses only (Figure 4.3). Ventilation rate and respiratory frequency were similar but tidal volume was 24% higher in men compared to women. The latter was most likely due to differences in body size between the genders. Similarly, men showed greater grip strength than women (34%), which might have induced the greater increase in physiologic responses during WBV combined with maximal rhythmic handgrip contractions. However, correlation coefficients (Table 4.4) were not consistent among three vibration tests 'With' and 'Without' backrest.

To our knowledge, no WBV study to date has differentiated physiological responses between men and women. Pope et al. (1990) demonstrated differences in resting oxygen uptake between men and women; however, they did not differentiate gender responses during WBV. In the present study, cardiac output, stroke volume, and mixed arterio-venous oxygen difference was 19%, 13%, and 12% higher in men than women, respectively. However, gender per se did not influence heart rate responses. This phenomenon suggests that an increase in cardiac output could be attributed purely to an increase in stroke volume. Also, the higher absolute oxygen uptake in men could be the result of increase in both cardiac output and mixed arterio-venous oxygen difference.

Role of Fitness

The peak aerobic capacity during arm cranking in women were less but not significantly different from men. Despite the low metabolic rates during WBV, the effect of aerobic fitness was evident only in men for absolute oxygen uptake ($r=0.73$, $P=0.005$), and relative oxygen uptake responses ($r=0.73$, $P=0.008$) during handgrip contractions. Further, fitness did not influence any other physiological responses. These findings are also consistent with the postulations made by Boff and Lincoln (1988) and Griffin (1990) that physical fitness does influence exposure to WBV. However, they did not report any WBV study that has identified the importance of aerobic fitness. At present it is not clear why such an intra- and inter-gender differences in correlations exist in these vibration tests.

A few studies have reported that during 'heavy work' such as repetitive lifting, aerobic fitness did not influence low-back complaints (Battie et al. 1989, Kujala et al. 1996). In contrast, several authors (Cady et al. 1979, Craig et al. 1998, Davis et al. 1982, Williford et al. 1999) showed a strong correlation between lack of physical fitness and injury. Factors such as work demanding high fitness in fire fighting (Cady et al. 1979, Davis et al. 1982, Williford et al. 1999) and high frequency lifting in some industries (Craig et al. 1998) might have been the reasons for such a discrepancy in the role of fitness. However, in the present study, based on the acute physiological responses obtained, the results suggest that the level of aerobic fitness in participating subjects does play a significant role during even 'light work' experienced in seated WBV.

CONCLUSION

In the present study, the role of dose, backrest, workload, and gender on whole-body acute physiological responses during seated WBV were investigated. No significant increase in metabolic responses was observed in men and women during exposure to discrete doses 3 Hz, 4.5 Hz, and 6 Hz. However, only ventilation rate and tidal volume responses reached significance during 3 and 6 Hz. The responses during sitting 'Without' backrest were significantly higher than 'With' backrest condition suggesting that postural muscular load imposed by static sitting might result in higher metabolic load. WBV alone showed much lower increase in physiological responses than WBV combined with maximal rhythmic handgrip contractions, suggesting WBV combined with physical workload can influence physiological responses in both men and women. Additionally, gender played a significant role during WBV combined with maximal rhythmic handgrip contractions in absolute and relative oxygen uptake, and oxygen pulse responses only. These responses suggest if subjects were exposed to WBV combined with physical workload, they would experience greater metabolic responses.

Cadiovascular responses were not influenced by the WBV dose. However, 'With' backrest, cardiac output showed lowest responses than either rest without WBV or 'Without' backrest during WBV. During WBV 'Without' backrest, heart rate values were higher than both sitting 'With' backrest during WBV and initial rest without WBV conditions. Higher stroke volume values were also reported 'Without' backrest than 'With' backrest conditions. However, mixed arterio-venous oxygen difference was not influenced by any condition. Men showed significantly highest cardiac output, stroke volume and mixed arterio-venous oxygen difference responses than women. Aerobic fitness played a significant role in determining the absolute and relative oxygen uptake, and oxygen pulse values during workload.

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Table 4.1A: Demographics of subjects

Gender	Age	Body Mass	Sitting Height	Standing Height	Body Mass Index Standing
	Yrs	Kgs	m	m	$Kg. m^{-2}$
Men N=13	24.7 ± 3.9	70.8 ± 12.1 [a]	0.86 ± 0.05	1.71 ± 0.07 [a]	24.0 ± 3.2
Women N=14	23.9 ± 3.5	60.3 ± 9.0	0.84 ± 0.08	1.63 ± 0.10	23.0 ± 3.7

[a] – significant difference between Men and Women ($p < 0.05$)

Table 4.1B: Demographics of subjects

Gender	Neck Dimension			Maximal Right Hand Grip Strength	Peak Oxygen Uptake Arm Cranking
	Length	C6 [Ψ]	Occipital [Ψ]		
	Cm	Cm	Cm	Kgs	$mL.Kg^{-1}.min^{-1}$
Men N=13	12.6 ± 1.4	37.8 ± 3.2 [a]	37.5 ± 2.8 [a]	34.2 ± 9.1 [a]	24.5 ± 6.6
Women N=14	12.3 ± 1.5	32.4 ± 1.7	31.5 ± 1.8	22.5 ± 3.6	21.4 ± 4.6

[Ψ] Diameter measured at the placement of accelerometer at C6 and at Occipital regions

[a] – significant difference between Men and Women ($p < 0.05$)

Table 4.2: Metabolic and Respiratory responses during WBV (Mean ± SD)

Variable	Gender	Back-rest	WBV Dose 3 Hz Alone[c]	3 Hz + Grip	4.5 Hz Alone[c]	4.5 HZ + Grip	6 Hz Alone[c]	6 Hz + Grip
Oxygen Uptake, L.min^{-1}	Men[d]	On[b]	0.207 ± 0.032	0.405 ± 0.016	0.249 ± 0.068	0.412 ± 0.013	0.241 ± 0.078	0.411 ± 0.013
		Off	0.261 ± 0.063	0.421 ± 0.016	0.287 ± 0.080	0.454 ± 0.015	0.276 ± 0.090	0.454 ± 0.014
	Women	On[b]	0.194 ± 0.050	0.285 ± 0.064	0.200 ± 0.048	0.286 ± 0.067	0.214 ± 0.030	0.304 ± 0.078
		Off	0.223 ± 0.055	0.326 ± 0.093	0.224 ± 0.061	0.327.± 0.087	0.237 ± 0.040	0.323 ± 0.076
Oxygen Uptake, ml.kg^{-1}.min^{-1}	Men[d]	On[b]	2.98 ± 0.6	5.72 ± 2.01	3.52 ± 0.73	5.87 ± 1.81	3.4 ± 0.93	5.94 ± 2.13
		Off	3.71 ± 0.7	5.93 ± 2.0	4.05 ± 0.78	6.38 ± 1.74	3.91 ± 1.03	6.7 ± 2.20
	Women	On[b]	3.28 ± 0.9	4.80 ± 1.2	3.30 ± 0.8	4.90 ± 1.5	3.62 ± 1.0	5.2 ± 1.7
		Off	3.78 ± 1.1	5.6 ± 1.9	3.8 ± 1.1	5.5 ± 1.5	4.0 ± 0.8	5.5 ± 1.7
Heart Rate, beats.min^{-1}	Men	On[b]	76 ± 9	91 ± 12	79 ± 10	95 ± 12	79 ± 6	92 ± 13
		Off	81 ± 13	96 ± 14	84 ± 10	99 ± 12	83 ± 7	99 ± 11
	Women	On[b]	75 ± 7	91 ± 9	77 ± 5	91 ± 4	78 ± 5	94 ± 6
		Off	79 ± 7	94 ± 8	81 ± 6	95 ± 6	84 ± 10	97 ± 8
Oxygen Pulse, ml.beat^{-1}	Men[d]	On[b]	2.8 ± 0.7	4.5 ± 1.8	3.2 ± 0.9	4.3 ± 1.3	3.1 ± 1.0	4.5 ± 1.5
		Off	3.3 ± 1.1	4.5 ± 1.8	3.4 ± 1.0	4.6 ± 1.4	3.4 ± 1.1	4.6 ± 1.3
	Women	On[b]	2.6 ± 0.7	3.2 ± 0.7	2.6 ± 0.6	3.1 ± 0.7	2.8 ± 0.6	3.4 ± 0.8
		Off	2.9 ± 0.8	3.5 ± 1.1	2.8 ± 0.8	3.5 ± 0.8	2.9 ± 0.6	3.4 ± 0.8
Ventilation Rate, l.min^{-1}	Men	On[b]	8.0 ± 1.4[a]	16.0 ± 9.0[a]	9.9 ± 2.5	14.3 ± 7.8	9.7 ± 2.6	18.1 ± 9.3
		Off	10.1 ± 2.7[a]	15.2 ± 7.8[a]	10.9 ± 2.8	16.5 ± 6.7	10.6 ± 2.6	19.2 ± 7.6
	Women	On[b]	8.4 ± 2.5[a]	11.3 ± 2.8[a]	8.5 ± 2.7	12.0 ± 3.9	9.2 ± 2.4	13.1 ± 5.3
		Off	8.8 ± 2.2[a]	12.8 ± 4.9[a]	9.4 ± 3.2	18.4 ± 3	9.8 ± 1.8	13.2 ± 5.2
Respiratory frequency, Breaths.min^{-1}	Men	On	19 ± 5[a]	21 ± 6[a]	22 ± 8	18 ± 7	22 ± 6	24 ± 6
		Off	22 ± 6[a]	21 ± 4[a]	23 ± 8	21 ± 5	20 ± 6	22 ± 5
	Women	On	24 ± 7[a]	25 ± 9[a]	23 ± 6	23 ± 6	24 ± 6	24 ± 5
		Off	25 ± 9[a]	25 ± 9[a]	24 ± 8	23 ± 6	24 ± 4	23 ± 6
Tidal Volume, L.breath^{-1}	Men	On	0.44 ± 0.1	0.81 ± 0.4	0.54 ± 0.2	0.93 ± 0.5	0.47 ± 0.17	0.80 ± 0.4
		Off	0.46 ± 0.11	0.76 ± 0.4	0.54 ± 0.26	0.84 ± 0.31	0.57 ± 0.25	0.90 ± 0.4
	Women	On	0.35 ± 0.06	0.49 ± 0.15	0.38 ± 0.12	0.56 ± 0.25	0.39 ± 0.06	0.56 ± 0.22
		Off	0.38 ± 0.10	0.53 ± 0.20	0.41 ± 0.13	0.95 ± 1.6	0.43 ± 0.11	0.64 ± 0.28

NOTE: All subjects were exposed to 3, 4.5 and 6 Hz doses.

[a] – significant difference between 3 Hz and 6 Hz when all other main effects were pooled ($p < 0.01$)

[b] – significant difference between WBV 'with' and 'without' backrest when all other main effects were pooled ($p < 0.01$).

[c] – significant difference between vibration alone and vibration combined with rhythmic handgrip (except for Respiratory frequency) when all other main effects were pooled ($p < 0.01$)

[d] – significant difference between gender and work ($p < 0.01$)

Table 4.3: Cardiovascular responses during WBV (Mean ± SD)

Variable	Dose	Men: Rest without WBV	Men: WBV 'with' Backrest	Men: WBV 'without' Backrest	Women: Rest without WBV	Women: WBV 'with' Backrest	Women: WBV 'without' Backrest
Cardiac Output, l.min^{-1}	3 Hz	6.5 ± 1.1^{a}	6.5 ± 1.0^{ab}	6.7 ± 0.9^{a}	5.6 ± 0.9	5.3 ± 1.3^{b}	5.7 ± 0.5
Heart Rate, beats. min^{-1}	3 Hz	70 ± 8^{cd}	76 ± 9^{b}	81 ± 12	71 ± 9^{cd}	79 ± 7^{b}	87 ± 7
Stroke Volume, ml.beat^{-1}	3 Hz	95 ± 21^{acd}	86 ± 13^{ab}	84 ± 14^{a}	79 ± 16^{cd}	60 ± 17^{b}	72 ± 9
Arterio-venous oxygen difference, ml%	3 Hz	6.50 ± 1.1^{a}	6.89 ± 1.3^{a}	6.9 ± 1.3^{a}	5.93 ± 1.0	5.88 ± 1.1	5.82 ± 1.1
Cardiac Output, l.min^{-1}	4.5 Hz	6.7 ± 1.5^{a}	6.2 ± 1.3^{ab}	6.7 ± 0.9^{a}	5.4 ± 0.9	4.8 ± 0.9^{b}	5.7 ± 0.8
Heart Rate, beats. min^{-1}	4.5 Hz	72 ± 10^{ac}	79 ± 10^{b}	84 ± 10	69 ± 8^{cd}	77 ± 5^{b}	81 ± 6
Stroke Volume, ml.beat^{-1}	4.5 Hz	94 ± 24^{acd}	78 ± 15^{ab}	80 ± 9^{a}	79 ± 13^{cd}	63 ± 12^{b}	70 ± 9
Arterio-venous oxygen difference, ml%	4.5 Hz	6.83 ± 1.2^{a}	6.50 ± 1.2^{a}	6.64 ± 1.1	6.11 ± 1.2	6.14 ± 1.0	6.18 ± 0.9
Cardiac Output, l.min^{-1}	6 Hz	6.9 ± 1.1^{a}	6.8 ± 1.9^{ab}	7.5 ± 2.2^{a}	5.1 ± 0.5	5.4 ± 0.6^{b}	5.9 ± 0.9
Heart Rate, beats. min^{-1}	6 Hz	72 ± 5^{cd}	79 ± 6^{b}	83 ± 7	71 ± 6^{cd}	78 ± 5^{b}	84 ± 10
Stroke Volume, ml.beat^{-1}	6 Hz	97 ± 16^{acd}	86 ± 23^{ab}	90 ± 26^{ab}	73 ± 9^{cd}	70 ± 9^{b}	71 ± 14
Arterio-venous oxygen difference, ml%	6 Hz	6.90 ± 1.0^{a}	6.80 ± 1.0^{a}	6.91 ± 1.0^{a}	5.91 ± 1.1	5.95 ± 0.8	5.98 ± 0.8

^{a} – significant difference between men and women when all other main effects were pooled ($p < 0.01$),
^{b} – significant difference between conditions WBV 'With' and 'Without' backrest when all other main effects were pooled ($p < 0.01$)
^{c} – significant difference between conditions rest and WBV 'With' backrest when all other main effects were pooled ($p < 0.01$)
^{d} – significant difference between conditions rest and WBV 'Without' backrest when all other main effects were pooled ($p < 0.01$)

Table 4.4: Pearson Correlations between Metabolic responses and Maximal Rhythmic Handgrip Contractions during WBV

GENDER	Selected Variables	3 Hz		4.5 Hz		6 Hz	
		'With' Backrest	'Without' Backrest	'With' Backrest	'Without' Backrest	'With' Backrest	'Without' Backrest
Men	Oxygen Uptake, L.min^{-1}	0.81$^{\Psi}$	0.69$^{\Psi}$	0.38	0.63$^{\Psi}$	0.42	0.24
	Oxygen Uptake, mL.kg^{-1}.min^{-1}	0.57$^{\Psi}$	0.44	-0.01	0.35	0.04	-0.12
	Heart Rate, beats.min^{-1}	-0.23	-0.52	0.20	0.23	0.21	-0.01
	Oxygen Pulse, mL.beat^{-1}	0.83$^{\Psi}$	0.76$^{\Psi}$	0.27	0.54	0.34	0.21
	Ventilation Rate, L.min^{-1}	0.60$^{\Psi}$	0.52	0.46	0.57$^{\Psi}$	0.37	0.52
	Respiratory frequency, breaths.min^{-1}	-0.10	0.02	-0.22	-0.13	-0.41	-0.49
	Tidal Volume, L.breath^{-1}	0.62$^{\Psi}$	0.46	0.51	0.62$^{\Psi}$	0.48	0.74$^{\Psi}$
Women	Oxygen Uptake, L.min^{-1}	-0.20	0.65$^{\Psi}$	0.54$^{\Psi}$	0.14	0.40	0.46
	Oxygen Uptake, mL.kg^{-1}.min^{-1}	0.27	0.67$^{\Psi}$	0.65$^{\Psi}$	0.28	0.44	0.54$^{\Psi}$
	Heart Rate, beats.min^{-1}	-0.08	0.02	-0.21	-0.23	-0.08	0.16
	Oxygen Pulse, mL.beat^{-1}	-0.18	0.56$^{\Psi}$	0.60$^{\Psi}$	0.21	0.39	0.38
	Ventilation Rate, L.min^{-1}	-0.12	0.69$^{\Psi}$	0.58$^{\Psi}$	-0.21	0.45	0.30
	Respiratory frequency, breaths.min^{-1}	-0.21	-0.01	-0.11	0.35	-0.07	0.08
	Tidal Volume, L.breath^{-1}	0.04	0.59$^{\Psi}$	0.36	-0.26	0.50	0.28

$^{\Psi}$- Significance at $P < 0.05$

Figure 4.1A Subject Setup for Metabolic Measurements

Figure 4.1B Noninvasive Cardiac Output Using CO_2 Rebreathing Technique

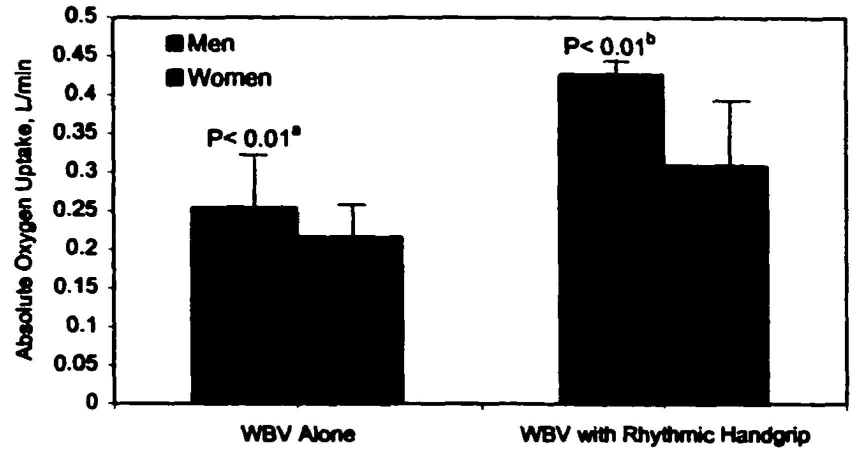

Figure 4.2A. Interaction between Gender and Work Absolute Oxygen Uptake Changes

NOTE: 1. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Backrest). Also, values represent mean ± SD from 13 men and 14 women.
2. Graph suggests that during both conditions of workload, men demonstrated greater changes in oxygen uptake compared to women.
a - significant difference between men and women during WBV alone
b - significant difference between men and women during WBV with Work Rthythmic Handgrip

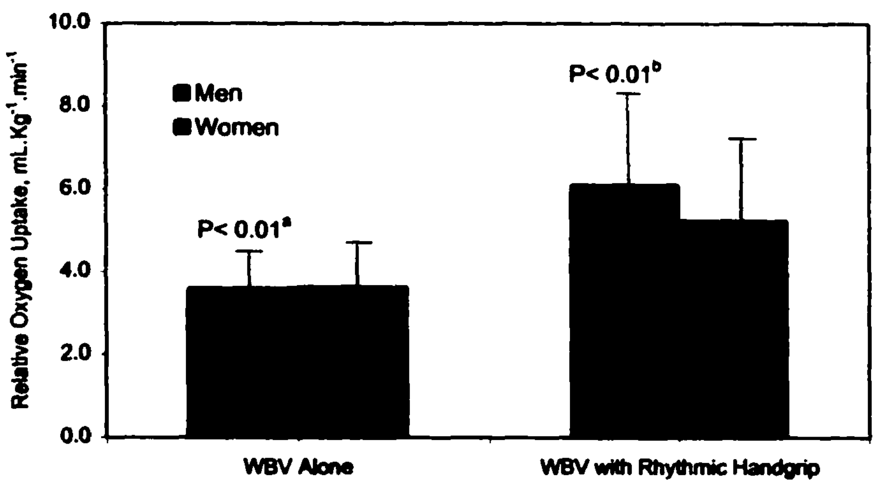

Figure 4.2B. Interaction between Gender and Work Relative Oxygen Uptake Changes

NOTE: 1. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Backrest). Also, values represent mean ± SD from 13 men and 14 women.
2. Graph suggests that during both conditions of workload, men demonstrated greater changes in oxygen uptake compared to women.
a - significant difference between men and women during WBV alone
b - significant difference between men and women during WBV with Work Rthythmic Handgrip

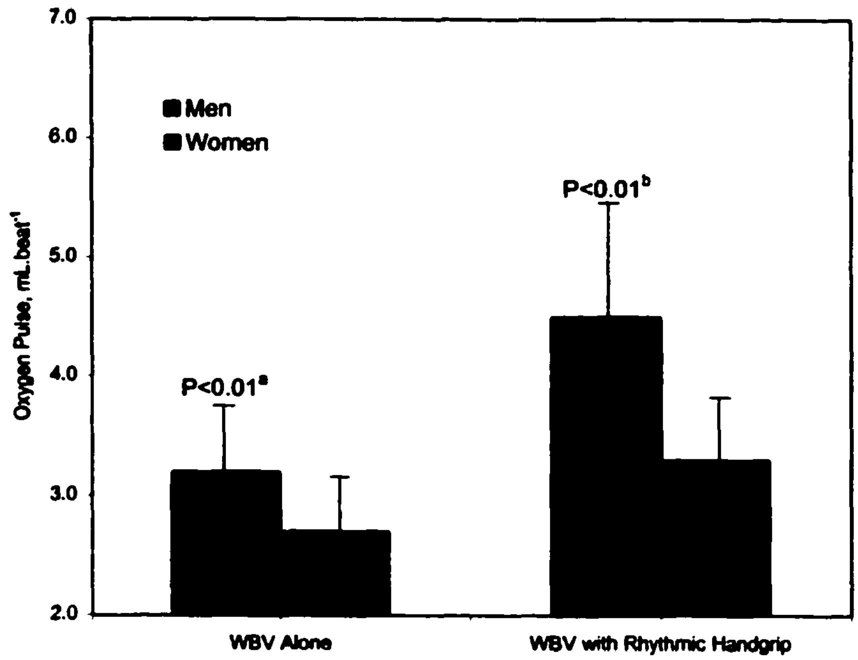

Figure 4.3. Interaction between Gender and Work Oxygen Pulse Changes ($P<0.01$)

NOTE: 1. Values for the graphs are based on the pooled mean values of remaining independent variables (Dose and Backrest). Also, values represent mean ± SD from 13 men and 14 women.

2. Graph suggests that during both conditons of workload, men showed greater differences in oxygen pulse compared to women.

a - significant difference between men and women during WBV alone

b - significant difference between men and women during WBV combined with Rhythmic Handgrip

CHAPTER 5

Cardiorespiratory and Biceps Brachii Oxygenation and Blood Volume Comparisons during Arm Cranking and Task-specific Pushing-Pulling

Pushing and pulling is a manual material handling activity, and is defined as the application of one or two handed force on an object or person, with feet either stationary (Chaffin et al. 1983, Gagnon et al. 1992, Garg et al. 1978) or moving (Lee et al. 1991, Snook and Ciriello 1991). For example, pushing and pulling loads from the shelves (Gagnon et al. 1992), floor mopping or snow shovelling can be treated as effort applied with feet stationary (Franklin et al. 1995, Søgaard et al. 1996). Cart pushing and pulling is an example with feet moving (Snook and Ciriello 1991). In pushing, the applied force is directed away from the body, and in pulling, the resistance is directed towards the body (van der Beek et al. 2000). Similar to a repetitive lifting and/or lowering activity, repetitive pushing and pulling is also accompanied by isometric muscle activity in the trunk and upper extremities of workers leading to localized fatigue and increased cardiovascular stress (Hoozemans et al. 1998). Further, this activity is often implicated in both low-back and upper extremity disorders (Bernard and Fine 1997, OSHA Draft 1999).

In the field of Occupational Health and Safety, it is standard practice to evaluate the worker's fitness for work using traditional incremental aerobic protocols on a treadmill, cycle ergometer or arm ergometer, instead of task-specific maximal or submaximal aerobic protocols. These diagnostic protocols, though informative, may or may not identify the individual's actual physical capacity to do the job due to the different movements involved in the tasks compared to standardized running, cycling, or arm cranking protocols (Garg et al. 1992, Khalil et al. 1985, McConnell et al. 1984, Sharp et al. 1988, Waters et al. 1993). A recent study by Nindl et al. (1998) showed a modest correlation in peak oxygen uptake values between repetitive lifting and treadmill running ($r = 0.73$ and $r = 0.60$ for men and women, respectively). Further, Sharp et al. (1988) estimated maximal aerobic power of repetitive lifting as 78% of treadmill, 89% of cycling and 125% of arm cranking values, whereas for various lifting tasks, Khalil et al. (1985) reported maximal aerobic power as 91% of cycling values. Furthermore, depending on the weight of the load lifted or lowered, and rate of the activity performed, average lifting and lowering maximal aerobic power values were 19% to 47% lower than the cycling values (Petrofsky and Lind 1978). However, to our knowledge comparison of peak aerobic values during maximal pushing and/or pulling to the standardized protocols have not been reported to date.

It is evident from the findings cited that there is considerable variation between standardized and task-specific protocols for the measurement of aerobic power. Moreover, these differences emphasize that the exercise mode selected to measure aerobic power should simulate the specific task to be performed in the occupational setting (Sharp et al. 1988). Few physiological studies have reported energy expenditure during pushing and pulling with feet stationary (Esmail et al. 1995, Garg et al. 1978). Gender comparisons during this activity are also scarce in the literature. In a regression model of pushing and pulling of loads at different heights, Garg et al. (1978) demonstrated higher energy expenditure in women compared to men. Esmail et al. (1995) established both biomechanical and physiological normative data in healthy males and females during a push-pull task on a work simulator for a period of 4 min. Their results showed significant differences between genders in their relative maximal aerobic capacity and energy expenditure per unit amount of work done (men showed 19% lower values than women).

Near infra-red spectroscopy (NIRS) is a non-invasive optical technique that has been used to measure relative changes in oxygenation and blood volume levels in skeletal muscle continuously in real-time during rest and work (Bhambhani et al. 1998, Boushel et al. 1998, Chance et al. 1992, Mancini et al. 1994, Murthy et al. 1997). Muscle oxygenation, defined as the relative saturation of oxyhemoglobin and oxymyoglobin, depends on the balance between oxygen delivery and oxygen utilization (Mancini et al. 1994). Blood volume is defined as the sum of oxygenated and deoxygenated states of hemoglobin and myoglobin in the illuminated region of the muscle. Detailed description of the NIRS theory, its validation with various established optical and magnetic techniques are provided in Chapter 1. The reliability of NIRS in the upper and lower extremity human skeletal muscles has also been reported in Chapter 1. Under ischemic conditions induced by 250 mm Hg blood pressure in the biceps brachii at rest, Maikala and Bhambhani (1999) showed correlations of 0.86 to 0.96 (between sessions), and 0.95 to 0.97 (within sessions) for oxygenation measurements.

To our knowledge, no studies to date have evaluated the whole-body physiological and oxygenation and blood volume trends of the biceps brachii muscle group during repetitive pushing and pulling, and compared these responses with a standardized incremental arm cranking protocol. Hence, the purposes of this study were to compare the: (1) whole-body physiological responses during incremental pushing-pulling (with feet stationary) and incremental arm cranking till volitional exhaustion; (2) oxygenation and blood volume responses of the biceps brachii muscle during both protocols, and (3) differences in these responses between genders. It was hypothesized that: (1) there would be no significant differences in the whole-body physiological responses between the two modes of exercise, (2) the biceps brachii oxygenation and blood volume trends would be similar during these exercise modes, and (3) there would be no significant gender differences in these responses.

MATERIALS AND METHODS

Subjects

Written informed consent was obtained from 11 healthy men (age 23.7 ± 4.5 yrs, mass 77.5 ± 13.8 kg, height 176 ± 8 cm) and 11 healthy women (age 24.5 ± 3.51 yrs, mass 57.6 ± 9.4 kg, height 163 ± 7 cm). Subjects were undergraduate and graduate students recruited from the university population (Table 5.1). They all completed the Revised Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology, 1994) to identify contraindications for exercise. The test protocols utilized were approved by the Human Research Ethics Board at this institution (APPENDIX A.2).

Description of the Baltimore Therapeutic Equipment (BTE) Work Simulator:

The BTE work simulator (Baltimore Therapeutic Equipment Co., Maryland, USA) is a multi-purpose instrument that can be used for the measurement of upper-extremity strength and endurance during functional tasks (Figure 5.1). With various customized attachments provided by the manufacturer, this simulator quantifies the work performed, force exerted (in terms of torque), and the power output during various simulated occupational activities. It is widely used in the rehabilitation centers by occupational and exercise therapists for static and dynamic testing in both work evaluation and work hardening.

The work simulator essentially consists of three components. First, a multi-purpose exercise head that is mounted on an arm that extends from the vertical column. Force output from the head is measured using a built-in strain gauge. This exercise head with an electronically controlled variable-resistance mechanism is adjustable to a vertical height of 33 cm to 167.6 cm. Second, various customized attachments provided by the manufacturer can be used to simulate common tasks in the occupational setting. For pushing-pulling without feet moving attachment # 171 is used. This attachment is a lever consisting of a straight handle with an articulating joint producing linear motion. The resistance can be applied in one (either away from or towards the subject) or both directions. For the current study, resistance was applied in both directions during the incremental pushing-pulling protocol. Third, a computer software program was developed for conversion of mechanical loads generated during work into power units. By using the manufacturer's conversion chart, one can convert the torque generated into the load (in-lbs) to be pushed or pulled. This information is displayed on the console and can be used to control the work rate. The software provided with the BTE work simulator calculates the force output in pounds and the power output in watts. Before each testing session, the BTE work simulator was balanced in such a way that the strain gauge in the exercise head was in synchrony with the electronics in the control console (Powell et al. 1991).

Thereafter, the simulator was calibrated as per the manufacturer instructions (BTE Operator's Manual, 1992).

Reliability of the BTE Work Simulator

To date, only few studies have compared the measurements obtained from the BTE work simulator with real (field) measurements. Beaton et al. (1995) tested the grip strength using both the hydraulic Jamar dynamometer and the BTE work simulator. Intra-class correlation coefficient between the Jamar instrument at 90° and the BTE work simulator was 0.87. Pearson's correlation coefficients at 45° and 90° elbow flexion were identical (0.90). Kennedy and Bhambhani (1991) studied the test-retest reliability and criterion validity of the BTE work simulator during three intensities (light, medium, and heavy) of real and simulated work. Correlation coefficients between trials of the same task for oxygen consumption ranged from r=0.74-0.87 and for heart rate from r=0.59-0.78. Higher correlation coefficients were observed for light work (oxygen consumption: r=0.81 and 0.83; heart rate: r=0.88 and 0.95), followed by heavy work (oxygen consumption: r=0.68 and 0.75; heart rate: r=0.91 and 0.90) and medium work (oxygen consumption: r=0.56 and 0.52; heart rate: r=0.91 and 0.92) respectively.

Test Protocols

Each subject completed a cuff ischemia test on the first day, and an incremental arm cranking exercise and pushing-pulling test on two separate days in a random order.

(1) Cuff Ischemia Measurements

The purpose of the cuff ischemia test was to establish minimum and maximum oxygenation and blood volume values for the biceps brachii muscle at rest. The subject sat in a chair with the arm resting on the armrest, thus minimizing any extraneous muscular activity (Figure 5.3A). A blood pressure cuff was placed around the right upper arm just above the NIRS sensor on the biceps. Initial baseline values were monitored for two minutes. The cuff was inflated to 250 mm Hg pressure for a period of six minutes so as to induce ischemia within the muscle at rest. The cuff was then deflated to restore blood flow to the muscle and recovery measurements were recorded for four minutes.

(2) Incremental Arm Cranking

In a separate testing session, the subject completed an incremental test on an arm cranking ergometer (Cybex, MET 300, USA). The axis of the ergometer crankshaft was adjusted to shoulder height of each seated subject. Position of the handle was adjusted in such a way that when the arms were fully extended, a slight flexion was present at the elbow joint. The legs and trunks were not restrained and their feet were flat on the ergometer base. After fitting each subject with a mouthpiece and headgear (Figure 5.3B), the test was initiated with a two-minute rest period. It was followed by two minutes of arm cranking at no load and subsequent increments of 25 watts every 2 minutes at 50 crank rotations per minute (rpm) until voluntary exhaustion, or attainment of two or more of the end points suggested by the American College of Sports Medicine (1993): (1) leveling off in the oxygen consumption (increase of $\leq$ 100 $ml.min^{-1}$) with increasing load, (2) age predicted maximal heart rate, equated to 220-age (in years), (3) respiratory exchange ratio of $\geq$1.10, and (4) rate of perceived exertion (RPE) $\geq$ 18 (Borg, 1982). Protocol was terminated with 2 minutes of active [cranking at zero load] and 4 minutes of passive recovery. During the last 30 s at each workload, the overall RPE was recorded using the Borg scale. Bar-Or and Zwiren (1975) and Davis et al. (1976) reported test-retest reliability coefficients of 0.94 and 0.92 respectively for the peak oxygen uptake at an arm cranking cadence of 50 rpm.

(3) *Incremental Pushing-Pulling*

In a separate testing session, each subject completed an incremental test on the BTE work simulator. After fitting the subject with a mouthpiece and headgear, the height of the push-pull lever #171 was adjusted to each subject's elbow crease in the standing upright posture (Figure 5.4). The right hand was used as the main grasping hand (adopting a power grip) in this two-handed effort. The elbows were unlocked and subjects were discouraged from trunk rotation, swaying the body, and moving their lower extremities during pushing-pulling. They were instructed to put their right leg (extended at the knee) backward at a comfortable distance, and the left leg forward [with a slight knee flexion]. The left toe was placed on a marker that was in line with the handle being pulled [similar to a posture adopted in Ayoub and McDaniel (1974)]. The subject was not permitted to lift the heels off the floor throughout the testing session.

The test was initiated with a two-minute rest period and was followed by two minutes of repetitive pushing-pulling at no load in the horizontal direction in a sagittal plane towards (Figure 5.5A) and away from the body (Figure 5.5B). Distance of pushing-pulling was restricted by a delimiter fixed on the circumference of the BTE work simulator wheel at a fixed distance of 10 cm. A push-pull cadence of 50 repetitions per minute was used for this protocol. Thereafter, the resistance was increased by 30 in-lb every two minutes until voluntary exhaustion or attainment of two or more of the following end points suggested above by the American College of Sports Medicine (1993). Protocol was terminated with 2 minutes of active [cranking at zero load] and 4 minutes of passive recovery.

(4) Cardiorespiratory Measurements

Gas exchange measurements were continuously monitored with an automated metabolic measurement cart (MMC Horizon, Sensormedics Corporation, Yorba Linda, CA). The oxygen (O_2) and carbon dioxide (CO_2) analyzers of the cart were calibrated before each test with commercially available precision gases (16% O_2, 4% CO_2, balance Nitrogen). The pneumotach was calibrated for volume using a three-liter syringe, as recommended by the manufacturer. Heart rate was recorded using a polar heart rate monitor (Polar Accurex Plus, Finland). Expired gases were analyzed in the mixing chamber mode. Calibration was verified at the end of each test to ensure accuracy of the data. Peak oxygen pulse was calculated as the ratio of peak absolute oxygen uptake and peak heart rate, and peak ventilatory equivalent for oxygen as the ratio of peak ventilation volume and the peak absolute oxygen uptake. Furthermore, ratios of peak absolute oxygen uptake to the power output (metabolic efficiency), and relative oxygen uptake to the power output generated (relative metabolic efficiency) during each incremental exercise were also calculated.

(5) Biceps Brachii Oxygenation and Blood Volume Measurements

A continuous dual wave NIRS unit (MicroRunman, NIM Inc., PA, USA) was used to evaluate relative changes in the biceps brachii oxygenation and blood volume during both arm cranking and pushing-pulling tests. This unit consists of: a superficial near infra-red sensor fitted with six light emitting tungsten lamps placed 2 cm, 3 cm, and 4 cm apart; two photo-diode detectors that absorb light in the near infrared range at 760 nm and 850 nm; and a display unit that amplifies and displays the absorbency signal generated (Figure 2.2). The sensor was placed on the right biceps brachii (Figure 5.2), approximately 6-8 cm from the elbow crease (Jensen-Urstad et al. 1995). A piece of clear plastic was wrapped around the sensor to prevent sweat from distorting the absorbency signal. A dark elastic bandage was wrapped around the sensor to secure it in place and minimize any loss of light. Biceps brachii muscle skin fold thickness at the sensor location was measured using a Lange skinfold caliper (Cambridge Scientific Industries, Inc. Maryland, USA) before placing the NIRS sensor on the muscle belly. The adipose tissue thickness (a sum of fat and skin layer) at the sensor site was calculated as half of the skinfold thickness. Position of the NIRS sensor on the muscle belly was noted to the nearest millimeter, thus ensuring the correct placement of NIRS sensor on each subject for all the testing sessions.

As per the manufacturer's specifications, the sensor was calibrated at 760 nm and 850 nm wavelengths before each session. The source-to-detector separation that also determines the vertical penetration depth of light was set to 4 cm. The difference in absorbency between these two wavelengths indicated the change in oxygen saturation and the sum of these absorbencies indicated the change in total blood volume. Both oxygenation and blood volume were measured in terms of optical density (OD), defined as the logarithmic ratio of the intensity of light calibrated at each wavelength to the intensity of measured light at the same wavelength (MicroRunman User Manual, NIM Inc., PA, USA, 1999). Real time data were recorded using the NIRCOM software provided by the manufacturer.

NIRS Data Analysis

All the real time NIRS values were averaged every 20 seconds using a customized Microsoft Excel software program specially designed for this study. Baseline values were recorded during initial 2 minutes rest. Minimum oxygenation and blood volume values for each subject were recorded during cuff ischemia. Maximum values were recorded during recovery from cuff ischemia. Further, minimum oxygenation values for each subject were recorded during both incremental protocols. Minimum blood volume values were recorded at the baseline [last 20 seconds] prior to the beginning of each exercise mode. Maximum oxygenation and blood volume were recorded during the recovery from exercise.

The range in oxygenation and blood volume responses for all the three protocols were calculated as the difference between the minimum and the maximum OD values. For each incremental protocol, muscle oxygenation and blood volume were calculated at 20, 40, 60 and 80% of the peak oxygen uptake obtained for that specific test. The oxygenation values obtained at these percentages were expressed as a percentage of the oxygenation range observed during each incremental session and recovery. The equation developed by Belardinelli et al. (1995) was used for this purpose:

Percent change in the biceps muscle oxygenation = $[(y-M) \div (m-M)] \times 100$

where 'y': is the OD value corresponding to the time interval at which the specific percentage of peak oxygen uptake was obtained; 'M' was the minimum OD observed during the incremental test; and 'm' was the maximum OD obtained during recovery from incremental work (Figure 1.4).

Statistical Analysis

Independent 't' tests were used to compare the physical characteristics of the men and women (Table 5.1). A two-way analysis of variance (ANOVA) with gender as a between-subjects factor, and mode (arm cranking and pushing-pulling) as a repeated measures factor was used to evaluate the differences in the peak biomechanical, cardiorespiratory, and perceptual responses. Also, a two-way ANOVA, with gender as a between-subjects factor, and protocol (arm cranking; pushing-pulling; and cuff ischemia) as a repeated factor was used to compare oxygenation and blood volume responses. To minimize the violation of the assumption of homogeneity of variance, the 'Greenhouse-Geiser' adjustment was used. Since multiple comparisons were made for each dependent variable in the present study, the Bonferroni adjustment for a P value of 0.05 was applied to minimize Type 1 error. The Bonferroni adjustment was calculated as the ratio of 0.05 and number of statistical comparisons (APPENDIX B.4). Thus, statistical significance was considered at $P < 0.01$. Significant F ratios were further analyzed with the Scheffe post hoc multiple comparison test.

Regression analysis was used to examine the relationship of whole-body oxygen uptake and percent change in biceps brachii oxygenation responses at equal percentages of peak oxygen uptake between the two exercise modes for both genders. A Spearman correlation test was used to examine the relationship between logarithmic value of adipose tissue thickness and [minimum and maximum] oxygenation and blood volume responses for the three protocols. Since the adipose tissue thickness of the subjects in the present study was normally distributed, a nonlinear correlation test was used to examine its role on the NIRS measurements. The Statistical Package for Social Sciences SPSS (version 10) was used for all statistical analyses (SPSS Inc., Chicago, USA).

RESULTS

Peak Biomechanical, Physiological, and Perceptual Responses

Comparison between Incremental Exercise Modes:

The peak biomechanical, physiological, and perceptual responses during incremental arm cranking and pushing-pulling in the men and women are reported in Table 5.2. In general, most of the peak physiological responses were significantly higher during arm cranking compared to pushing-pulling in both men and women. A significant interaction between exercise mode and gender was obtained only for power output (Watts) implying power output during arm cranking was significantly higher (by 79%) than pushing-pulling, with men demonstrating significantly greater power output (30%) during both exercise modes ($P<0.01$). Absolute oxygen uptake ($L.min^{-1}$) during arm cranking was 24% greater than that attained during pushing-pulling ($P<0.01$). When oxygen uptake values were corrected for subjects' body weight, the relative oxygen uptake ($mL.min^{-1}.Kg^{-1}$) during arm cranking was 22% greater than pushing-pulling ($P<0.01$). The lower power output generated during pushing-pulling resulted in significantly greater ratios for the absolute peak oxygen uptake to the power output (by 72%); and relative peak oxygen uptake to the power output (by 74%), when compared to arm cranking ($P<0.01$).

Heart rate ($beats.min^{-1}$) during pushing-pulling was 91% of arm cranking but was not significantly different ($P>0.05$). Oxygen pulse, calculated as the ratio of oxygen uptake and heart rate ($mL.beat^{-1}$) was approximately 22% higher during arm cranking compared to pushing-pulling ($P<0.01$). Further, ventilation rate ($L.min^{-1}$) and respiratory frequency ($breaths.min^{-1}$) were approximately 22% and 17% greater during arm cranking compared to pushing-pulling ($P<0.01$). However, tidal volume ($L.breath^{-1}$), a ratio of ventilation rate and respiratory frequency ($breaths.min^{-1}$), did not demonstrate any significant difference between the exercise modes ($P>0.05$). Ventilatory equivalent for oxygen did not demonstrate significant difference between these exercise modes ($P>0.05$). Respiratory exchange ratio, a measure indicating the ratio of carbon dioxide produced to oxygen consumed, was significantly greater by 5% during arm cranking (P<0.05). Unlike the physiological measures that showed greater responses during arm cranking, the rating of perceived exertion was significantly higher during pushing-pulling (P<0.05).

Comparison between Genders

The peak absolute oxygen consumption during pushing-pulling was approximately 74% (in men) and 79% (in women) of the respective values attained during arm cranking (P<0.01). Gender did not influence the oxygen consumption responses when it was corrected for body weight (P>0.05). Similarly, ratios of absolute and relative oxygen uptake to power output were not significantly different between genders (P>0.05). Peak heart rate did not demonstrate any significant difference between men and women during both modes of exercise (P>0.05). However, oxygen pulse was significantly higher [pushing-pulling - 30%, arm cranking - 45%] in men compared to women (P<0.01). Ventilation rate was significantly higher in men (37%) than in women due to a significantly greater (37%) tidal volume (P<0.01). However, no gender differences were observed for the respiratory frequency, ventilatory equivalent for oxygen, respiratory exchange ratio, and rating of perceived exertion (P>0.05).

Biceps Brachii Oxygenation and Blood Volume Trends

The oxygenation and blood volume trends during cuff ischemia and both incremental exercise modes in a typical male and female subject are shown in Figures 5.6 and 5.7, respectively.

Cuff Ischemia

During the cuff ischemia protocol, both oxygenation and blood volume decreased continuously with time. Further, these trends reached a full desaturation at the end of four to five minutes, suggesting a complete occlusion of blood flow to this muscle. During recovery both these variables increased very rapidly and exceeded their resting baseline values indicating a supersaturation in the biceps.

Incremental Arm Cranking

At the onset of the two-minute warm-up period, there was an immediate increase in oxygenation for a brief period in half-of the subjects followed by a systematic decrease in oxygenation. However, the rest of the subjects demonstrated a decrease in oxygenation at the onset of exercise. As the workload increased, oxygenation rapidly decreased (in all the subjects) and demonstrated a leveling off at approximately 80% of their work intensity (in most of the subjects). The blood volume trends showed a systematic increase with work rate with a leveling off as the peak oxygen uptake was attained.

During the recovery period from arm cranking, oxygenation and blood volume increased rapidly and showed three distinct patterns. In majority of the subjects, both oxygenation and blood volume trends increased beyond the baseline demonstrating hyperaemia for a brief period. By the end of the recovery period, only few subjects approached the baseline values for both oxygenation and blood volume values, and some did not reach the baseline.

Incremental Pushing-Pulling

During the warm-up phase of pushing-pulling, the oxygenation and blood volume trends were similar to those observed during arm cranking. However, in majority of the male subjects, unlike the oxygenation trends during arm cranking, the oxygenation trends decreased very rapidly with increasing workload. Only a few subjects demonstrated a leveling off pattern that was observed in the arm cranking protocol. However, at their maximum workload, there was a greater decrease in oxygenation than that observed in arm cranking. Blood volume trends increased significantly with increasing workload, with leveling off at the maximal workload. During the recovery from pushing-pulling, oxygenation and blood volume values increased rapidly and showed the three distinct trends observed during arm cranking.

Comparison of Biceps Brachii Oxygenation and Blood Volume Responses

Comparisons among Cuff Ischemia and Incremental Exercise Modes

No significant interaction between the three exercise protocols and gender was observed for the oxygenation and blood volume responses. It should be noted that comparison of the main effects was based on the pooled values of the remaining independent variable in the experimental design. Highest mean deoxygenation values were obtained during cuff ischemia (Table 5.3), however, they were significantly greater (by 62%) compared to the arm cranking protocol only ($P<0.05$). Interestingly, pushing-pulling demonstrated 42% more deoxygenation in the biceps than during arm cranking ($P<0.01$). Post-exercise mean reoxygenation values from arm cranking were the highest, but not significantly different from the other protocols ($P>0.05$). Further, maximal oxygenation obtained after arm cranking was greater (by 62%) than that obtained after pushing-pulling ($P<0.05$).

Based on the percent of cuff ischemia values (Table 5.3), significant differences between pushing-pulling and arm cranking were observed for minimum and maximum oxygenation values ($P<0.05$). Minimum oxygenation for arm cranking and pushing-pulling were 36% and 78% of that obtained during cuff ishemia, respectively. Further, maximum oxygenation during arm cranking and pushing-pulling were 183% and 86% of that obtained during cuff ischemia, respectively.

In the blood volume comparisons for both men and women, cuff ischemia showed the greatest minimum blood volume response, and was significantly greater than both arm cranking (by 74%) and pushing-pulling (by 88%) ($P<0.05$). However, the minimum blood volume values obtained at rest between the incremental protocols were similar. The maximum blood volume responses obtained after incremental exercise were highest during arm cranking, and were 44% greater than pushing-pulling ($P<0.05$), and 55% greater than cuff ischemia ($P<0.05$). When compared to arm cranking, deoxygenation cost, calculated as the ratio of minimum oxygenation and absolute oxygen uptake (OD. L^{-1} min^{-1}) ,was significantly higher (by 34%) during pushing-pulling ($P<0.05$). Also, correlations of NIRS measurements (Table 5.4) among the three protocols were not significant ($P>0.05$).

Comparison between Genders

Men showed higher deoxygenation values than women during the three protocols but none of the values were significantly different ($P>0.05$) (Table 5.3). All other responses were also not significantly different between genders ($P>0.05$). Further, gender did not influence the oxygenation and blood volume responses when expressed as a percentage of cuff ischemia ($P>0.05$). Deoxygenation ratio was also similar between genders ($P>0.05$).

Relationship between Whole-body Oxygen Uptake and Percent Change in Oxygenation

Based on the regression analysis and R^2 values, the relationship between absolute oxygen uptake and percent change in biceps brachii oxygenation at different percentages of peak aerobic capacity was best described by a linear trend. The regression analysis shown in the Figure 5.8, demonstrated that there were significant inverse relationships between percent change in biceps brachii oxygenation and percent of peak oxygen uptake during each exercise mode in both genders. In men, the R^2 values were 0.95 and 0.99 during pushing-pulling and arm cranking, respectively. In women, the R^2 values were 0.91 and 0.98 during pushing-pulling and arm cranking, respectively. ANOVA showed that there was no significant interaction between exercise mode and gender for these percent change in biceps brachii oxygenation values, suggesting that the rate of decline in biceps oxygenation for a given change in absolute oxygen uptake was similar between men and women during both pushing-pulling and arm cranking.

Correlations between Skinfold and Oxygenation and Blood Volume

Adipose tissue thickness calculated from biceps skinfolds for men and women (mean ± SD) were: 2.8 ± 1.5 mm and 4.0 ± 1.8 mm, respectively. They were not significantly different from each other ($P>0.05$). Spearman correlations between adipose tissue thickness and mean changes in oxygenation and blood volume data for both men and women during the three protocols are shown in Table 5.5. A significant correlation was found between adipose tissue thickness of men at the biceps and maximum oxygenation ($r=-0.61$, $P<0.05$) and maximum blood volume ($r=0.70$, $P<0.05$) during recovery from pushing-pulling. However, correlations were not significant ($P>0.05$) between adipose tissue thickness and other NIRS variables for both genders among the three protocols.

DISCUSSION

Comparison between Incremental Exercise Modes

Whole-body Physiological, Perceptual and Biomechanical Responses

The physiological responses observed in the present study during incremental arm cranking are comparable to those reported in previous investigations (Bar-Or and Zwiren 1975, Bhambhani et al. 1998, Davis et al. 1976, Price and Campbell 1997, Warren et al. 1990, Washburn and Seals 1984). Sawka (1986) in an extensive review, indicated that the physiological responses during upper body exercise were influenced by gender, populations studied, fitness levels, workload increments, type of exercise protocol, crank cadence, etc. In the current study, most of the physiological responses obtained during arm cranking were significantly greater than those observed during pushing-pulling, demonstrating that arm cranking is physiologically more strenuous on the upper body.

Some of the biomechanical factors that can account for these large physiological differences are: (1) pushing-pulling was performed in a different geometric plane compared to arm cranking; (2) to-and-fro horizontal motion was employed during pushing-pulling to generate maximum torque in the specified range of motion, whereas a circular motion away from the body was adopted during arm cranking; (3) length of the lever arm from the crankshaft and range of motion during both exercise modes were different; (4) differences in force exertion to generate the required power output - holding the pushing-pulling lever in the semi-supine position vs holding the arm crank handle in the prone position during arm cranking exercise; (5) asynchronous activity during arm cranking vs synchronous activity during pushing-pulling; and (6) biomechanical advantage of work performance in standing during pushing-pulling vs sitting during arm cranking.

In addition to the biomechanical differences between pushing-pulling and arm cranking explained above, one can argue that in the physiological responses differences might be due to the postural differences in the work performed during the two exercise modes. During arm cranking the position of the arms was closer to the level of the heart, whereas during pushing-pulling the arms were positioned on the lever below the heart level. The influence of arm position on the physiological responses during upper body work is controversial. Pendergast et al. (1979) demonstrated that the decrease in the peak oxygen uptake with the arms positioned above the heart level during exercise might be due to lower blood perfusion of the arm muscles. During occupational activities, Astrand et al. (1968) showed greater heart rate responses when subjects hammered nails into ceiling compared to across the wall (at the head level) or on the bench (closer to the waist level). However, Cummins and Gladden (1983) demonstrated no significant difference in physiological responses (oxygen uptake, heart rate, ventilation rate, cardiac output, stroke volume, and arterio-venous oxygen difference) during submaximal and maximal arm work with arms positioned above, at, and below the heart level.

Bhambhani et al. (1994) and Esmail et al. (1995) also showed no significant difference in physiological responses between pushing-pulling at the elbow height and repetitively pulling down an overhead attachment on the BTE work simulator. It is likely that the discrepancy amongst these studies might be due to the type of arm work investigated. Further, less isometric effort may be required in holding the crank handle during arm cranking compared to a much greater static and postural component during hammering above the overhead (Cummins and Gladden 1983). Based on these results, it is likely that arm position during upright exercise has a lower impact on the physiological responses compared to the amount of isometric work involved in the exercise.

Research pertaining to the physiological responses during arm cranking while standing is limited. Boucahrd et al. (1979) and Intranont (1983) reported that the peak oxygen uptake of men during arm cranking in the standing position was significantly lower than the values attained during upright and supine cycling, treadmill walking/running, bench stepping and lifting at various heights. In the current study, the peak oxygen uptake for men during incremental arm cranking in the seated position was less than that reported by Boucherd et al. (1979) and Intranont et al (1983). Based on these cross sectional observations, one can argue that the peak oxygen uptake during arm cranking while standing is greater than that observed during arm cranking while sitting or pushing-pulling while standing.

In the current study, power output achieved during arm cranking was 79% greater than during pushing-pulling, with men generating 30% greater power output than women during both exercise modes. The biomechanical differences suggested above might have resulted in such a large difference in the power output between the exercise modes. When the results of the men and women were pooled, the peak oxygen uptake values during pushing-pulling were 32% lower compared to arm cranking. As a result, the oxygen cost per unit amount of power generated [ratio of absolute oxygen uptake and power output] was 72% higher ($P<0.01$) during pushing-pulling compared to arm cranking. In other words, pushing-pulling was metabolically less efficient than arm cranking.

The National Institute for Occupational Safety and Health (NIOSH 1981) proposed that in order to avoid undue fatigue, the time-weighted average oxygen uptake during an eight-hour work day should not exceed 33% of the individual's aerobic capacity obtained on a treadmill running test. Later, they modified the limit to 33% of repetitive lifting either below or above the waist (Waters et al. 1993). Based on this proposed limit and the data from Table 5.2, a healthy young male with an arm cranking peak oxygen uptake of 2.36 $l.min^{-1}$ should not exceed an average oxygen uptake of 0.78 $l.min^{-1}$ (33%) during task-specific pushing-pulling. However, based on peak oxygen uptake results obtained from pushing-pulling (1.74 $l.min^{-1}$), this limit equates to 44% of pushing-pulling, which exceeds the NIOSH standard by 11%. This difference may result in premature fatigue over an eight-hour work day and may increase the susceptibility to injury. A similar discrepancy in repetitive lifting and standardized aerobic protocols were also reported in previous investigations (Petrofsky and Lind 1978, Sharp et al. 1988).

Further, eight out of 22 subjects in the present study had similar peak oxygen uptake during arm cranking, however, their oxygen uptake values were different during identical pushing-pulling tasks. Sharp et al. (1988) suggested that factors such as skill-level, task-specific techniques, and physiological or morphological differences among individuals play an important role in work performance. Health care professionals such as ergonomists, exercise physiologists and occupational therapists who work in the area of Occupational Health and Safety should be aware of the limitations of using peak oxygen uptake values in setting limits for performance during an eight-hour work day.

Interestingly, in the current study, the rating of perceived exertion was the only variable that demonstrated significantly greater responses during pushing-pulling. Most of the subjects complained a much greater discomfort in the arms during pushing-pulling. However the present study did not investigate local rating of perceived exertion responses. According to the review of Sawka (1986): "perceptual sensitivity to process the physiological information may be enhanced during small muscle mass (upper body) exercise". In the current study, factors such as mode of grip during pushing-pulling, recruitment of muscles other than smaller muscles, and prolonged standing posture throughout the session might have resulted in greater perceptual responses during pushing-pulling. It should also be noted that the time to reach exhaustion by our subjects during maximal incremental pushing–pulling (13 to 18 minutes) was greater compared to maximal incremental arm cranking sessions (8 to 10 minutes). The longer duration of 'monotonous' work in the standing posture might have played a significant role in the greater rating of perceived exertion responses reported during pushing-pulling.

Biceps Brachii Oxygenation and Blood Volume Responses During Incremental Exercise

In differentiating the importance of exercise mode selection, Sawka et al. (1983) commented: "protocol selection may be particularly important for upper body exercise where peak oxygen uptake is probably limited by peripheral factors (i.e., local fatigue and muscle perfusion) rather than central circulatory factors". Pushing-pulling and arm cranking involve predominantly upper body work (OSHA Draft 1999, Sawka 1986). In order to evaluate the peripheral responses during arm cranking and pushing-pulling, NIRS was used to evaluate the oxygenation and blood volume trends during these two exercise modes.

From Table 5.1, it is evident that peak oxygen uptake values during arm cranking were greater compared to pushing-pulling. Also, the correlation coefficients of the peak oxygen uptake between the two exercise modes for all the subjects was significant ($r=0.67$, $P<0.05$). However, the correlation between these two modes for minimum oxygenation was not significant ($r=0.05$, $P>0.05$), suggesting that peripheral responses during these two exercise modes were not similar. In this study, cardiac output measurements were not undertaken to evaluate the central contribution. However, the results of biceps brachii deoxygenation suggested that there was a significant difference in the peripheral contribution between these two exercise modes. This further strengthens our argument that development of task-specific aerobic protocols are essential at the workplace.

At the onset of Exercise

In both exercise modes during the rest-to-exercise period for 2 min, majority of the subjects demonstrated a rapid increase in oxygenation and blood volume for at least 40 to 60 seconds. At the onset of exercise, the muscle pump is activated with the first contraction and relaxation phase, leading to an exponential increase (within 10 seconds of exercise) in the blood flow to the active muscles (Hughson et al. 1996). Few authors reported similar oxygenation trends during dynamic exercise (Belardinelli et al. 1995, Bhambhani et al. 2000, 1998). These authors suggested that such an increase in oxygenation might be due to an increase in blood flow to the active 'focal' region of the muscle, resulting in redistribution of intramuscular blood volume within the biceps. Furthermore, the role of increase in skin blood flow at the onset of exercise was also suggested for such an increase in oxygenation and blood volume trends (Maehara et al. 1997). However, Mancini et al. (1994) demonstrated that absorption range of NIRS signals were not influenced by the skin blood flow, and concluded that these signals essentially monitor the skeletal muscle and not skin oxygenation.

Few subjects demonstrated a decrease in oxygenation with a simultaneous increase in blood volume for a brief period at the onset of both exercise modes [and decrease in blood volume in three female subjects during arm cranking]. Bhambhani et al. (1998), Chance et al. (1992), and Jensen-Urstad et al. (1995) reported similar trends at the onset of exercise. To this effect, Bhambhani et al. (1998) hypothesized that zero and/or 25 Watts workload during an initial period of upper body exercise may be considerably high for few subjects to overcome, thus resulting in an increased deoxygenation. Accordingly, at the onset of submaximal arm cranking exercise, Jensen-Urstad et al. (1995) attributed a similar decrease in oxygenation to a transient imbalance between oxygen supply to the biceps brachii and oxygen uptake, thus resulting in higher anaerobic metabolism. Tamaki et al. (1994) suggested a similar hypothesis during the first contraction of repetitive biceps curls in body builders. These authors demonstrated a relative lack of oxygen supply (reflecting a decrease in oxygenation) and attributed this phenomenon to the unexpectedly high proportion of slow-twitch fibers in these athletes. Schmalbarch and Kaminecka (1974) showed that the biceps brachii is predominantly rich in slow twitch motor units.

It has been demonstrated that at the onset of exercise, cardiac output increases more rapidly than oxygen uptake (Davies et al. 1972, Yoshida and

Whipp 1994). Further, a rapid increase of muscle blood flow at the onset of exercise has also been reported (Bangsbo 2000, Walloe and Wesche 1988). To this effect, Hughson et al. (1996) demonstrated that oxygen uptake in the muscle depends on the supply of oxygen (aided by increase in blood flow) at the onset of exercise. These authors also showed that the increase in forearm blood flow kinetics was much slower during rhythmic squeezing of a lever above the heart level compared to the responses observed below the heart level.

However, similar to the findings of other authors (Boushel et al. 1998, Chance et al. 1992, Grassi et al. 1999, Tamaki et al. 1994), few subjects in the current study showed a decrease in blood volume at the onset of exercise as well. Chance et al. (1992) attributed such a decrease in blood volume at no load cycling to redistribution of blood in the lower limb. Further, during biceps curls Tamaki et al. (1994) reported that "venous blood in the muscle was squeezed out by the muscle milking action and venous return was enhanced after the first contraction, thus temporarily decreasing the muscle blood volume". Moreover, Boushel et al. (1998) attributed reduction in blood volume during the rest-to-exercise transition to the muscle pump directing blood to the heart.

During the Incremental Effort

As the workload increased during arm cranking, biceps muscle oxygenation started decreasing steadily as indicated in Figures 1A and 2A. This trend is consistent with that reported by Bhambhani et al. (1998) in healthy men and women. Such a systematic decrease in oxygenation with increase in work intensity during both exercise modes implies a greater release of oxygen by hemoglobin/myoglobin via the Bohr effect (Belardinelli et al. 1995, Chance et al. 1992). However, the myoglobin dissociation curve does not exhibit the Bohr effect, hence its overall role in determining muscle deoxygenation is relatively minor (Mancini et al. 1994). To this effect, Stringer et al. (1994) and Wasserman et al. (1991) suggested that metabolic acidosis during exercise was essential for skeletal muscle deoxygenation to take place. In other words, the presence of hydrogen ions associated with lactate accumulation was necessary for oxygen to be released from oxygenated hemoglobin in the skeletal muscle via the Bohr effect. Therefore, a steady decrease in the venous oxygen saturation in the muscle with increase in workload might suggest an increase in the oxygen demand exceeding the muscle saturation, thus resulting in an increase in deoxygenation (reflecting increased oxygen extraction from the biceps).

In theory, the degree of deoxygenation measured by NIRS is attributed to the amount of oxygen released by both oxyhemoglobin and oxymyoglobin (Mancini et al. 1994a). However, the current NIRS technique is unable to differentiate between the amount of deoxygenation that is attributed to hemoglobin and myoglobin because the absorbency signals of hemoglobin and myoglobin overlap in this region (Chance et al. 1992). During knee extension exercise, Richardson et al. (1995) demonstrated that myoglobin desaturation occurred rapidly and reached a maximal value at approximately 50% of maximal oxygen consumption. Recently, Tran et al. (1999) showed that the decline in oxygenation obtained with the NIRS signal in the gastrocnemius muscle closely matched myoglobin desaturation measured from the nuclear magnetic resonance spectra.

During maximal exercise, greater mean deoxygenation values were observed during pushing-pulling compared to arm cranking in both genders. This was despite the fact that the peak oxygen uptake was significantly lower during pushing-pulling. In fact, when the ratio between the minimum deoxygenation and peak oxygen uptake was calculated (herein refereed to as the deoxygenation cost), the values were significantly higher during pushing-pulling, implying a greater peripheral limitation during this exercise mode.

In the current study, a cuff ischemia protocol (Maikala and Bhambhani 1999) was used to establish vascular occlusion and obtain a fully reduced state (minimum) of the biceps oxygenation and blood volume values. When the minimum oxygenation values of the incremental exercise protocols were expressed relative to the cuff ischemia value, pushing-pulling values were significantly higher compared to arm cranking (78% vs 36%). Chance et al. (1992) reported that the application of cuff ischemia to the vastus laterlais muscle following maximal rowing exercise increased the maximum deoxygenation value by only 3%, implying the vastus lateralis muscle was nearly maximally deoxygenated at the point of exhaustion. The fact that the biceps brachii muscle was not maximally deoxygenated in comparison to cuff ischemia protocol during these two upper body exercise modes clearly indicate a peripheral limitation to performance during dynamic work in men and women. Interestingly, maximum oxygenation resulting from post-arm cranking was significantly higher than pushing-pulling but not with respect to cuff ischemia values.

During both exercise modes muscle blood volume increased systematically with increasing power output, with a leveling off as the peak oxygen uptake was attained. This trend suggests that during upper body exercise, muscle oxygen extraction is matched by the elevated blood flow, and therefore by an equivalent increase in the volume of arterialized blood (Boushel et al. 2000). This is in contrast with the observations of Grassi et al. (1999) who demonstrated that the blood volume in the vastus lateralis increased until approximately 60% to 65% of the maximal oxygen uptake during leg cycling, and remained constant until the peak oxygen uptake was attained.

It has been well established that peak oxygen uptake during leg exercise is limited by the rate of oxygen delivery to the active muscles, whereas during arm cranking it is limited by the reduced blood flow to the 'smaller' active muscle mass (Sawka 1986). However, a proportionate increase in blood volume with the increase in workload suggests that blood flow to biceps is greater during upper body exercise compared to legs during cycling exercise. To this effect, Sawka (1986) cited the observations of Clausen (1973) who found equal absolute muscle blood flow during both arm cranking and leg cycling at the same oxygen uptake. Sawka (1986) further stated that " ..since upper body exercise uses a smaller skeletal muscle mass (than lower body exercise), blood flow should be higher for a given muscle mass". The continual increase in muscle blood volume in the biceps during incremental pushing-pulling and arm cranking exercise is consistent with these observations. Similar to the maximal oxygenation values reported, higher maximum blood volume responses were also reported for arm cranking compared to pushing-pulling. These findings indicate that the oxygen requirements of the exercising muscle after the termination of the test may be influenced by the exercise mode selected, and also may be dependent on the biomechanical and postural variations between these exercise modes described earlier.

Comparison between Genders:

Peak Cardiorespiratry Responses

Men demonstrated significantly greater (30%) peak power output during both exercise modes. As s result, the peak absolute oxygen uptake was also significantly higher in men (29% during pushing-pulling and 33% during arm cranking). This gender difference was maintained when the peak oxygen uptake was corrected for body mass. These observations during arm cranking are consistent with those of previous investigations (Bhambhani et al. 1998, Falkel et al. 1986, Washburn and Seals 1984). However, when the metabolic efficiency (oxygen uptake/power output) was calculated, no significant gender differences were observed for either pushing-pulling or arm cranking. This is consistent with the findings of Esmail et al. (1995) who reported no significant gender differences during submaximal simulated work during pushing-pulling on the BTE. Overall, these observations suggest that any gender differences in muscle fatigue are not related to the metabolic efficiency of the tasks performed. In the current study, the men and women did not reach their age-predicted maximal heart rate. During pushing-pulling the peak heart rate was approximately 88% in women and 90% in men of age-predicted maximal heart rate, while during arm cranking the values were approximately 90% in women and 95% in men. These values are consistent with the average value of 93% reported by Sawka (1986) in his comprehensive review of studies pertaining to upper body exercise.

Since heart rate was not influenced by either gender or exercise mode, greater gender differences in oxygen pulse in men during each exercise mode were due to the influence of peak oxygen uptake responses only. Since the peak oxygen uptake is closely related to the cardiac output, the lower peak oxygen uptake in the women was most likely due to their lower cardiac output (Wells 1991). During both exercise modes, men demonstrated significantly greater (37%) ventilation rates compared to women, with arm cranking values being significantly higher (23%) compared to pushing-pulling. Similar gender differences during arm cranking were reported by other investigators (Bhambhani et al. 1998, Washburn and Seals 1984). However, no significant gender differences were observed for the ventilatory equivalent for oxygen which is an index of the economics of ventilation. These observations suggest that the ventilatory stress during upper body exercise is similar in both genders, and corroborates previous findings (Bhambhani et al. 1998; Falker et al. 1986).

Biceps Brachii Oxygenation and Blood Volume Responses

It has been well established that women have a smaller upper body muscle mass (Hettinger 1961, Ikai and Fukunga 1968, Miller et al. 1993, Sharp 1994), and have lower strength for upper body muscle groups (Laubach 1976, Miller et al. 1993). In the current study, men showed no significant differences in the oxygenation and blood volume responses compared to women during both cuff ischemia and the two incremental exercise modes. Further, the deoxygenation cost was also similar between men and women during both exercise modes, suggesting similar oxygen extraction capacity of the biceps muscle in both genders. Shephard et al. (1988) demonstrated that women have less muscle volume in the arms than men, and suggested that

> "female-to-male ratio of peak oxygen uptake tended to rise as the volume of active muscle was reduced".

Additionally, women have 10-14% less hemoglobin than men, resulting in a less oxygen carrying capacity (Wells 1991). However, it is not clear why gender did not influence oxygenation and blood volume responses in these two upper body exercise modes.

The relationship between percent change in oxygenation calculated from the Belardinelli equation (Belardinelli et al. 1995) and the absolute oxygen uptake at different percentages of peak aerobic power (20%, 40%, 60% and 80%) in both men and women are shown in the Figure 5.8. Significant inverse relationships were observed during the two exercise modes for both genders. The common variance between these two variables was high, ranging between 95% and 99% in men, and 91% and 98% in women, with values being slightly higher during arm cranking compared to pushing-pulling. No significant differences were observed between the slopes of these regression equations, suggesting that the rate of deoxygenation in the biceps muscle was similar in both sexes during two incremental exercise modes. Bhambhani et al. (1998) reported a similar finding during arm cranking exercise in men and women.

Role of Adipose Tissue Thickness on NIRS measurements

van Beekvelt et al. (2001) reported that adipose tissue metabolism is lower than muscle metabolism, hence muscle oxygenation determined using NIRS is underestimated. In the current study, there was no significant difference between men and women for the adipose tissue thickness at the biceps (Table 5.1). In the flexor digitorum super-ficialis muscle during rest and sustained isometric handgrip contractions, van Beekvelt et al. (2001) demonstrated a significant decrease in muscle oxygen consumption in both men and women with increase in the thickness of adipose tissue ($r=-0.70$, $P<0.05$). These investigators showed a significantly lower muscle oxygenation in women than in men during both rest and submaximal isometric contractions. In the current investigation, adipose tissue thickness in women was not significantly correlated to NIRS measurements [at a source-detector separation of 4 cm] during the three protocols (Table 5.4). However, a significant negative correlation was obtained in men for maximum oxygenation responses during recovery from pushing-pulling ($r=-0.61$, $P<0.05$). *This may suggest that at the same source-detector separation of 4 cm, the greater the thickness of adipose tissue the lower the oxygenation values obtained during recovery from the incremental pushing-pulling activity.* However, regression analysis between adipose tissue thickness and maximum oxygenation in men did not achieve statistical significance:

[=0.29-0.45*log(adipose tissue thickness), $r=-0.61$, $P=0.18$]

Further, this trend in men was not significant either after cuff ischemia or during recovery from arm cranking. These findings confirm that the correlations obtained in the current investigation occurred by chance.

In contrast to significant decrease in oxygenation with increase in adipose tissue thickness reported in van Beekvelt et al. (2001), the current investigation did not demonstrate a significant correlations with minimum oxygenation during three protocols. Additionally, van Beekvelt et al. (2001) found a significant but a weak correlation of 0.29 between forearm blood flow and adipose tissue thickness, suggesting an increase in blood flow with increase in the thickness of adipose tissue. This is in agreement with Coppack et al. (1990, 1999) who demonstrated a higher blood flow in adipose tissue compared with that in muscle. In the current investigation, a significant positive correlation ($r=0.70$, $P<0.05$) was also obtained between the adipose tissue thickness and maximal blood volume in men during recovery from pushing-pulling. This suggests that the greater the thickness of adipose tissue, the higher the blood volume (and blood flow during recovery). However, regression analysis between adipose tissue thickness and blood volume did not achieve statistical significance:

[=0.08+0.66* log(adipose tissue thickness), $r=0.70$, $P=0.07$]

Also, this trend in men was not evident during the other exercise modes. These findings further confirm that the correlations obtained in the current investigation occurred by chance. The influence of skin blood flow on the NIRS blood volume signal may arise as well. However, with a source-to-detector separation of 40-50 mm, Hampson and Piantadosi (1988) showed that NIRS measurements are not affected by skin blood flow, and attributed such findings to a small volume of skin relative to muscle between the NIRS optodes, and the low concentration of cyctochorme oxidase in skin. In the current investigation, the source to detector distance was set to 40 mm for each subject during the three protocols. Other authors also reported negligible influence of skin blood flow on NIRS signals (Mancini et al. 1994, Piantadosi et al. 1986).

A significant negative correlation for maximum oxygenation and positive correlation for maximum blood volume observed in the current investigation may be the result of chance alone. Women also participated in the current investigation, and if such a significant relationship truly exists for men, correlations should be reliable for women as well [especially when the adipose tissue thickness was similar between genders]. However, as evident from the Table 5.5, this was not the case in the current investigation. Furthermore, calculating common variance for the r value of −0.61 results in 37% common variance, suggesting that approximately one third of the variability in the maximum oxygenation during recovery from pushing-pulling can only be explained by variance in the adipose tissue thickness (or vice versa). Hence, the remaining 63% of the variance in maximum oxygenation during recovery from pushing-pulling might be influenced by other factors. Similarly, 49% of the variability in the maximum blood volume changes during recovery from pushing-pulling can be explained by variance in the adipose tissue thickness (or vice versa), and the remaining 51% of the variance might be attributed to prediction error.

It is well-established that a significant correlation between two variables does not imply causality (Cody and Smith 1987, Vincent 1999). Some of the data points in the Figures 5.9A and 5.9B are extreme, and that might have caused larger correlation coefficients as well. The discrepancy observed in the current investigation and the study of van Beekvelt et al. (2001) might be due to their larger sample size of 44 men and 34 women. Also, the exercise protocols used and quantification of NIRS signals were different between these two studies. Hence based on the current limited sample size (11 men and 11 women), the fact that adipose tissue thickness and maximum oxygenation and blood volume during recovery from pushing-pulling are related does not mean that a change in one is necessary to produce a corresponding change in other.

Further, Feng et al. (2001) showed that for an adipose thickness of 8 mm, the optimal source-detector distance was 45 mm. These authors have also identified the optimal distance of 35-40 mm for an adipose tissue thickness range of 2.5-5 mm, and 50 mm for a thickness of 17 mm. However, irrespective of the differences in the subjects' variation in the skinfolds the current investigation used a fixed source-detector distance. This might have resulted in non-significant differences between men and women as well.

CONCLUSION

In evaluating a client's functional capacity, McConnell et al. (1984) suggested the maximal cardiorespiratory and hemodynamics responses are a function of exercise adopted, and do not represent the client's actual maximal consumption. These authors further stated that classification based on such a "not true" maximal aerobic capacity could result in assigning the clients' to either lower or higher fitness categories for the work demand. Sawka (1986) also stressed the importance of protocol selection for the upper body work, suggesting the peak aerobic capacity during this type of activity is limited by peripheral factors rather than the central circulatory factors. In the present study, in both men and women the task-specific pushing-pulling cardiorespiratory responses were lower than a standardized arm cranking test results. Such a current finding is similar to the pervious investigations (Khalil et al. 1985, Nindl et al. 1998, Petrofsky and Lind 1978, Sharp et al. 1988) that have compared standardized exercise protocols with the task-specific ones. The current investigation also demonstrated that pushing-pulling is metabolically less efficient than arm cranking.

The most interesting finding of the present study is the greater peripheral limitation during pushing-pulling compared to the corresponding arm cranking exercise responses, indicating upper extremity muscles are influenced by the exercise mode. Further, the rate of perceived exertion was also greater during pushing-pulling compared to arm cranking. Biomechanical and postural differences such as sitting vs standing, postural stability, mode of grip, the range of motion, position of hands below and above the heart level, and the forces being applied by the upper extremities are some of the reasons that can be attributed to the physiological differences between these two exercise modes. Also, adipose tissue thickness did not influence NIRS measurements.

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Table 5.1: Demographics of subjects (Mean ± SD)

Gender	Age	Body Mass	Height	Body Mass Index	Biceps Skinfold Thickness	PUSH-PULL HEIGHT
	Yrs	Kgs	m	$Kg.m^{-2}$	mm	cm
Men N=11	23.7 ± 4.5	77.5 ± 13.8 [a]	1.76 ± 0.08 [a]	24.6 ± 3.3 [a]	5.6 ± 3.0	119 ± 7 [a]
Women N=11	24.5 ± 4.0	57.6 ± 9.4	1.63 ± 0.06	21.4 ± 2.4	8.0 ± 3.6	111 ± 6

[a] – significant difference between men and women, $p<0.05$

Table 5.2: Peak Physiological, Perceptual and Biomechanical Responses during Incremental Pushing-Pulling and Incremental Arm Cranking in Healthy Men and Women (Mean ± SD)

VARIABLE	GENDER	ACTIVITY	
		PUSH-PULL	ARM CRANKING
Power output (W)	Men	32 ± 8[acd]	161 ± 32[c]
	Women	25 ± 8[a]	114 ± 20
Oxygen Uptake, $L.min^{-1}$	Men	1.74 ± 0.51[ac]	2.36 ± 0.51[c]
	Women	1.23 ± 0.32[a]	1.56 ± 0.50
Oxygen Uptake, $mL.Kg^{-1}.min^{-1}$	Men	22.7 ± 6.1[a]	30.3 ± 3.8
	Women	20.9 ± 6.4[a]	27.3 ± 8.5
Oxygen Uptake/Peak Power, ($mL.min^{-1}.Watt^{-1}$)	Men	55.2 ± 11.0[a]	14.8 ± 3.3
	Women	52.3 ± 12.0[a]	14.2 ± 4.6
Oxygen Uptake/Peak Power, ($mL.Kg^{-1}.min^{-1}.Watt^{-1}$)	Men	0.76 ± 0.32[a]	0.19 ± 0.04
	Women	0.84 ± 0.25[a]	0.25 ± 0.08
Heart Rate, $beats.min^{-1}$	Men	174 ± 16	182 ± 15
	Women	171 ± 14	176 ± 16
Oxygen Pulse, $mL.beat^{-1}$	Men	10.11 ± 3.1[ac]	13.12 ± 3.1[c]
	Women	7.10 ± 1.7[a]	8.9 ± 3.0
Ventilation Rate, $L.min^{-1}$ (BTPS)	Men	90.9 ± 28.0[ac]	124.6 ± 31.6[c]
	Women	62.4 ± 21.3[a]	73.6 ± 19.3
Ventilatory Equivalent for Oxygen	Men	54.2 ± 14.3	53.8 ± 10.7
	Women	51.3 ± 13.6	49.2 ± 14.0
Tidal Volume, $L.breath^{-1}$	Men	1.9 ± 0.4[c]	2.1 ± 0.6[c]
	Women	1.2 ± 0.3	1.3 ± 0.3
Respiratory Frequency $breaths.min^{-1}$	Men	48 ± 13[b]	58 ± 6
	Women	49 ± 11[b]	57 ± 14
Respiratory Exchange Ratio	Men	1.07 ± 0.07[b]	1.15 ± 0.04
	Women	1.05 ± 0.08[b]	1.10 ± 0.07
Rating of Perceived Exertion	Men	18.8 ± 1.0[b]	18.2 ± 1.5
	Women	18.7 ± 1.2[b]	17.5 ± 1.6

[a] – significant difference between arm cranking and pushing-pulling ($p < 0.01$)
[b] – significant difference between arm cranking and pushing-pulling ($p < 0.05$)
[c] – significant difference between men and women ($p < 0.01$)
[d] – significant interaction between gender and exercise [arm cranking and pushing-pulling] ($p < 0.05$)

Table 5.3: Biceps Brachii Oxygenation and Blood Volume responses during Incremental Pushing-Pulling and Incremental Arm Cranking in Healthy Men and Women in Optical Density (Mean ± SD)

GENDER	TASK	Oxygenation			Blood Volume		
		Min	Max	RangeΨ	Min	Max	RangeΨ
Men	Push-Pull	-0.212 ± 0.170 [c]	0.115 ± 0.221 [c]	0.330 ± 0.300 [d]	-0.005 ± 0.290 [b]	0.339 ± 0.249 [c]	0.340 ± 0.240 [bc]
	Arm Cranking	-0.121 ± 0.181 [a]	0.235 ± 0.251	0.356 ± 0.145 [d]	0.112 ± 0.344 [a]	0.678 ± 0.221 [a]	0.566 ± 0.382
	Cuff Ischemia	-0.270 ± 0.172	0.168 ± 0.214	0.438 ± 0.262 [d]	-0.317 ± 0.223	0.314 ± 0.086	0.631 ± 0.203
	Push-Pull - %of Cuff Ischemia	78 ± 98 [c]	50 ± 64 [c]	75 ± 114	2 ± 130	107 ± 290 [c]	60 ± 118 [c]
	Arm Cranking - %of Cuff Ischemia	45 ± 105	140 ± 117	81 ± 55	35 ± 154	215 ± 256	89 ± 188
	Deoxygenation Cost[e] [Push-Pull], $OD.L^{-1}.min^{-1}$	-12 ± 33 [c]					
	Deoxygenation Cost[e] [Arm Cranking], $OD.L^{-1}.min^{-1}$	-5 ± 36					
Women	Push-Pull	-0.150 ± 0.132 [c]	0.075 ± 0.080 [c]	0.220 ± 0.140	0.061 ± 0.126 [b]	0.335 ± 0.229 [c]	0.270 ± 0.160 [bc]
	Arm Cranking	-0.050 ± 0.100 [a]	0.205 ± 0.127	0.255 ± 0.103	0.047 ± 0.161 [a]	0.523 ± 0.231 [a]	0.476 ± 0.236
	Cuff Ischemia	-0.193 ± 0.173	0.090 ± 0.038	0.284 ± 0.175	-0.274 ± 0.173	0.232 ± 0.104	0.506 ± 0.249
	Push-Pull - %of Cuff Ischemia	78 ± 76 [c]	104 ± 129 [c]	78 ± 80	22 ± 73	144 ± 220 [c]	58 ± 64 [c]
	Arm Cranking - %of Cuff Ischemia	26 ± 58	227 ± 334	90 ± 60	17 ± 93	225 ± 222	94 ± 94
	Deoxygenation Cost[e] [Push-Pull], $OD.L^{-1}.min^{-1}$	-12 ± 41 [c]					
	Deoxygenation Cost[e] [Arm Cranking], $OD.L^{-1}.min^{-1}$	-3 ± 20					

RangeΨ is defined as the difference between Maximum Optical Density (Max) and Minimum Optical Density (Min). [a] – significant difference between arm cranking and cuff ischemia ($p < 0.05$); [b] – significant difference between pushing-pulling and cuff ischemia ($p < 0.05$); [c] – significant difference between arm cranking and pushing-pulling ($p < 0.05$): [d] – significant difference between men and women ($p < 0.01$) [e] - Deoxygenation Cost is defined as the ratio of muscle deoxygenation and whole-body oxygen uptake during specific incremental exercise.

Table 5.4: Correlations of Biceps Brachii Oxygenation and Blood Volume Responses among Three Protocols (n=22)

Variable	Protocols		
Oxygenation	Cuff Ischemia Vs Pushing-pulling	Cuff Ischemia Vs Arm Cranking	Pushing-pulling Vs Arm Cranking
Minimum	0.23	0.32	0.05
Maximum	0.23	-0.05	0.02
Range	0.18	0.23	-0.20
Blood Volume	Cuff Ischemia Vs Pushing-pulling	Cuff Ischemia Vs Arm Cranking	Pushing-pulling Vs Arm Cranking
Minimum	-0.28	0.41	0.12
Maximum	0.12	0.32	**0.45** [a]
Range	0.03	0.42	0.05

[a] – significant difference at P<0.05

Table 5.5: Spearman Correlation Coefficients between Adipose Tissue Thickness and Biceps Brachii Oxygenation and Blood Volume responses in Healthy Men and Women

GENDER	TASK	Oxygenation		Blood Volume	
		Min	Max	Min	Max
Men	Push-Pull	0.04	**-0.61** [a]	0.60	**0.70** [a]
	Arm Cranking	-0.10	-0.40	0.20	0.34
	Cuff Ischemia	-0.56	-0.21	-0.55	-0.25
Women	Push-Pull	0.01	-0.08	-0.19	-0.18
	Arm Cranking	0.08	-0.06	0.19	0.57
	Cuff Ischemia	-0.11	-0.18	0.45	-0.57

[a] – significant difference at $P<0.05$

Figure 5.1 BTE Work Simulator for Repetitive Pushing-Pulling

Figure 5.2 NIRS Sensor Placement on the Biceps Brachii

Figure 5.3A Subject Setup for Cuff Ischemia

Figure 5.3B Subject Setup for Arm Cranking

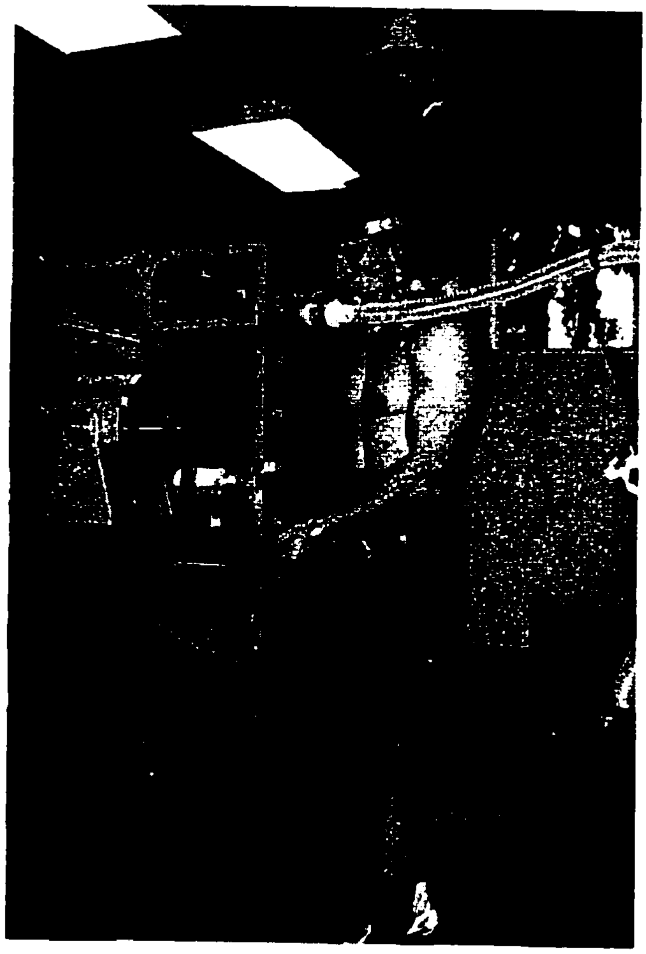


Figure 5.4 Subject Stance during Pushing-Pulling

Figure 5.5A Subject during Pulling Phase

Figure 5.5B Subject during Pushing Phase

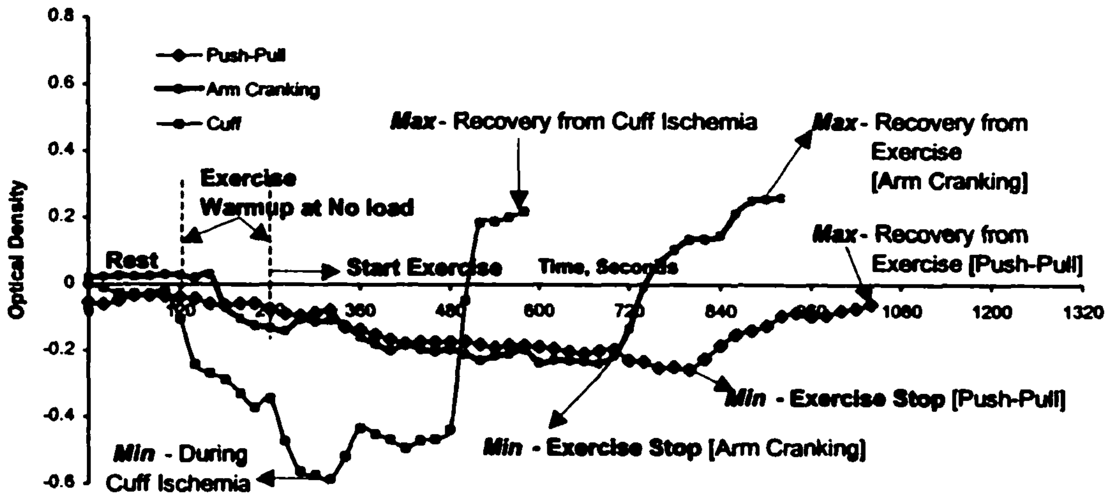


Figure 5.6A: Biceps Oxygenation Trends in a Typical Female

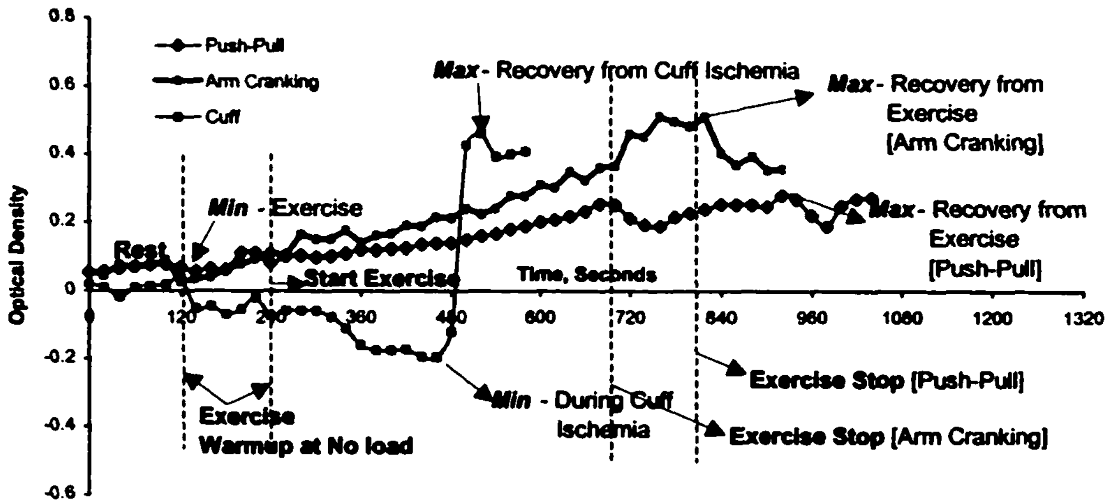


Figure 5.6B: Biceps Blood Volume Trends in a Typical Female

Min - Minimum Oxygenation [or Blood Volume] value obtained during specific Protocol
Max - Maximum Oxygenation [or Blood Volume] value obtained during recovery from specific Protocol

Biceps brachii oxygenation (top panel) and blood volume (bottom panel) trends in a typical female subject during cuff ischemia, arm cranking and pushing-pulling, and recovery

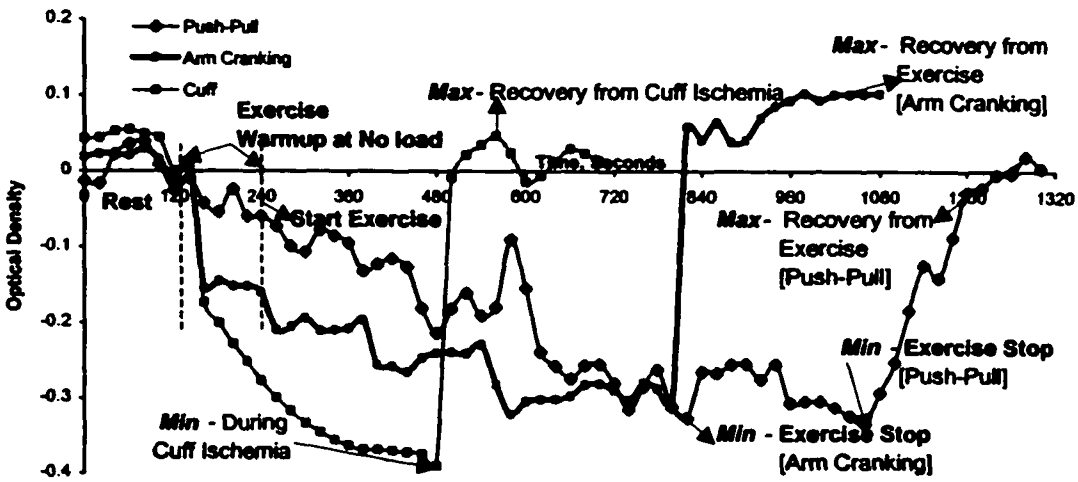


Figure 5.7A: Biceps Oxygenation Trends in a Typical Male

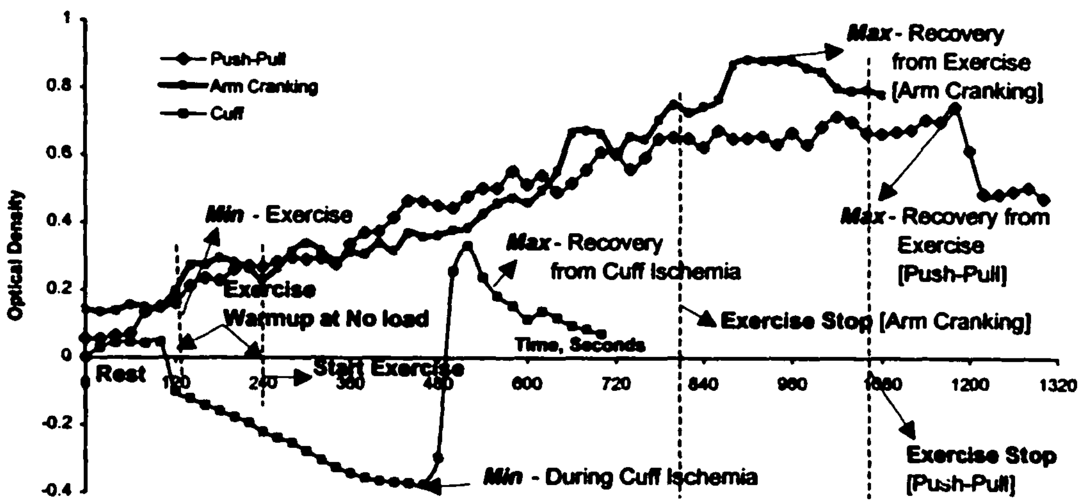
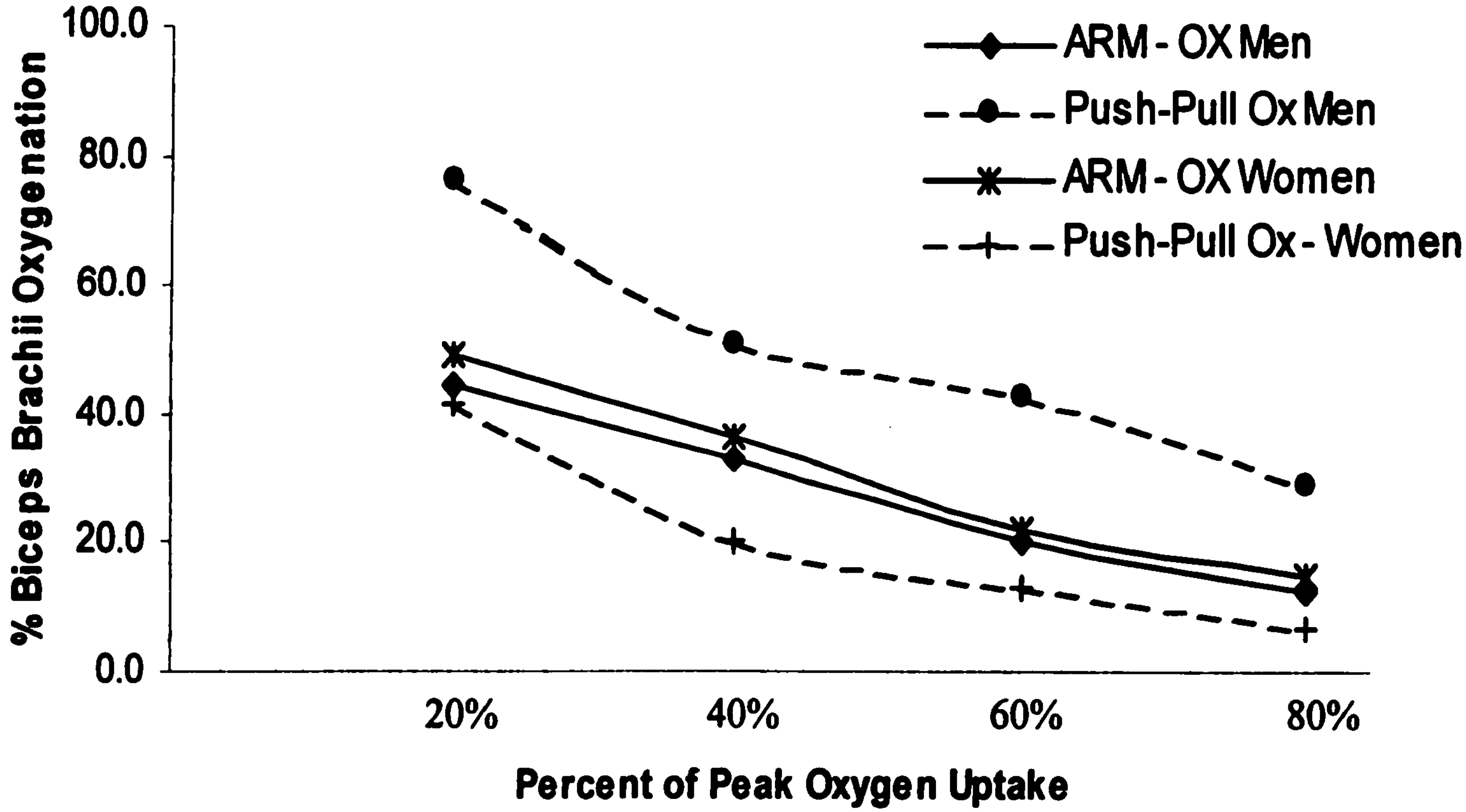


Figure 5.7B: Biceps Blood Volume Trends in a Typical Male

Min - Minimum Oxygenation [or Blood Volume] value obtained during specific Protocol
Max - Maximum Oxygenation [or Blood Volume] value obtained during recovery from specific Protocol

Biceps brachii oxygenation (top panel) and blood volume (bottom panel) trends in a typical male subject during cuff ischemia, arm cranking and pushing-pulling and recovery

Figure 5.8. Relationship between Muscle oxygenation and Oxygen uptake



REGRESSION EQUATIONS

% ARM-Ox Men = -22.79 VO_2 + 54.5, R^2=0.99, SE = 1.64, F=0.00

% Push-Pull Ox Men = -43.68 VO_2 + 87.6, R^2=0.95, SE = 5.45, F=0.026

% ARM-Ox Women = -37.5 VO_2 + 59.9, R^2=0.98, SE = 2.3, F=0.00

% Push-Pull Ox Women = -45.91 VO_2 + 49.04, R^2=0.91, SE = 5.53, F=0.046

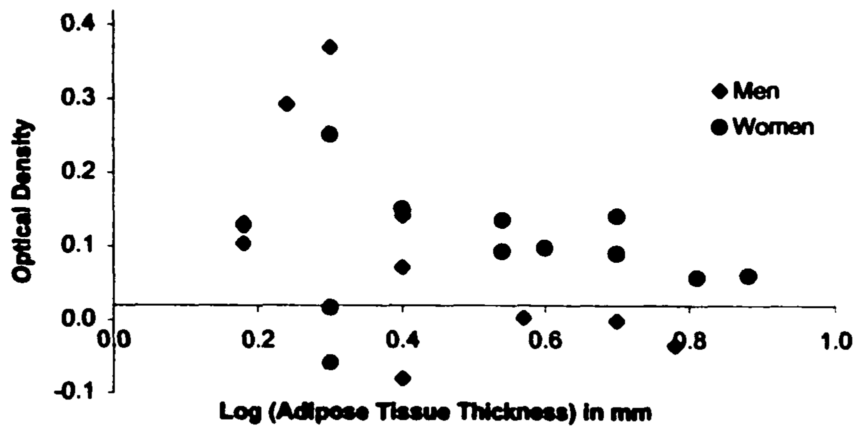


Figure 5.9A. Correlation between Adipose Tissue Thickness and Maximum Oxygenation during Recovery (Pushing-Pulling)

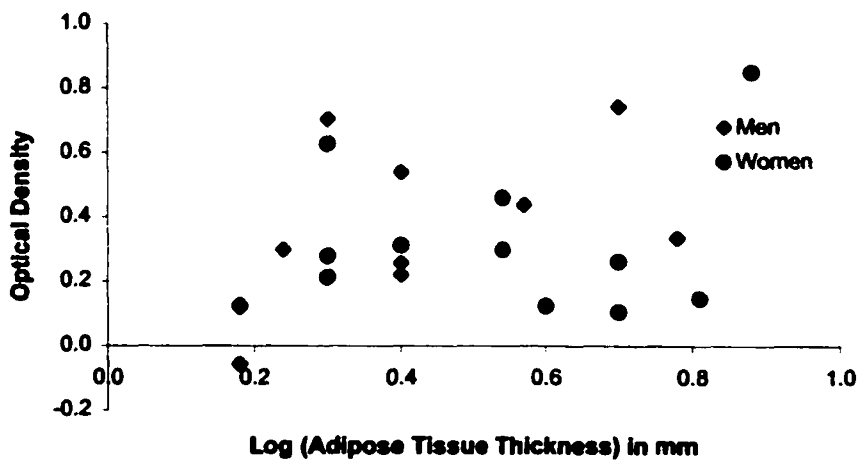


Figure 5.9B Correlaion between Adipose Tissue Thickness and Maximum Blood Volume during Recovery (Pushing-Pulling)

CHAPTER 6

Lumbar Erector Spinae Oxygenation and Blood Volume Comparisons during Arm Cranking and Task-specific Pushing-Pulling

Pushing and pulling is a manual material handling activity, and is defined as the application of one or two handed force directed away from the body [pushing] and directed towards the body [pulling] on an object or person, with feet either stationary (Chaffin et al. 1983, Gagnon et al. 1992, Garg et al. 1978) or moving (Lee et al. 1991, Snook and Ciriello 1991). Pushing and pulling of loads from the shelves (Gagnon et al. 1992), floor mopping or shovelling of snow (Franklin et al. 1995, Søgaard et al. 1996), and cart pushing and pulling (Snook and Ciriello 1991) are some of the activities that involve substantial amount of muscle activity in the trunk and upper extremities of workers (Bernard and Fine 1997).

The whole human body is involved in repetitive pushing and pulling of loads. In addition to the upper extremities, a significant amount of effort is required from the trunk musculature in stabilizing the body. Hence, it is important to understand the local physiological responses in the trunk muscles during pushing and pulling activities at the workplace. In a critical review by the National Institute for Occupational Safety and Health (NIOSH), Bernard and Fine (1997) reported the evidence for low-back related discomfort, pain, and injuries at the workplace during activities such as lifting, pushing and pulling, carrying, whole-body vibration, etc. In the province of Alberta, CANADA during 1995 and 1996, twenty nine-percent of total compensation claims were related to the lower back resulting mostly from overexertion injuries due to lifting, pushing and pulling (Alberta Labour 1997). Further, in a warehouse distribution study in the province of Quebec, CANADA, Lortie and Baril-Gingras (1998) reported pushing and pulling accounted for 69.9% and 46.4% of material handling, respectively.

Several studies have documented significant differences in aerobic power between standardized exercise and task-specific protocols (Khalil et al. 1985, Petrofsky and Lind 1978, Nindl et al. 1998, Sharp et al. 1988). However, to the best of our knowledge, comparison of local oxygenation and blood volume responses during maximal pushing and/or pulling to these standardized protocols has not been reported to date. Investigations related to gender responses during pushing and pulling are also very limited. Esmail et al. (1995) demonstrated that torque, work, and power output generated by men are significantly greater compared to women. However, when these values were corrected for their body mass, gender didn't influence the results. In another investigation, Ayoub and McDaniel (1974) reported that men had higher static push and pull horizontal forces in the sagittal plane compared to women.

Near infra-red spectroscopy (NIRS) is a non-invasive optical technique that has been used to measure relative changes in oxygenation and blood volume levels in skeletal muscle continuously in real-time during rest and work (Bellardinelli et al. 1995, Bhambhani et al. 1998a, Boushel et al. 1998, Chance et al. 1992, Mancini et al. 1994). Muscle oxygenation, defined as the relative saturation of oxyhemoglobin and oxymyoglobin, depends on the balance between oxygen delivery and tissue oxygen utilization (Mancini et al. 1994). Blood volume is defined as the sum of oxygenated and deoxygenated states of hemoglobin and myoglobin in the illuminated region of the muscle. Detailed description of the NIRS theory, its validation with various established optical and magnetic techniques are provided in Chapter 1. The reliability of NIRS in the upper and lower extremity human skeletal muscles has been reported in Chapter 1 as well. In establishing the reliability of NIRS in the erector spine muscle during maximal back extension, Maikala et al. (2000) reported significant correlation coefficients of 0.83 and 0.84 for minimum oxygenation during sitting and standing respectively, and 0.99 for the minimum blood volume during both postures. To date, erector spinae oxygenation and blood volume changes using NIRS have been limited to sub-maximal and maximal isometric contractions (Jensen et al. 1999, McGill et al. 2000, Maikala et al. 2000, Maikala and Bhambhani 1999, Maronitis et al. 2000, Yoshitake et al. 2001).

To the best of our knowledge, no studies to date have evaluated the oxygenation and blood volume trends of lumbar erector spinae muscle during repetitive pushing and pulling, and compared these responses with a standardized incremental arm cranking protocol. Hence, the purposes of this study were to compare the: (1) lumbar erector spinae oxygenation and blood volume differences during incremental pushing-pulling (with feet stationery) and incremental arm cranking till volitional exhaustion; and (2) differences in these responses between genders. It was hypothesized that: (1) the lumbar erector spinae oxygenation and blood volume trends would be similar between the two modes of exercise, and (2) there would be no significant gender differences in these responses.

MATERIALS AND METHODS

Subjects

Written informed consent was obtained from 11 healthy men (age 23.7 ± 4.5 yrs, mass 77.5 ± 13.8 kg, height 176 ± 8 cm) and 11 healthy women (age 24.5 ± 3.5 yrs, mass 57.6 ± 9.4 kg, height 163 ± 7 cm). They all completed the Revised Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology, 1994) to identify contraindications for exercise. The test protocols utilized were approved by the Human Research Ethics Board at this institution (APPENDIX A.2).

Description of the Baltimore Therapeutic Equipment (BTE) Work Simulator:

The BTE work simulator (Baltimore Therapeutic Equipment Co., Maryland, USA) is a multi-purpose instrument that can be used for assessing upper-extremity strength and endurance during functional tasks (Figure 5.1). This simulator consists of three components: a) exercise head; b) task-specific attachments; and c) computer software to convert the mechanical resistance to respective functional units. For pushing-pulling without feet moving, attachment # 171 is used. This attachment is a lever consisting of a straight handle with an articulating joint that result in linear motion when connected to the exercise head. Mechanical resistance in the linear motion can be controlled manually in both push and pull directions. Force output from the head is measured using an in-built strain gauge. The torque generated is calculated from the force output and the distance traveled by the lever, and displayed on the console. Before each testing session, the BTE was balanced in such a way that the strain gauge in the exercise head was synchronized with the electronic components in the control console (Powell et al. 1991), and calibrated as per the manufacturer's instructions (BTE Operator's Manual, 1992). Greater details of the BTE and its reliability in measuring various isometric and isokinetic activities were reported in Chapter 5.

Test Protocols

Each subject completed a back muscle endurance test on the first day, and incremental arm cranking exercise test and pushing-pulling test on two separate days in a random order.

(1) Back Muscle Endurance Measurements

For establishing the minimum and the maximum oxygenation and blood volume values for the lumbar erector spinae muscle of each subject, the Biering-Sørensen test for back muscle endurance was adapted (Biering-Sørensen 1984). The NIRS sensor was placed at the 3rd lumbar vertebra (Maikala et al. 2000) and a dark elastic bandage was wrapped around the lower back during standing posture (Figures 3.1A and 3.1B). The subject was then asked to lie prone on an adjustable plinth, with the anterior border of the iliac crest adjusted to the edge of a marker on the plinth (Figure 6.1A). One pillow was placed on the mid-thigh and another beneath the tibialis region with two elastic straps positioned at mid-thigh and mid-calf region (Ciriello and McGorry 2000). These straps were tightened so that the subjects' lower body was completely restrained at those positions (Figure 6.1B).

An adjustable rope with a weight attached at its edge was lowered to the position between the subject's scapula to serve as a reference point for the trunk alignment. Two minutes of NIRS data were collected for baseline measurements.

Just five seconds before the endurance test began, a countdown was started and the section of the plinth supporting only the upper body was lowered at the final countdown. The subject was instructed to place the arms across their chest throughout the endurance session and maintain contact with the reference point for as long as possible (Figure 6.2). When the subject was unable to maintain contact with this reference point the test was terminated, and the plinth support to the upper body was restored. Endurance time to the nearest second was recorded. Thereafter, the subjects were allowed to recover for four minutes in the prone position, at the end of which the session was terminated.

(2) Incremental Arm Cranking

For this session, the subject completed an incremental aerobic test on an arm cranking ergometer (Cybex, MET 300, USA). The axis of the ergometer crankshaft was adjusted to shoulder height of each seated subject. Position of the handle was adjusted in such a way that when the arms were fully extended, a slight flexion was present at the elbow joint. The legs and trunks were not restrained and their feet were flat on the ergometer base (Figure 5.3B). The test was initiated with a two-minute rest period. It was followed by two minutes of arm cranking at no load and subsequent increments of 25 Watts every 2 minutes at 50 crank rotations per minute (rpm) until voluntary exhaustion, or attainment of two or more of the end points suggested by the American College of Sports Medicine (1993): (1) leveling off in the oxygen consumption (increase of $\leq$ 100 $ml.min^{-1}$) with increasing load, (2) age predicted maximal heart rate, equated to 220-age (in years), (3) respiratory exchange ratio of $\geq$1.10, and (4) rate of perceived exertion (RPE) $\geq$ 18 (Borg, 1982). During the last 30 s at each workload, the overall RPE was recorded using the Borg scale. Protocol was terminated with 2 minutes of active [cranking at zero load] and 4 minutes of passive recovery.

(3) *Incremental Pushing-Pulling*

For this session, each subject completed an incremental aerobic test on the BTE work simulator. Before beginning the session the height of the push-pull lever #171 was adjusted to each subject's elbow crease in the standing upright posture (Figure 5.4). The right hand was used as the main grasping hand (adopting a power grip) in this two-handed effort. The elbows were unlocked and the subject was discouraged from trunk rotation, swaying the body, and moving the lower extremities during pushing-pulling. The subject was instructed to put the right leg (extended at the knee) backward at a comfortable distance, and the left leg forward with a slight knee flexion so that the toe was placed on a marker that was in line with the handle being pulled [similar to a posture adopted in Ayoub and McDaniel (1974)]. Further, the subject was not permitted to lift the heels off the floor, and a nonskid flooring was used for this testing session.

The test was initiated with a two-minute rest period and was followed by two minutes of repetitive pushing-pulling in the sagittal plane at no load in the horizontal direction (Figures 5.5A and 5.5B). The distance of pushing-pulling was restricted by a delimiter fixed on the circumference of the BTE work simulator wheel at a fixed distance of 10 cm. A cadence of 50 push-pulls per minute was used for this protocol. Thereafter, the resistance was increased by 30 in-lb every two minutes until voluntary exhaustion or attainment of two or more of the following end points suggested above by the American College of Sports Medicine (1993). Protocol was terminated with 2 minutes of active [cranking at zero load] and 4 minutes of passive recovery. Total force output in pounds and the power output in Watts for each subject were obtained from the printer attached to the BTE work simulator.

(4) Lumbar Erector Spinae Oxygenation and Blood Volume measurements

A continuous dual wave NIRS unit (MicroRunman, NIM Inc., PA, USA) was used to evaluate relative changes in the lumbar erector spinae oxygenation and blood volume during both arm cranking and pushing-pulling tests. This unit consists of: a superficial near infra-red sensor fitted with six light emitting tungsten lamps placed 2 cm, 3 cm, and 4 cm apart; two photo-diode detectors that absorb light in the near infrared range between 760 nm and 850 nm; and a display unit that amplifies and displays the absorbency signal (Figure 2.2). The sensor was placed on the right erector spinae muscle at the 3rd lumbar vertebra, approximately 3 cm from the midline of the spine (Maikala et al. 2000) [Figure 3.1A]. A piece of clear plastic was wrapped around the sensor to prevent sweat from distorting the absorbency signal. A dark elastic bandage was wrapped around the sensor to secure it in place and minimize any loss of light (Figure 3.1B). Muscle skin fold thickness at the sensor location was measured twice using a Lange skinfold caliper (Cambridge Scientific Industries, Inc. Maryland, USA) before placing the NIRS sensor on the muscle belly. The adipose tissue thickness (a sum of fat and skin layer) at the sensor site was calculated as half the skinfold thickness. Position of the NIRS sensor at the 3rd lumbar region from the mid line of the spine was noted to the nearest millimeter, thus ensuring the correct placement of NIRS sensor on each subject for all the testing sessions.

As per the manufacturer's specifications, the sensor was calibrated at 760 nm and 850 nm wavelengths before the test for each subject. The light source-detector separation was set to 4 cm. The difference in absorbency between these two wavelengths indicated the change in oxygenation and the sum of these absorbencies indicated the change in total blood volume. Both oxygenation and blood volume were measured in terms of optical density (OD) which is defined as the logarithmic ratio of intensity of light calibrated at each wavelength to the intensity of measured light at the same wavelength (MicroRunman User Manual, NIM Inc., PA, USA, 1999). Real time data were recorded using the NIRCOM software provided by the manufacturer.

NIRS Data Analysis

All the real time NIRS values were averaged every 20 seconds using a customized Microsoft Excel program specially designed for this study. Baseline values were recorded during the initial rest. Minimum oxygenation and blood volume values of muscle tissue for each subject were recorded during both incremental protocols and the Sørensen test. Maximum values were recorded during recovery from all these protocols as well. Furthermore, the range for oxygenation and blood volume responses for three protocols were calculated as the difference between the maximum and minimum values. Deoxygenation cost was calculated as the ratio of minimum oxygenation and peak oxygen uptake during each incremental exercise test.

Statistical Analysis

Independent 't' tests were used to compare the physical and performance characteristics of the men and women (Table 6.1A and 6.1B). A two-way analysis of variance (ANOVA), with gender as a between-subjects factor, and protocol (arm cranking; pushing-pulling; and the Sorensen test) as a repeated measure factor was used to compare the oxygenation and blood volume responses (measured in OD units). Also, a three-way ANOVA, with gender as a between-subjects factor, muscle (lumbar erector spinae and biceps brachii) and exercise mode (arm cranking and pushing-pulling) as repeated measure factors was used to compare the oxygenation and blood volume responses between these two muscles. To minimize the violation of the assumption of homogeneity of variance, the 'Greenhouse-Geiser' adjustment was used. Since multiple comparisons were made for each dependent variable in the present study, the Bonferroni adjustment for a P value of 0.05 was applied to minimize Type 1 error. The Bonferroni adjustment was calculated as the ratio of 0.05 and number of statistical comparisons (APPENDIX B.5). Thus, statistical significance was considered at $P < 0.01$. Significant F ratios were further analyzed with the Scheffe post hoc multiple comparison test.

Pearson product moment correlations were calculated to examine the relationship between minimum, maximum, and range of NIRS measurements among the three protocols. A Spearman correlation test was used to examine the relationship between logarithmic value of adipose tissue thickness and oxygenation and blood volume responses during three protocols. Since there was no normal distribution in the adipose tissue thickness of the subjects in the present study, a nonlinear Spearman correlation test was used to examine its role on the NIRS measurements. The Statistical Package for Social Sciences SPSS (version 10) was used for all statistical analyses (SPSS Inc., Chicago, USA).

RESULTS

Peak Lumbar Erector Spinae Oxygenation and Blood Volume Trends

The oxygenation and blood volume trends during both incremental exercise modes and the Sørensen test in a typical subject are shown in the Figures 6.3 and 6.4.

The Sørensen Test

At the onset of the test majority of the subjects demonstrated a decrease in both oxygenation and blood volume for at least 20 to 30 seconds, and only six subjects showed both increase in oxygenation and blood volume for a brief period of 15-20 seconds. However, during the reminder of the isometric test, majority of the subjects showed a steady decline followed by a leveling off in the deoxygenation at the end of contraction period of 60-90 seconds, suggesting a complete restriction of blood flow to the erector spinae muscle. During this contraction period, a rapid increase in blood volume was observed with increase in holding time.

From the onset to the end of the contraction period, two men and one woman demonstrated an increase in oxygenation and blood volume with increase in the duration of the endurance test. Further, only two subjects demonstrated decrease in blood volume with increase in contraction period. During recovery, oxygenation and blood volume reached baseline values within a minute in most of the subjects, with some of them demonstrating a supersaturation in both these variables.

Incremental Arm Cranking

In 70% of the subjects, there was an immediate increase in oxygenation for a brief period of 30-40 seconds during the warmup period followed by a decrease in oxygenation. However, the rest of the subjects demonstrated a decrease in oxygenation at the onset of exercise. As the workload increased, oxygenation followed two distinct trends. It increased during lighter loads in most of the subjects and leveled off as the workload increased. A rapid decrease in oxygenation resulted at the final workload. However, few subjects demonstrated a decrease in oxygenation and leveling off at the initial loads, followed by a steady decrease in oxygenation as the work intensity increased. In 40% of the subjects blood volume trends showed an increase at the onset of exercise, and others demonstrated a decrease in blood volume for a brief period. Blood volume trends in most of the subjects did not change at lighter loads, but leveled off with increase in workload. Only few subjects demonstrated increase in blood volume during submaximal work increments. At their maximal workloads, blood volume either leveled off or decreased farther than the previous stages.

During the recovery from arm cranking, oxygenation and blood volume values increased rapidly and showed three distinct patterns. In majority of the subjects, both oxygenation and blood volume trends increased beyond the baseline demonstrating hyperaemia for a brief period. This hyperaemic response was not evident in some subjects, while in others these trends did not recover to the baseline values.

Incremental Pushing-Pulling

At the onset of the warmup period, half of the subjects showed a rapid decrease and the other half demonstrated an increase in both oxygenation and blood volume trends for a period of 30-60 seconds. As the workload increased, half of the subjects demonstrated a steady and rapid decrease in oxygenation, reaching maximum deoxygenation at the final workload. However, 30% of the subjects showed an initial decrease in oxygenation for a brief period and leveled off during the initial loads, followed by a rapid decrease observed at the final workloads. The rest of the subjects showed an initial increase in oxygenation during lighter workloads, leveling off, and a rapid decrease at the final workload. In the majority of the subjects, blood volume trends leveled off at initial loads, followed by compromised blood flow with increase in workload. During the recovery from pushing-pulling, oxygenation and blood volume values increased rapidly and showed three distinct trends. In the majority of the subjects, both oxygenation and blood volume trends did not reach the baseline. However, some subjects reached the baseline values and few demonstrated hyperaemia.

Comparison among Incremental Exercise Modes and the Sørensen test

No significant interaction between the three exercise protocols and gender was observed in both oxygenation and blood volume responses. It should be noted that comparison of the main effects was based on the pooled values of the remaining independent variable in the experimental design. Minimum and maximum oxygenation values were not significantly different among the three protocols ($P>0.01$). However, the range for oxygenation during the Sørensen test was significantly lower by 35% and 42% compared to arm cranking and pushing-pulling, respectively ($P<0.01$) (Table 6.2). There was no significant difference in the range for oxygenation values between arm cranking and pushing-pulling ($P>0.01$). When NIRS measurements obtained during incremental exercise modes were expressed as the percent of maximal desaturation obtained during the Sørensen test values (Table 6.2), no significant differences between pushing-pulling and arm cranking were observed for minimum, maximum and range for oxygenation values ($P>0.01$). Additionally, no significant difference in deoxygenation cost was observed between pushing-pulling and arm cranking ($P>0.01$).

Minimum and maximum blood volume comparisons among the three protocols were also not significantly different ($P>0.01$). However, the range for blood volume values were the highest during arm cranking, with values being 72% greater than the Sørensen test ($P<0.01$). Additionally, the pushing-pulling values were significantly greater (by 65%) compared to the Sørensen test ($P<0.01$). However, there was no significant difference in the range for blood volume values between arm cranking and pushing-pulling ($P>0.01$). Based on the percent of the Sørensen test values (Table 6.2), no significant differences between pushing-pulling and arm cranking were observed for minimum, maximum and range for blood volume values ($P>0.01$).

Comparison between Genders

Gender did not influence either oxygenation or blood volume responses among the three protocols investigated ($P>0.01$). Further, when the oxygenation and blood volume responses were expressed as a percentage of the Sørensen test, gender differences did not achieve statistical significance ($P>0.01$). Also, deoxygenation cost was not significantly different between genders (Table 6.2) ($P>0.01$).

Correlations among Three Protocols and NIRS measures

To relate peak oxygen uptake and minimum oxygenation between the two incremental exercise modes, specific correlations are reported in Table 6.3A. It is evident from this table that significant correlations were not obtained for minimum oxygenation between the arm cranking and pushing-pulling modes ($r=0.11$, $P>0.05$). Relationship between NIRS measurements during incremental arm cranking, pushing-pulling and the Sørensen test are given in Table 6.3B. A significant correlation was observed between the minimum and range for oxygenation during pushing-pulling ($r=-0.93$, $P<0.05$). This suggests that significant difference in range for oxygenation between pushing-pulling and the Sørensen test was attributed mainly to the minimum oxygenation during pushing-pulling rather than corresponding maximum oxygenation values ($r=0.53$, $P>0.05$). A similar conclusion for the range in oxygenation cannot be made due to non-significant correlations between arm cranking and the Sørensen test (Table 6.3). Based on the ANOVA statistics, significant correlations for the range in the Sørensen test corresponded to minimum ($r=0.45$, $P<0.05$) and maximum ($r=0.51$, $P<0.05$) blood volume during pushing-pulling compared to corresponding arm cranking values.

Correlations between Adipose Tissue Thickness and Oxygenation and Blood Volume

Adipose tissue thickness calculated from the right side of erector spinae skinfolds at 3rd lumbar region for men and women (mean ± SD) were: 5.4 ± 1.5 mm, and 6.0 ± 2.3 mm, respectively. They were not significantly different from each other ($P>0.05$). Spearman correlations between adipose tissue thickness and mean changes in oxygenation and blood volume data for both men and women during the three protocols are shown in Table 6.4. A significant correlation was found between adipose tissue thickness and minimum oxygenation ($r=-0.70$, $P<0.05$) for men during the Sørensen test. However, correlations were not significant ($P>0.05$) between adipose tissue thickness and other NIRS variables for both genders among three protocols.

DISCUSSION

In a skeletal muscle, a complete range of oxygenation conditions is necessary to establish both the 'minimum' (0% oxygenation) and the 'maximum' (100% oxygenation) spectral values (Piantadosi 1993). Such a range helps in evaluating the role of dynamic exercise in influencing the 'true' hypoxic values of the specific muscle under study. This is usually obtained during cuff ischemia ('minimum' condition) for a period of 6 to 8 min to the specific muscle followed by subsequent hyperaemia indicating 'maximum' condition (Chance et al. 1992). However, occluding arterial supply to the trunk muscles is not possible. In the current investigation, a well-established back muscle endurance test was used to identify both minimum and maximum oxygenation and blood volume limits for the lumbar erector spinae muscle, which were used for comparison with incremental exercise protocols.

The Sørensen Test

The Biering-Sørensen method, also known as the "Sørensen test" has been utilized to evaluate static back muscle endurance in healthy populations

(Biering-Sørensen 1984). In the current investigation, most of the subjects demonstrated a steep decline in oxygenation till 60-90 seconds and leveled off after that period, suggesting a compromised blood flow in the erector spinae muscles during isometric contraction. However, the blood volume decreased rapidly in the beginning of isometric contractions, and then increased with holding time. These blood volume trends were not in agreement with maximal trunk extensions (Jensen et al. 1999, Maikala et al. 2000, Yoshitake et al. 2001).

Recently, Yoshitake et al. (2001) used the isometric trunk extension in prone position to establish the minimum and maximum lumbar erector spinae oxygenation and blood volume responses in healthy men at 0° and 15° of trunk extension for 60 seconds with reference to the horizontal plane. They demonstrated that oxygenation and blood volume were significantly reduced to a greater extent during 15° compared to 0° of trunk extension. However, in the present study subjects were asked to perform maximum voluntary contractions at 0° of trunk extension till exhaustion, and as the contraction period increased the majority demonstrated a rapid muscle desaturation, resulting in restriction of blood flow due to a greater intramuscular pressure in the erector spinae muscle. Several authors also reported a similar decrease in oxygenation trends during isometric back extension in both standing and sitting postures (Jensen et al. 1999, McGill et al. 2000, Maikala et al. 2000).

It is well established that at all exercise intensities, blood flow to the working muscles varies with changes in intramuscular pressure (Saltin et al. 1998). During back extension in a standing posture, Jensen et al. (1999) demonstrated a decrease in the lumbar erector spinae muscle oxygenation that remained unchanged after a period of 30 seconds. This suggests that a local homeostatic adjustment over a period may result in constant capillary oxygen tension thus further preventing decrease in hemodynamics in these paraspinal muscles (Jensen et al. 1999). Under such circumstances, these authors reported that at an intramuscular pressure range of 30-40 mm Hg, oxygenation in the paraspinal muscles was significantly reduced suggesting a greater demand for oxygen compared to oxygen supply. Maikala et al. (2000) demonstrated a similar decrease in oxygenation and blood volume trends during both sitting and standing low-back extension postures. However, these authors did not report the intramuscular pressure values in the lumbar erector spinae muscles.

Based on the oxygenation responses from a seated isometric low-back extension, McGill et al. (2000) postulated that a decrease in oxygenation during an isometric contraction might be due to compromised blood flow in the smaller blood vessels because the intramuscular pressure exceeds the intravascular pressure as the duration of contraction increases. Another possible mechanism suggested by these authors is reduced perfusion and a concomitant increase in oxygen extraction from the muscle during the contraction period (McGill et al. 2000). However, these authors did not report the blood volume responses.

Incremental Exercise Modes

Several authors reported the involvement of shoulder and trunk muscles during arm cranking (Davis et al. 1976, Nag 1986, Sawka 1986, Toner et al. 1983). Constant gripping of the crank handle during arm cranking in a sitting posture results in an additional isometric component for torso stabilization (Sawka 1986). According to Davis et al. (1976), during the early stages of incremental arm cranking, involvement of arm muscles is greater, however as the workload increases the possibility of non-uniform recruitment of shoulder and trunk muscles results, reaching maximal values at peak workloads. Using electromyography, Nag (1986) demonstrated that the erector spinae muscles were minimally active during arm cranking but suggested that rhythmic component of trunk muscle activity is greater in arm work compared to leg work such as cycling.

During arm cranking at a constant load of 76 Watts, Toner et al. (1983) suggested that in addition to the linear increase of arm percent muscle volume with increase in oxygen uptake, the linear increase in oxygen uptake was also proportional to torso stabilization of the upper body. However, at a workload of 109 Watts, these authors demonstrated a curvilinear relationship suggesting the involvement of excessive body movements. Furthermore, from the current investigation, the oxygenation and blood volume trends (Figures 6.3 and 6.4) in the lumbar erector spinae muscles suggest that during arm cranking, not only the upper extremity muscles (Chapter 5) but also the trunk muscles were being recruited, particularly at the maximal effort. As the workload increased, lumbar erector spinae oxygenation trends in the majority of the subjects during arm cranking showed either a smaller decrease or leveling off in oxygenation, suggesting recruitment of this muscle may not be influential during lighter workloads. However, at the final workloads when subjects were reaching exhaustion, there was a rapid decline in oxygenation indicating the importance of trunk muscle recruitment and stabilization during maximal effort.

Research pertaining to the erector spinae oxygenation and blood volume during low-back intensive occupational activities (e.g., repetitive lifting and lowering) is very limited (Maikala et al. 1999, Maronitis et al. 2000). As well, NIRS trends in the erector spinae oxygenation and blood volume during task-specific pushing-pulling have not been reported. In the current investigation, majority of men and women demonstrated a leveling off in both oxygenation and blood volume trends at initial loads, followed by a decrease in blood volume to the low-back muscles with simultaneous and greater decrease in oxygenation to these muscles. Such a decrease in oxygen saturation in smaller blood vessels of the lumbar erector spinae muscle during pushing-pulling suggests an imbalance between oxygen supply and demand during repetitive contraction of the trunk muscles.

However, a decrease in oxygenation and blood volume in the trunk extensor muscles during repetitive pushing-pulling is similar to the incremental arm cranking responses obtained in the present study. Several pushing-pulling studies have demonstrated the involvement of trunk muscles in both the sitting and standing postures (Ayoub and McDaniel 1977, Chaffin et al. 1983, Gagnon et al. 1992, Nadeau and Gagnon 1996, Troup and Chapman 1969). However, none of these previous studies were of repetitive nature, i.e., rather than repetitively pushing-pulling the lever in a stepwise fashion as investigated in the present study, these studies investigated the static push and/or pull forces applied either for a single instant or frequently for a brief period. Further, the application of force in these investigations was only in one direction (either pushing forward or pulling towards the body) per activity.

As the workload increased during pushing-pulling, muscle oxygenation and blood volume started decreasing steadily with an increase in workload (Figures 6.3 and 6.4). Such a systematic decrease in oxygenation with increase in work intensity implies a greater release of oxygen by hemoglobin/myoglobin via the Bohr effect (Belardinelli et al. 1995, Chance et al. 1992). However, the myoglobin dissociation curve does not exhibit the Bohr effect, hence its overall role in determining muscle deoxygenation is relatively minor (Mancini et al. 1994). To this effect, Stringer et al. (1994) and Wasserman et al. (1991) suggested that metabolic acidosis during exercise was essential for skeletal muscle deoxygenation to take place. In other words, the presence of hydrogen ions associated with lactate accumulation was necessary for oxygen to be released from oxygenated hemoglobin in the skeletal muscle via the Bohr effect. Therefore, a steady decrease in the oxygen saturation in the muscle with increase in workload might suggest an increase in the oxygen demand exceeding the muscle saturation, thus resulting in an increase in deoxygenation (reflecting increased oxygen extraction from the lumbar erector spinae muscle).

In theory, the degree of deoxygenation measured by NIRS is attributed to the amount of oxygen released by both oxyhemoglobin and oxymyoglobin (Mancini et al. 1994). However, the current NIRS apparatus is unable to differentiate between the amount of deoxygenation that is attributed to hemoglobin and myoglobin due to the overlap of the absorbency signals of these chromophores in the near infra-red region (Chance et al. 1992). During knee extension exercise, Richardson et al. (1995) demonstrated that myoglobin desaturation occurs rapidly and reaches a maximal value at approximately 50% of maximal oxygen consumption. Recently, Tran et al. (1999) showed decline in the oxygenation obtained with the NIRS signal in the gastrocnemius muscle closely matches myoglobin desaturation from the nuclear magnetic resonance spectra.

Based on the lumbar erector spinae oxygenation and blood volume results obtained from arm cranking and pushing-pulling (Table 6.2), it is safe to say that trunk muscles respond similarly during both incremental exercise modes, and the postural difference (sitting Vs standing) might not influence in the muscle oxygenation and blood volume responses. This finding is in agreement with that of Troup and Chapman (1969) who demonstrated that the applied extensor forces during pushing-pulling were greater in sitting compared to standing, however, the forces transmitted by the erector spinae (turning moment) were of similar magnitude during both postures. These authors hypothesized that during standing, the lumbar spine is extended and the erector spinae is shortened, thus providing a relatively greater mechanical advantage in transmitting extensor forces than during the sitting posture. However, during sitting the lumbar spine is flexed; thus a smaller mechanical advantage in the sitting posture is compensated for by a shorter lever arm between the pelvis and upper limbs, resulting in a turning moment similar to that of the standing position (Troup and Chapman 1969). Hence in both postures identical forces exerted by the erector spinae might have led to similar oxygenation and blood volume responses during both pushing-pulling and arm cranking.

In the current study, subjects performed incremental exercises at their comfortable height, i.e., during arm cranking the shaft was adjusted to their shoulder level, and during pushing-pulling subjects performed at their respective waist heights (Table 6.1A). It has been previously demonstrated that pushing-pulling at comfortable heights is less strenuous on the lower-back (Chaffin et al. 1983). Thus, similar oxygenation and blood volume responses can also be attributed to adjustable workstation height during human performance. Deoxygenation cost during pushing-pulling was similar to arm cranking, suggesting that oxygen desaturation [or tissue oxygen consumption] in the lumbar erector spinae muscle per unit of oxygen uptake is similar during both task-specific and standardized protocols.

Comparison between Genders

Gender did not influence any of the oxygenation and blood volume responses among the three protocols. However, endurance (holding) time during the Sørensen test was significantly greater in women (by 32%) than in men (Table 6.1A), and is in agreement with several studies (Biering-Sørensen 1984, Jorgensen 1997, Mayer et al. 1995). Some of the reasons that might be attributed to greater endurance time in women are: a) upper-body weight is much lower in women than men (Jorgensen 1997), and b) women have greater percentages of slow twitch fibers in the trunk musculature, and large relative cross-sectional area of slow twitch and type A fast twitch fibers compared to men (Jorgensen 1997). Also, Mayer et al. (1995) hypothesized that load-to-maximum voluntary contraction ratio in women will be greater than men. However, in the current investigation both oxygenation and blood volume responses were not significantly different between men and women during the Sørensen test. This suggests, irrespective of greater holding time in women, both genders reported similar desaturation during trunk extension.

Men reported greater deoxygenation values but were not significantly different ($P>0.05$) compared to women during pushing-pulling. Even though not significant, a greater decrease in deoxygenation in men can be attributed to less oxidative capacity due to lower percentages of slow twitch fibers compared to women (Jorgensen 1997). However, such a trend was reversed for women with greater deoxygenation cost ($P>0.05$) during arm cranking. These results essentially suggest that even though men demonstrate greater whole-body oxygen uptake (Table 6.1B), their peripheral limitations at the erector spinae level are similar to women (Table 6.2).

Relationship between Peak Oxygen uptake and Minimum deoxygenation:

From Table 6.1, it is evident that peak oxygen uptake during arm cranking values were greater compared to pushing-pulling. Also, correlations of peak oxygen uptake between these exercise modes for the total sample was significant ($r=0.67$, $P<0.05$). However, the correlation between these two exercise modes for minimum oxygenation was not significant (r=0.11, P>0.05), suggesting that peripheral responses during these two exercise modes are not similar. Since cardiac outputs were not investigated in the current study, and based on the lumbar erector spinae deoxygenation one can confirm that there is a significant difference in peripheral contribution between two incremental exercise modes. This finding (in addition to the findings suggested in Chapter 5) further strengthens our argument that developments of task-specific aerobic protocols are essential at the workplace.

The Optimal Test in Establishing Minimum and Maximum Physiological Limits for the Erector Spinae Muscle

In the present study, contrary to our assumption that maximum deoxygenation would result during the Sørensen test, greatest deoxygenation (P>0.05) was observed during pushing-pulling (Table 6.2A). However, this value was not significantly different among the three protocols. Further, maximum oxygenation values were also similar during three protocols. Interestingly, the range for oxygenation values showed significantly higher responses during both pushing-pulling and arm cranking separately, compared to the Sørensen test. From Table 6.4, it is evident that oxygenation range (based on the total sample size of 22 subjects) for pushing-pulling was significantly correlated to corresponding minimum than maximum oxygenation values (r=-0.93, P<0.05), suggesting greater deoxygenation during pushing-pulling can be a better measure among the three protocols in predicting the minimum value for the lumbar erector spinae muscle.

Furthermore, oxygenation and blood volume responses during isometric endurance test demonstrated in the present study might also suggest that unlike cuff ischemia protocols (see also Chapter 5) that have been adopted to establish fully oxidized and reduced states for specific skeletal muscles such as biceps brachii (Maikala and Bhambhani 1999) and vastus lateralis muscle (Bhambhani et al. 1998b, Chance et al. 1988, 1992), the Sørensen test might not be a good protocol in establishing minimum and maximum calibration limits for the erector spinae muscle. Questions that then arise are: why is the Sørensen test not a true protocol in establishing these limits? Are there any alternatives in establishing fully oxidized and reduced states for the lumbar erector spinae muscle?

Since the torque generated at the center of lumbopelvic joint is equivalent to the load lifted [the weight of the unsupported upper body only] and the lever arm from the center of joint to the center of gravity of the upper body, Mayer et al. (1995) criticized that during the Sørensen test subjects do not perform maximal voluntary contractions. Thus, these authors concluded that this test might evaluate a load equivalent to less than 50% of the subjects' maximal voluntary contraction. Further, Hultman et al (1993) demonstrated that in healthy subjects the cross sectional muscle area of the erector spinae at the 3rd lumbar region was not significantly related to static back muscle endurance, but was highly correlated with isokinetic trunk muscle strength.

Other techniques for evaluating endurance of the trunk muscles include: (1) pulling against a dynamometer in a standing position, thus measuring endurance 'dynamically' through the full range of motion rather than 'statically' in determining the back muscle endurance (Graves et al. 1990, Jorgensen 1997); (2) using force feedback during back extension at higher levels of force during positions such as standing, semi-standing or sitting (Elfving et al. 2000). Based on the present results (Table 6.2A), it may be also suitable to adopt task-specific protocols to establish minimum and maximum physiological limits for the trunk extensor muscles. Research needs to be conducted to evaluate the muscle oxygenation and blood volume responses during muscle oxygenation and blood volume responses during these methods to fully understand the localized responses elicited by these tests.

Interestingly, three subjects (two men and one women) showed an increase in oxygenation and blood volume during the Sørensen test. Initially it was speculated that such a response might be due to the side dominance of trunk muscles. Previous studies have shown conflicting evidence regarding right and left side EMG profiles of back muscles during isometric contractions (Elfving et al. 2000, Mannion et al. 1997, Merletti et al. 1994, Tsuboi et al. 1994). However during both incremental protocols, the oxygenation and blood volume trends in these subjects were similar to all other subjects. Such conflicting evidence during the Sørensen test may be due to the asymmetrical trunk rotation in adjusting the left and right side of their trunk during the maximal effort (Tsuboi et al. 1994). These authors also hypothesized that such a discrepancy in the asymmetry may be due to "compensatory hypertrophy or atrophy resulting from specific muscle training or as a result of scoliosis which may cause uneven mechanical strain on the muscles". Hence, we believe such an increase in oxygenation and blood volume trends observed in three subjects during maximal back extension might be due to the inconsistent trunk rotation only.

Role of Adipose Tissue Thickness on NIRS measurements

van Beekvelt et al. (2001) reported that adipose tissue metabolism is lower than muscle metabolism hence muscle oxygenation determined using NIRS is underestimated. In the current study, there was no significant difference between men and women for the adipose tissue thickness at the L3 region of the erector spinae muscle (Table 6.1A). In the flexor digitorum super-ficialis muscle during rest and sustained isometric handgrip contractions, van Beekvelt et al. (2001) demonstrated a significant decrease in muscle oxygen consumption in both men and women with increase in the thickness of adipose tissue ($r=-0.70$, $P<0.05$). These authors further showed significant lower muscle oxygenation in women than in men during both rest and submaximal isometric contractions. Additionally, these authors found a significant but a weak correlation of 0.29 between forearm blood flow and adipose tissue thickness, suggesting an increase in blood flow with increase in the thickness of adipose tissue.

In the current investigation, adipose tissue thickness in women was not significantly correlated to any of the NIRS measurements among the three protocols (Table 6.4). However, a significant negative correlations was obtained in men for minimum oxygenation responses during the Sørensen test ($r=-0.70$, $P<0.05$). The regression between adipose tissue thickness and minimum oxygenation in men was:

[=0.57-0.95*log(adipose tissue thickness), r=-0.70, P=0.01]

This suggests that at the same source-detector separation of 4 cm, greater the thickness of adipose tissue lower the oxygenation values obtained during the Sørensen test. However, this correlation of minimum oxygenation in men was not significant during either arm cranking or pushing-pulling. Further, any other NIRS measurements in men were not significantly correlated among three protocols.

Such a significant negative correlation for minimum oxygenation during the Sørensen test in the current investigation may be a result of chance alone. Women also participated in the current investigation, and if such a significant relationship truly exists for men, correlations should be reliable for women as well [especially when the adipose tissue thickness was similar between genders]. However, as evident from the Table 6.4, this is not the case in the current investigation. Furthermore, calculating common variance for the *r* value of –0.70 results in 49% common variance, suggesting that 49% of the variability in the minimum oxygenation during the Sørensen test can only be explained by variance in the adipose tissue thickness (or vice versa). Hence, the remaining 51% of the variance might be influenced by other factors attributed to prediction error.

The major limitation of analyzing the correlation coefficients is that a significant correlation does not imply causality (Cody and Smith 1987, Vincent 1999). Some of the data points in the Figures 6.5 are extreme, and that might have caused larger correlation coefficients as well. Further, discrepancy observed in the current investigation and the study of van Beekvelt et al. (2001) might be due to their larger sample size of 44 men and 34 women. Also, factors such as exercise protocols used, specific muscle under investigation, and quantification of NIRS signals were different between these two studies. Hence based on the current limited sample size (11 men and 11 women), the fact that adipose tissue thickness and minimum oxygenation during the Sørensen test are related does not mean that a change in one variable will necessarily produce a corresponding change in other.

One question may also arise here, i.e., role of skin blood flow in the contamination of NIRS blood volume signal. With source-to-detector separation of 40-50 mm, Hampson and Piantadosi (1988) showed that NIRS measurements are not affected by skin blood flow, and attributed such findings to a small volume of skin relative to muscle between the NIRS optodes, and the low concentration of cyctochorme oxidase in skin. In the current investigation, the source to detector distance was set to 40 mm for every subject during three protocols. Other authors also reported negligible influence of skin blood flow on NIRS signals (Mancini et al. 1994, Piantadosi et al. 1986). Further, Feng et al. (2001) showed that for an adipose thickness of 8 mm, the optimal source-detector distance was 45 mm. These authors have also identified the optimal distance of 35-40 mm for an adipose tissue thickness range of 2.5-5 mm, and 50 mm for a thickness of 17 mm. However, irrespective of the differences in the subjects' variation in the skinfolds, the current investigation used a fixed source-detector distance, which might have resulted in non-significant differences between men and women as well.

Further, Chance et al. (1992) reported a total pathlength of light in muscles as 7-10 cm that corresponded to a penetration depth of 25-30 mm. Using an ultrasound imaging technique, Jensen et al. (1999) measured the distance from the skin surface to the lumbar erector spinae muscle at the NIRS sensor site, and reported a distance of 9.0 ± 0.3 mm (at the cranial aspect) and 9.3 ± 0.5 mm (at distal aspect), respectively. Thus, measurements obtained with the existing NIRS setup (e.g., source-detector separation, photon penetration depth) in the current investigation are well within the range for the lumbar muscle.

CONCLUSION

In the present study, erector spinae oxygenation and blood volume responses were similar in men and women during both task-specific pushing-pulling and arm cranking, indicating peripheral limitations at the trunk musculature were not influenced by the exercise mode. These results agree with our predicted hypotheses: (1) the erector spinae oxygenation and blood volume trends would be similar between the two modes of exercise, and (2) there would be no significant gender differences in these responses. Further, deoxygenation cost during pushing-pulling and arm cranking are also similar.

Greater desaturation values were reported in men but were not significant compared to responses in women during both exercise modes, suggesting even though men can generate greater power output, their peripheral limitations at the erector spinae level are similar to women. Deoxygenation cost in men and women were also similar suggesting, men and women can extract similar amounts of oxygen from the lumbar erector spinae muscle. However, the most interesting finding of the present study is the greatest desaturation during incremental exercise modes compared to the back muscle endurance 'Sørensen test'. Based on the significant correlations for the range in oxygenation between pushing-pulling and the Sørensen test, maximum deoxygenation was obtained during pushing-pulling which may suggest faster fatiguability of these muscles during task-specific protocols. Simultaneous comparisons of NIRS measures in biceps and the lumbar erector spinae muscles demonstrated that blood volume increased in biceps with increase in the workload, however, compromised blood flow from limited oxygen delivery was evident in the erector spinae muscle. The role of adipose tissue thickness on NIRS measures was not consistent in both genders during the three exercise test protocols.

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Table 6.1A: Demographics of subjects (Mean ± SD)

Gender	Age	Body Mass	Height	Body Mass Index	Back Muscle Skinfold at L3	Back Muscle Endurance Time	Push-Pull Height
	Yrs	Kgs	m	$Kg.m^{-2}$	mm	sec	cm
Men N=11	23.7 ± 4.5	77.5 ± 13.8[a]	1.76 ± 0.08[a]	24.6 ± 3.3[a]	10.8 ± 3.0	139 ± 53[b]	119 ± 7[a]
Women N=11	24.5 ± 4.0	57.6 ± 9.4	1.63 ± 0.06	21.4 ± 2.4	12.0 ±4.5	203 ±72	111 ± 6

[a] – significant difference between men and women, $p<0.05$
[b] – significant difference between men and women, $p<0.01$

Table 6.1B: Demographics of subjects (Mean ± SD)

Gender	Peak Oxygen Uptake $L.min^{-1}$		Peak Power output Watts	
	Push-Pull	Arm Cranking	Push-Pull	Arm Cranking
Men N=11	1.74 ± 0.51[ab]	2.36 ± 0.51[a]	32 ± 8[c]	161 ± 32
Women N=11	1.23 ± 0.32[b]	1.56 ± 0.50	25 ± 8	114 ± 20

[a] – significant difference between men and women, $p<0.01$
[b] – significant difference between Arm cranking and Pushing-pulling, $p<0.01$
[c] – significant difference between gender and exercise mode [Arm cranking and Pushing-pulling], $p<0.01$

Table 6.2: Erector Spinae Oxygenation and Blood Volume responses during Incremental Pushing-Pulling and Incremental Arm Cranking in Healthy Men and Women in Optical Density (Mean ± SD)

GENDER	TASK	Oxygenation			Blood Volume		
		Min	Max	RangeΨ	Min	Max	RangeΨ
Men	Push-Pull	-0.302 ± 0.440	0.045 ± 0.185	0.347 ± 0.542 [b]	-0.314 ± 0.526	0.188 ± 0.448	0.503 ± 0.405 [b]
	Arm Cranking	-0.177 ± 0.178	0.172 ± 0.210	0.350 ± 0.282 [a]	-0.328 ± 0.484	0.395 ± 0.688	0.723 ± 0.583 [a]
	Sorensen Test	-0.087 ± 0.245	0.056 ± 0.331	0.140 ± 0.202	0.083 ± 0.322	0.092 ± 0.281	0.094 ± 0.308
	Push-Pull, %Sorensen Test	347 ± 180	80 ± 56	250 ± 268	378 ± 163	204 ± 150	535 ± 131
	Arm Cranking, %Sorensen Test	203 ± 138	307 ± 63	250 ± 139	395 ± 150	429 ± 244	769 ± 189
	Deoxygenation Cost [d] [Push-Pull], $OD.L^{-1}.min^{-1}$	-17 ± 86					
	Deoxygenation Cost [d] [Arm Cranking], $OD.L^{-1}.min^{-1}$	-8 ± 35					
Women	Push-Pull	-0.166 ± 0.196	0.086 ± 0.125	0.252 ± 0.221 [b]	-0.195 ± 0.406	0.279 ± 0.478	0.474 ± 0.341 [b]
	Arm Cranking	-0.223 ± 0.618	0.147 ± 0.470	0.370 ± 0.504 [a]	-0.158 ± 0.369	0.348 ± 0.378	0.507 ± 0.472 [a]
	Sorensen Test	-0.093 ± 0.195	0.018 ± 0.230	0.110 ± 0.133	-0.077 ± 0.206	0.251 ± 0.450	0.328 ± 0.485
	Push-Pull, %Sorensen Test	178 ± 100	477 ± 54	227 ± 169	253 ± 197	111 ± 106	145 ± 70
	Arm Cranking, %Sorensen Test	240 ± 317	816 ± 204	336 ± 387	205 ± 179	138 ± 84	155 ± 97
	Deoxygenation Cost [d] [Push-Pull], $OD.L^{-1}.min^{-1}$	-13 ± 38					
	Deoxygenation Cost [d] [Arm Cranking], $OD.L^{-1}.min^{-1}$	-14 ± 123					

RangeΨ is defined as the difference between Maximum Optical Density (Max) and Minimum Optical Density (Min): [a] – significant difference between Arm cranking and Sorensen test ($p < 0.01$): [b] – significant difference between Pushing-pulling and Sorensen test ($p < 0.01$): [c] – significant difference between Arm cranking and Pushing-pulling ($p < 0.01$): [d] - Deoxygenation Cost is defined as the ratio of muscle deoxygenation and whole-body oxygen uptake during specific incremental exercise.

Table 6.3A: Correlations of Erector Spinae Oxygenation and Blood Volume Responses among Three Protocols (n=22)

Variable	Protocols		
Oxygenation	Sorensen Vs Pushing-pulling	Sorensen Vs Arm Cranking	Pushing-pulling Vs Arm Cranking
Minimum	**-0.58** [a]	0.07	0.11
Maximum	0.25	0.12	-0.31
Range	0.31	0.37	0.27
Blood Volume	Sorensen Vs Pushing-pulling	Sorensen Vs Arm Cranking	Pushing-pulling Vs Arm Cranking
Minimum	-0.30	-0.10	0.30
Maximum	0.21	0.21	0.35
Range	0.07	0.26	**0.51** [a]

[a] – significant difference at $P<0.05$

Table 6.3B: Correlations of Erector Spinae Oxygenation and Blood Volume Responses among Three Protocols (n=22)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		0.11	0.07	**0.52**	-0.22	-0.26	**-0.65**	-0.18	**-0.52**	**0.45**	-0.25	0.25	-0.21	**-0.50**	**-0.56**	**-0.58**	-0.30	**-0.69**
2			**-0.58**	-0.23	-0.25	**-0.59**	-0.33	**-0.93**	-0.24	0.10	**0.42**	0.14	**-0.62**	-0.06	0.08	**-0.64**	**-0.61**	-0.01
3				0.34	0.10	**0.80**	0.22	**0.52**	0.04	0.32	-0.27	0.24	**0.53**	-0.20	0.27	0.29	0.10	0.10
4					-0.31	0.12	0.31	0.07	-0.24	0.16	**-0.50**	0.23	0.21	***-0.52***	-0.21	0.10	-0.02	-0.34
5						0.25	-0.03	**0.59**	0.29	0.25	**0.43**	***-0.51***	**0.60**	**0.62**	0.01	0.41	0.23	0.34
6							0.40	**0.60**	**0.63**	0.32	-0.11	-0.03	**0.68**	0.05	**0.50**	**0.43**	0.21	**0.48**
7								0.27	0.37	-0.36	-0.16	-0.07	**0.42**	0.09	**0.45**	**0.73**	0.31	**0.46**
8									0.31	0.09	-0.20	-0.31	***0.74***	0.29	-0.06	**0.69**	**0.60**	0.14
9										0.13	0.17	-0.37	**0.43**	0.34	**0.47**	0.34	0.22	**0.67**
10											0.30	-0.10	**0.43**	0.07	0.12	-0.37	-0.28	0.18
11												-0.30	0.13	**0.68**	0.27	-0.11	-0.42	**0.45**
12													-0.31	**-0.49**	0.25	-0.24	-0.23	-0.41
13														0.35	0.21	**0.68**	0.28	0.40
14															0.21	0.30	0.38	**0.51**
15																0.12	-0.08	**0.78**
16																	**0.51**	0.26
17																		0.07

1 – Minimum Oxygenation – Arm Cranking
2 – Minimum Oxygenation – Pushing-pulling
3 – Minimum Oxygenation – Sorensen Test
4 – Maximum Oxygenation – Arm Cranking
5 – Maximum Oxygenation – Pushing-pulling
6 – Maximum Oxygenation – Sorensen Test
7 - Range Oxygenation – Arm Cranking
8 - Range Oxygenation – Pushing-pulling
9 - Range Oxygenation – Sorensen Test
10 – Minimum Blood Volume – Arm Cranking
11 – Minimum Blood Volume – Pushing-pulling
12 – Minimum Blood Volume – Sorensen Test
13 – Maximum Blood Volume – Arm Cranking
14 – Maximum Blood Volume – Pushing-pulling
15 – Maximum Blood Volume – Sorensen Test
16 - Range Blood Volume – Arm Cranking
17 - Range Blood Volume – Pushing-pulling
18 - Range Blood Volume – Sorensen Test

Significance at $P < 0.05$

Table 6.4: Spearman Correlation Coefficients between Adipose Tissue Thickness and Erector Spinae Oxygenation and Blood Volume responses in Healthy Men and Women

Gender	Protocol	Oxygenation		Blood Volume	
		Min	Max	Min	Max
Men	Push-Pull	0.26	-0.46	0.06	0.23
	Arm Cranking	0.15	-0.32	-0.36	-0.19
	Sorensen Test	-0.70 [a]	-0.46	0.07	0.13
Women	Push-Pull	0.30	-0.24	0.24	0.19
	Arm Cranking	0.39	0.26	-0.09	0.28
	Sorensen Test	0.40	-0.18	-0.02	-0.46

[a] – significant difference at $P<0.05$

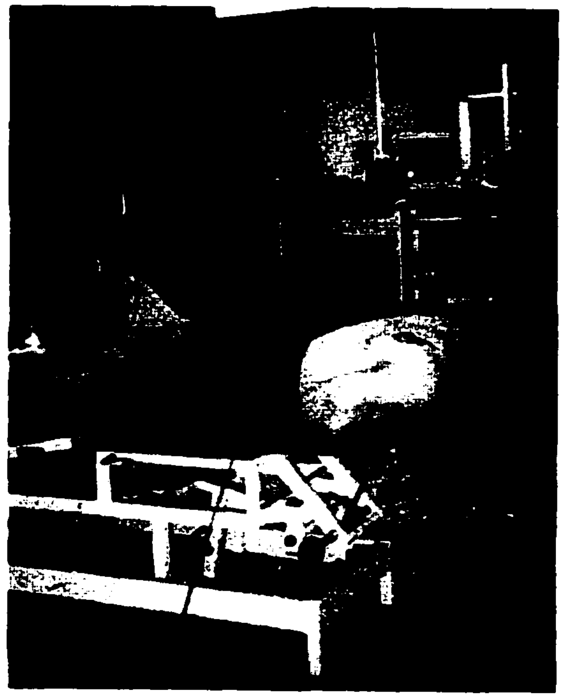

Figure 6.1A Subject Setup for the Sorensen Test

Figure 6.1B Securing the Subject on the Plinth

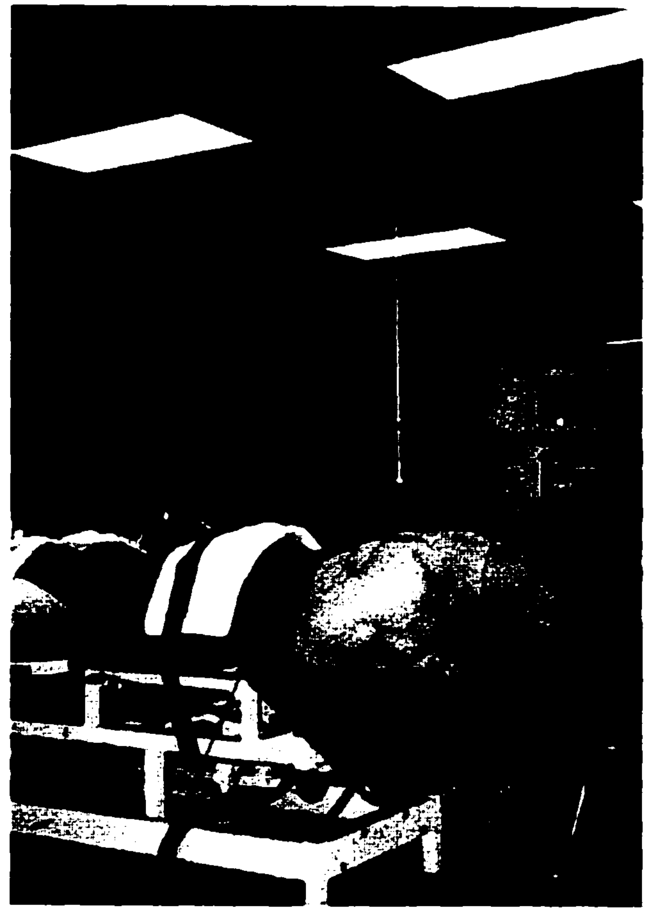

Figure 6.2 Subject Performing the Maximal Isometric Extension Test

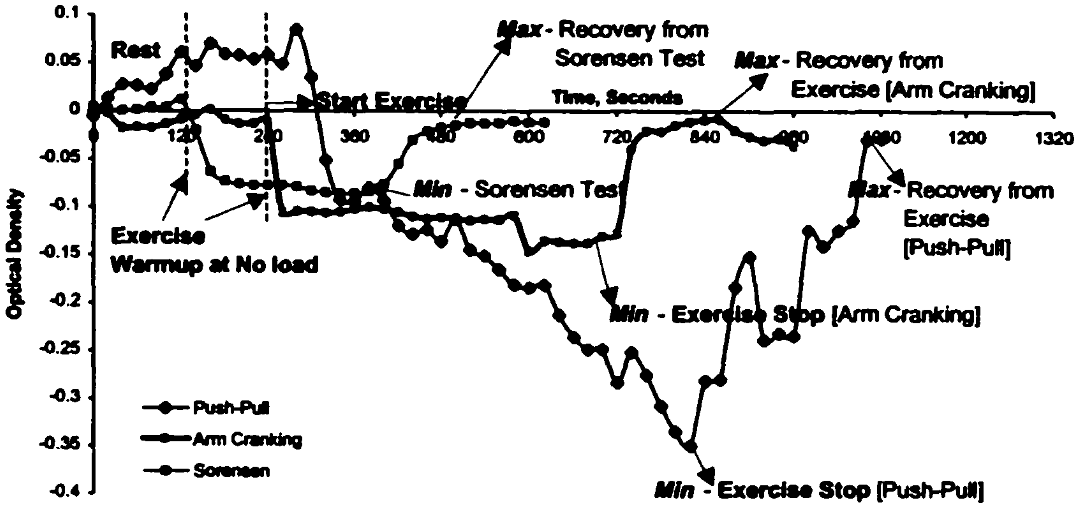

Figure 6.3A: Erector Spinae Oxygenation Trends in a Typical Female

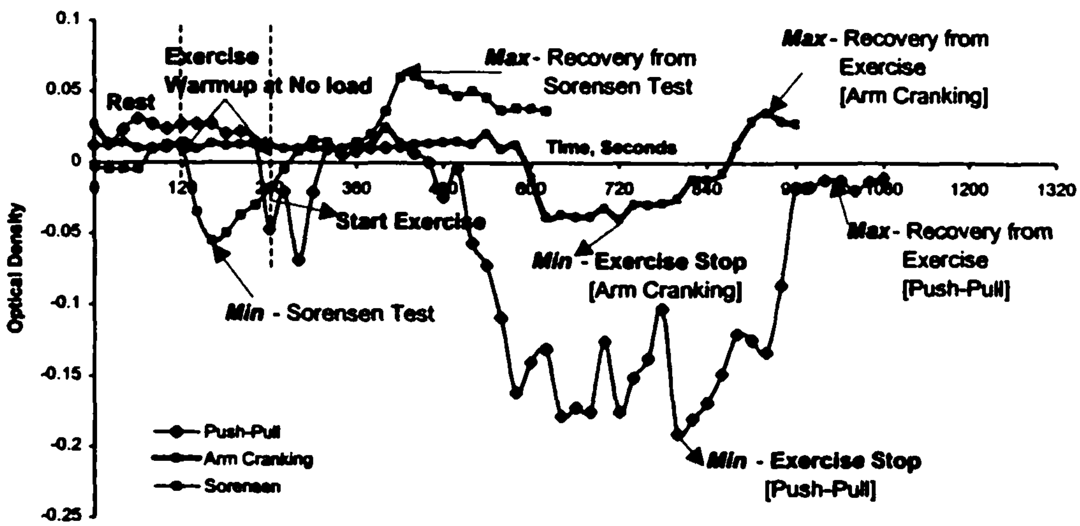

Figure 6.3B: Erector Spinae Blood Volume Trends in a Typical Female

Min - Minimum Oxygenation [or Blood Volume] value obtained during specific Protocol
Max - Maximum Oxygenation [or Blood Volume] value obtained during recovery from specific Protocol

Erector spinae oxygenation (top panel) and blood volume (bottom panel) trends in typical female subject during sorensen test, arm cranking and pushing-pulling, and recovery

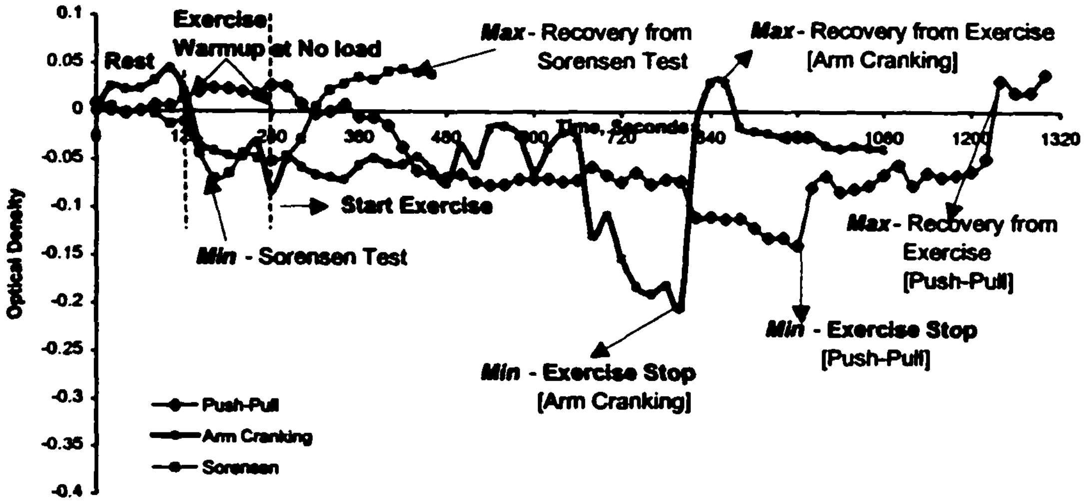

Figure 6.4A: Erector Spinae Oxygenation Trends in a Typical Male

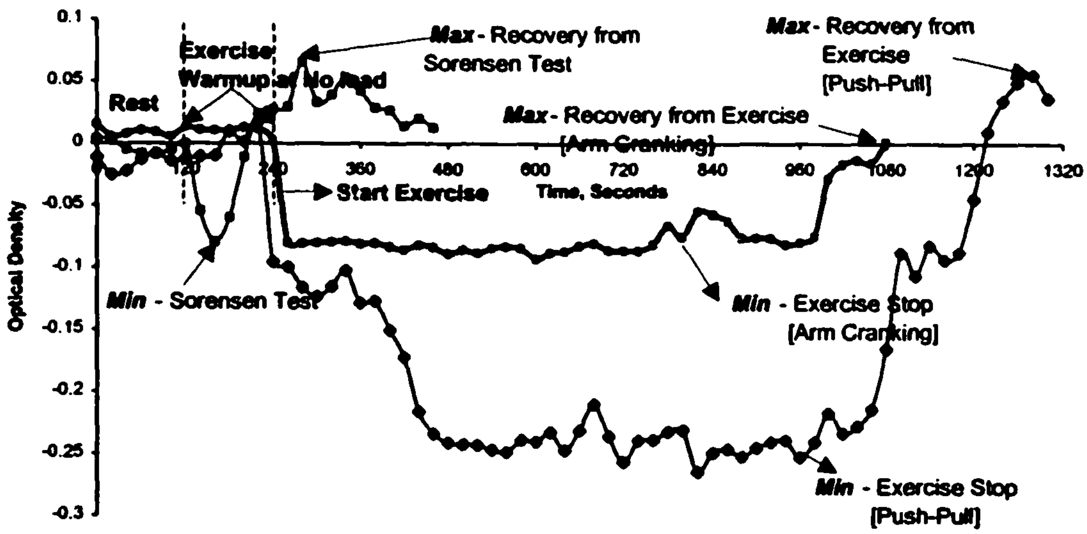

Figure 6.4B: Erector Spinae Blood Volume Trends in a Typical Male

Min - Minimum Oxygenation [or Blood Volume] value obtained during specific Protocol
Max - Maximum Oxygenation [or Blood Volume] value obtained during recovery from specific Protocol

Erector spinae oxygenation (top panel) and blood volume (bottom panel) trends in a typical male subject during sorensen test, arm cranking and pushing-pulling, and recovery

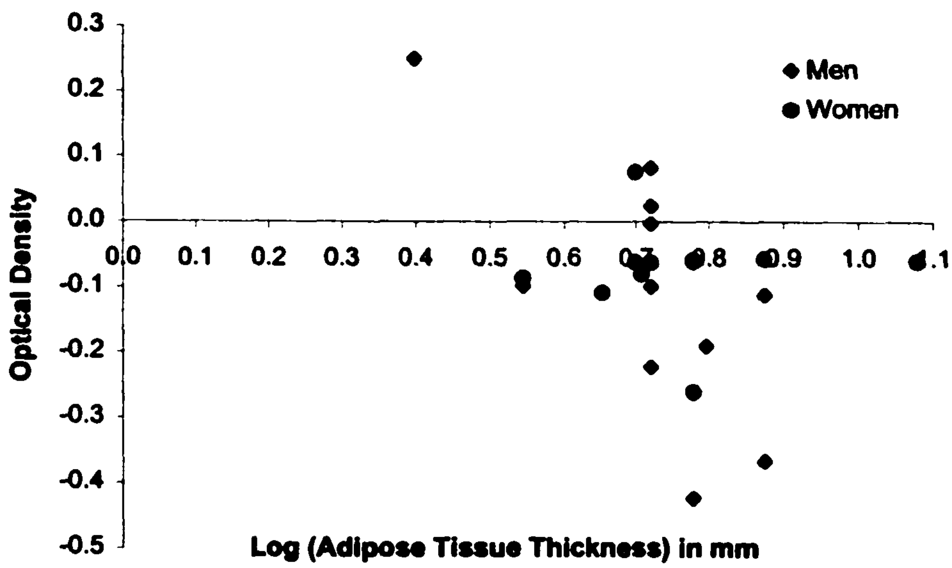

Figure 6.5 Correlaion between Adipose Tissue Thickness and Minimum Oxygenation during the Sorensen Test

CHAPTER 7

General Discussion

Study #1: Dose – Response Effects of Whole-body Vibration (WBV):

Occupations which involve exposure to WBV are often associated with factors such as awkward (and often prolonged) posture, constant attention during driving, operating various controls and hand-held levers, etc. These activities combined with WBV can be both physically demanding and mentally challenging. Such combined exposures have been implicated in both low-back disorders (Pope et al. 1998), and development of neck pain leading to headaches (Scutter et al. 1997). Hence, it is important to understand the energetics of specific tissues, in particular the 'focal' changes in cerebral and muscle regions that may be recruited simultaneously during exposure to WBV.

In this study, Near Infra-red Spectroscopy (NIRS), was used to examine the acute changes in oxygenation and blood volume simultaneously in the lumbar erector spinae muscle (as an indirect measure of evaluating physical workload) and pre-frontal cortex region (as an indirect measure of evaluating psychological workload) during exposure to 3 Hz, 4.5 Hz and 6 Hz WBV in healthy men and women. Open circuit spirometry was also used to monitor the cardiorespiratory measurements during these exposures. The subjects were asked to perform a motor task (maximal rhythmic handgrip contractions for a period of one minute) during WBV.

Exposure to WBV elicited an increase in cerebral oxygenation and blood volume with a concomitant decrease in these variables in the erector spinae muscle in both genders. These changes were not dependent upon the WBV dose, but were greater without the backrest support. Addition of handgrip work elicited an increase in cerebral activation (indicated by increases in both cerebral oxygenation and blood volume responses [Chapter 2, Figure 2.6]) with a concomitant decrease in the lumbar erector spinae muscle oxygenation (and blood volume responses in majority of subjects [Chapter 3, Figure 3.2]). Men demonstrated significantly greater mean deoxygenation values than women during work combined with WBV, suggesting in men greater deprivation of oxygen occurs (without significant changes in muscle blood volume) in the erector spinae muscles. However, the greater cerebral and muscle oxygenation and blood volume responses in men were not significantly correlated to their maximal grip strength.

These observations raise several interesting questions. Why is an increase in cerebral oxygenation and blood volume associated with a concomitant decrease in lumbar erector spinae oxygenation and blood volume during WBV, and vice versa? Why does such an inverse relationship exist between these two tissues? Does an increase in cerebral activation observed in the right prefrontal cortex in the present study demonstrate a physiological pathway from the muscle to the brain during WBV?

During WBV, a decrease in substance P [in the dorsal root ganglion, a major output structure of the frontal cortex and considered as the 'brain' of the functional spinal unit (Weinstein 1991)] has been considered to be an indication of increased axonal transport in the brain. Based on animal WBV studies, several authors reported an increase of axonal transport in the frontal cortex due to WBV, thus affecting the neuropeptides (e.g. substance P) present in the sensory parts of the nervous system (Nakamura et al. 1994 and 1988, Weinstein 1991, Weinstein et al. 1988). The present findings (Chapter 2 of study #1) demonstrated that there was an increase in the 'focal' cerebral oxygenation and blood volume in the prefrontal cortex during all conditions of WBV (compared to rest without WBV or post-WBV period), suggesting an increase in neuronal activity with a subsequent increase in perfusion to the prefrontal cortex (Villringer and Chance 1997). This indirect evidence suggests a possible afferent feedback to the cerebral cortex during exposure to WBV in humans. *It appears, therefore, that the increase in synaptic activity resulting from exposure to WBV elicits an increase in cerebral oxygenation and blood volume in the pre-frontal cortex which can be monitored non-invasively using NIRS.*

Spinal reflex studies have demonstrated a decrease in human sensorimotor performance during WBV, suggesting a possible feedback mechanism induced by vibration via the proprioceptive and central nervous systems (Gauthier et al. 1981, Martin et al. 1984, Roll et al. 1980). Martin et al. (1984) regarded the role of WBV as a combination of synchronous vibration applied 'locally' and simultaneously to several muscle tendons. The current observations in the specific paraspinal muscle suggest that WBV induces a 'localized vasoconstrictor stimulus' in the regions of the lumbar erector spinae muscle. Consequently, the reduction in blood flow would result in a lower blood volume and greater deoxygenation in this area monitored by NIRS. Based on electromyographic investigations, Hansson et al. (1991) hypothesized that there was a lack of blood flow to the back muscles during exposure to WBV. Kauppila and Tallroth (1993) investigated postmortem lumbar arteriorgrams of subjects with and without low-back pain in the lumbar and middle sacral arteries, and demonstrated that "insufficient arterial blood flow may be an underlying factor for low-back symptoms". *Thus, the current evidence (Chapter 3 of study #1), demonstrates that the decrease in oxygenation may be the result of a compromised blood flow to the paraspinal muscles during WBV, and supports the use of NIRS in evaluating these changes.*

It has been shown that 'localized' vibration (e.g. hand-arm vibration during a drilling task in 'construction' occupations) results in vasoconstriction of blood vessels in the hand thereby enhancing peripheral circulatory disturbances. This condition is termed "Vibration-induced White Finger" or "Raynaud Phenomenon" (Griffin 1990). Martin and Park (1997) showed that such localized vibration triggers the tonic vibration reflex in active muscles. However, to date there are no studies that have demonstrated the tonic vibration reflex in the trunk muscles during WBV. It could be argued that since exposure to WBV is a 'cumulative' of local vibrations being transmitted from the seat, floor, backrest, body segments, etc., a mechanism similar to the 'Raynaud Phenomenon' might occur 'locally' at the paraspinal muscles during prolonged exposure to WBV which, thus resulting in a decrease in muscle oxygenation and blood volume in this area.

Several authors have demonstrated an increase in the erector spinae muscle activity during cycling or repetitive loading due to WBV results in a greater recruitment of motor units in this muscle group (Pope et al. 1998, Seroussi et al. 1989, Wilder et al. 1982). Based on the current investigations of Study #1 (Chapters 2 and 3), this increase in muscular activity might lead to increased cortical activation. It should be noted that the increased acceleration measured at C6 in the current study (Chapter 2, Table 2.2) indicates considerable vibration being transmitted from the vibrating base ('With' and 'Without' a backrest) to the head. It can be argued that in contrast to the vasoconstrictor stimulus observed in the lumbar erector spinae muscle (demonstrated through decrease in oxygenation and blood volume), WBV elicits a cerebral 'vasodilator stimulus' as a result of increased vibration transmission to the head.

Another factor that should be considered is the cerebral oxygen extraction factor. Based on human positron emission tomography studies of somatosensory and visual stimulation, Fox and Raichle (1984) and Fox et al. (1988) demonstrated a greater proportion of increase in cerebral blood flow and cerebral glucose utilization, but a very small increase in the cerebral oxygen uptake. Such an imbalance in these variables suggests that less oxygen is being removed from the blood; i.e., a low cerebral oxygen extraction factor. This phenomenon might result in vasodilation and opening of precapillaries (thus maintaining autoregulation), accompanied by an increase in both cerebral blood volume and oxygenation trends. In contrast, based on the trunk muscle NIRS trends observed in the Chapter 3, it could be argued that the oxygen extraction in the muscle is considerably greater than that occurring simultaneously in the brain during WBV. This could be the result of vasoconstriction in the 'focal' muscle during this period, which would compromise blood flow and therefore result in reduced blood volume and oxygenation. Along these lines, Jorgensen (1997) stated that: "muscle contraction may increase the intramuscular pressure and thereby cause restriction of the blood flow which limits the rate of energy supply".

The reverse cerebral and muscle trends observed concomitantly during exposure to WBV may suggest a redistribution of blood [the 'stealing' phenomenon as addressed by McAllister (1997)] to the brain to match the needs of neuronal activity due to WBV. Similarly, Schumacker and Cain (1987) proposed that *optimization of blood flow* occurs in such a way that the regional redistribution in the tissues matches its metabolic activity, thereby minimizing the possibility of overperfusing some organs. Moreover, Sibbald et al. (2000) suggested a positive correlation between perfusion heterogeneity and heterogeneous tissue metabolic demand, and concluded that:

"..heterogeneity of perfusion and oxygen delivery is a physiological property at all levels of the heterogeneously distributed metabolic demands. Tight coupling between the two indicates autoregulation. The ultimate site of sensing and controlling presumably is the consumer, the cell itself".

It is conceivable, therefore, that during WBV a differential outflow of blood to these two regions in need (i.e., cerebral and lumbar erector spinae muscle) at the same time might have resulted in the contrasting trends observed in the oxygenation and blood volume responses. If such an argument is tenable, such a dual and out-of-phase phenomenon suggests that the human body is trying to maintain homeostasis while matching the needs of oxygen demand at the 'focal' lumbar erector spinae muscle region to the oxygen delivery to the brain at the same time. To further strengthen these arguments, Gandevia (1999) lucidly stated that "muscles are the servants of the brain and the motoneurone constitutes the final common path for output from the central nervous system".

The increases in the acute physiological responses as a result of exposure to 3 to 6 Hz WBV (Chapter 4) are similar to those observed during light physical activity (McArdle et al. 1996, Pope et al. 1990), suggesting that the whole-body physiological system is not heavily stressed under these conditions. In general, men showed significantly greater physiological responses as a result of exposure to WBV than women. The subjects demonstrated significantly greater physiological responses during sitting 'Without' backrest support compared to sitting 'With' back support. However, the highest physiological responses were observed during WBV combined with handgrip contractions compared to WBV alone, suggesting a combination of physical work and exposure to WBV results in a greater cardiovascular stress and higher metabolic cost.

Changes in the mean cerebral and erector spinae oxygenation and blood volume responses were not dependent upon the peak oxygen uptake in either gender, suggesting that the level of aerobic fitness did not influence the tissue responses to WBV. However, despite the low metabolic rates reported during WBV, the effect of aerobic fitness was evident on the absolute and relative oxygen uptake responses, and oxygen pulse during isometric work. These observations suggest that high levels of aerobic fitness can buffer the increase in metabolic cost during exposure to WBV, most likely by acting on the oxygen transport system. As well, the degree of deoxygenation of the lumbar erector spinae muscle was not influenced by adipose tissue thickness in men and women.

Implications for Ergonomists:

Seated humans exhibit spinal resonance in the frequency range of 4.5 to 5.5 Hz, which falls within the range of 3 to 6 Hz usually experienced in the working and vehicular environments. The findings of the acute exposures to 3, 4.5 and 6 Hz in this study have several important implications that should be considered by ergonomists.

1. *Development of dose response guidelines based on changes in cerebral and muscle oxygenation and blood volume:*

   The present findings indicated that the increases in the cardiorespiratory and metabolic responses during exposure to WBV were quite small and did not place excessive stress on the cardiorespiratory system. However, the muscle oxygenation and blood volume changes measured by NIRS indicated that blood volume and oxygenation to lumbar muscles decreased during exposure to WBV, thereby making them more susceptible to fatigue. To this effect, electromyographic studies have demonstrated low-back muscle fatigue during exposure to WBV. Similarly, cerebral responses increased during WBV suggested an increased axonal transport in the brain. Although these acute responses provide useful information, as an ergonomist, it is essential to study the effects of chronic exposure (hours per shift to days and years of exposure) to WBV to determine the long term effects on these tissues. These results will help health professionals to develop dose-response guidelines for populations exposed to WBV in various industries; information that is currently lacking in the widely used ISO document (ISO 2631/part 1, 1997).

2. *Recommendations for the use of backrest in vehicles:*

Cerebral oxygenation and blood volume responses were not influenced by the presence or absence of a backrest. However, erector spinae oxygenation and blood volume decreased to a greater extent during sitting 'Without' backrest compared to sitting 'With' backrest. As well, higher cardiorespiratory responses were observed during sitting 'Without' a backrest. These observations highlight the importance of utilizing a backrest in transportation vehicles to support the postural muscles during prolonged exposure to WBV.

3. *Design of manual controls in occupations where exposure to whole-body vibration is prevalent:*

Many of the occupations in which individuals are exposed to WBV necessitate manual work such as the operation of controls, gripping tools, etc. Based on the present findings, addition of rhythmic isometric work significantly increased the cardiorespiratory stress, elevated cerebral oxygenation and blood volume, and reduced muscle oxygenation and blood volume to a greater extent compared to the absence of such work. These factors should be considered by ergonomists in designing workstations, recommending non-vibration tools to be used by employees, etc. in order to minimize undue fatigue and reduce the risk of injury.

4. *Development of specific guidelines for men and women:*

The absolute changes in the cardiorespiratory responses, cerebral and muscle oxygenation and blood volume were greater in men compared to women. As well, the acceleration values obtained at the cervical region were higher in men than women. These findings suggest a differential gender response to WBV, implying that it may be necessary to develop specific guidelines for men and women.

5. *Inclusion of regular physical activity into the lifestyle.*

In the present study, the peak aerobic fitness of the subjects attenuated the acute cardiorespiratory responses during exposure to WBV, but not the tissue oxygenation and blood volume responses during handgrip contractions. This suggests that improved aerobic fitness is important even for light work performed during WBV, especially when the exposure is for the greater part of the working day. It is important, therefore for ergonomists and occupational health and safety professionals to encourage workers to participate in employee fitness programs in order to minimize the stress associated with such activities.

Study #2: Comparison Between Arm Cranking and Repetitive Pushing-Pulling:

Pushing-pulling is an important task in many occupations. Research has suggested that individuals performing such an activity over extended periods may be more susceptible to low back problems (Bernard and Fine 1997, Burdorf and Sorock 1997). A reduction in localized blood flow has been implicated in this disorder. In this study the cardiorespiratory responses during pushing-pulling and arm cranking were compared using open circuit spirometry in healthy men and women. As well, NIRS, was used to evaluate the acute changes in oxygenation and blood volume in the biceps brachii muscle groups which were directly involved in both these exercise modes, and the lumbar erector spinae muscle which was an accessory muscle involved in the exercise.

The peak cardiorespiratory responses (absolute and relative oxygen uptake, oxygen pulse, respiratory exchange ratio, ventilation rate, and respiratory frequency) were significantly higher during arm cranking compared to pushing-pulling. Power output during arm cranking was significantly higher (by 79%) than pushing-pulling, with men demonstrating significantly 30% greater power output during both exercise modes. The lower power output generated during pushing-pulling resulted in significantly greater ratios of peak oxygen uptake to peak power output (by 72%) compared to arm cranking. In general, men showed greater cardiorespiratory responses (absolute oxygen uptake, oxygen pulse, ventilation rate, tidal volume) than women. However, gender did not influence the relative oxygen consumption, heart rate, respiratory frequency, ventilatory equivalent for oxygen, respiratory exchange ratio, rating of perceived exertion, and ratios of absolute and relative oxygen uptake to power output during both modes of exercise.

The oxygenation trends in the biceps brachii and erector spinae muscles decreased significantly during both exercise modes in both genders. During both exercise modes the oxygen demand was greater in the primary muscles (biceps), resulting in a greater blood volume in this region. However, the blood volume responses in the biceps brachii and erector spinae muscles demonstrated opposing trends. From the Figures 5.6B and 5.7B, it is evident that as the workload increased, biceps brachii blood volume increased. However, blood volume in the lumbar erector spinae decreased at the onset of exercise (Figures 6.3B and 6.4B) and demonstrated a compromised blood flow (in majority of the subjects) with increasing workload. This difference in blood volume profiles during the same exercise suggests that muscle co-contraction is possible (Kahn et al. 2000), and the blood flow to individual muscle tissue differs based on the oxygen demand. According to Sibbald et al. (2000), tissue perfusion and metabolic demand are heterogeneously distributed.

The increase in biceps brachii blood volume could be attributed to an increase in perfusion pressure (Boushel et al. 2000a). It appears that some of the increased blood volume in the biceps muscle during these two exercise modes may be due to a redistribution from the postural muscles, thereby making them more susceptible to fatigue. To this effect, Boushel et al. (2000b) demonstrated variability in the magnitude of blood flow in different muscles of the same muscle group. However, the biceps and lumbar erector spinae are two different muscle groups, and based on the heterogeneity in the muscle blood volume trends (Figures 5.6B, 5.7 B and Figures 6.3B, 6.4B), it is likely that oxygen supply and demand is regulated depending on the muscle location and muscle group (biceps and lumbar erector spinae). To this effect, Vallet (1998) stated that:

> "According to the metabolic theory of microvascular regulation, metabolic vasodilation in tissues with relatively high metabolic rates competes with sympathetic vasoconstrictor tone, thereby adjusting the balance between local tissue oxygen supply and demand."

Further, in explaining the redistribution of blood flow during acute dynamic exercise, McAllister (1997) stated significant increase in blood flow to the active muscle and heart. However, blood flow to the non-exercising skeletal muscle decreases significantly. This author also stated that such a redistribution of blood flow, thus increased cardiac output is achieved through vasoconstriction in these inactive organs, and vasodilation in the active muscles. This might have resulted in reverse erector spinae blood volume trends compared to the biceps blood volume trends. However, the range for blood volume responses calculated in both biceps (Table 5.3) and lumbar erector spinae muscles (Table 6.2) was not significantly different suggesting that regulation of blood flow to the individual muscle tissues at the end of exercise is similar.

Despite the lower cardiorespiratory responses during pushing-pulling, a greater degree of deoxygenation was observed in the biceps during this mode compared to arm cranking, suggesting a greater peripheral limitation in the biceps during pushing-pulling. This limitation was evident in the lumbar erector spinae muscle as well, further strengthening the argument that preference for task-specific aerobic protocols over standardized arm cranking protocols are essential at the workplace. Adipose tissue thickness of the biceps brachii and lumbar erector spinae did not influence the muscle oxygenation and blood volume measurements in both genders.

Implications for Ergonomists

Currently, many occupational fitness screening programs routinely use standardized exercise protocols for assessing cardiorespiratory fitness of potential applicants and employees. It is highly recommended that these screening protocols be specific to the job in question so as to increase the validity of the findings. In many physically demanding occupations such as the firefighters, police force and emergency medical services, physical ability tests that best reflect job requirements are also undertaken as part of the screening program. The results of the present study highlight the importance of using task-specific protocols, and demonstrate several points that have implications for ergonomists involved in occupational fitness testing programs.

1. *Assessment of the peak oxygen uptake during arm cranking may overestimate an individuals' functional work capacity:*

   The current results indicated that the peak oxygen uptake during arm cranking was significantly higher than that attained during pushing-pulling in both genders. This difference between the two exercise modes could be due to both biomechanical and physiological factors that could influence performance. Therefore, ergonomists should be aware that recommendations for job suitability based on arm cranking values could be erroneous if the job requirement involved extensive pushing-pulling.

2. *Relative contribution of the peripheral system:*

   The current findings demonstrated that the deoxygenation cost of the biceps brachii muscle (deoxygenation per unit amount of work) during pushing-pulling was significantly greater than that attained during arm cranking (i.e. pushing-pulling was less efficient than arm cranking). This suggests a greater peripheral contribution and limitation during pushing-pulling compared to arm cranking. Therefore, individuals employed in occupations that involve extensive pushing-pulling will most likely be predisposed to earlier fatigue than what an arm cranking test would suggest.

3. *Recruitment of accessory muscles:*

   Epidemiological studies have suggested that individuals employed in jobs that involve extensive pushing-pulling have a greater incidence of low back problems. The current evidence indicates that during simulated pushing-pulling in the laboratory, muscle oxygenation and blood volume to the erector spinae muscle are compromised. This suggests that these accessory muscles may be predisposed to fatigue.

General Limitations of the Present Studies:

All the subjects who participated in these studies were young, healthy volunteers from a university population and were not a representative sample of the actual workforce in a typical industry. Factors such as age and job experience that can affect work performance could influence the generalizability of these findings to the workplace. To this effect, Mital (1986) demonstrated that in general, responses of volunteers from a non-industrial workforce [such as student populations] to task variables [frequency of lift, lifting height, and size of carton lifted] were similar to those observed on an industrial workforce during repetitive lifting. However, they also showed that the lifting capabilities [maximum acceptable lifting weight] of such representative populations were significantly lower compared to experienced industrial workers. This implies that there is considerable adaptation in the physical work capacity of experienced workers, and therefore, the current observations on untrained student volunteers should be interpreted with caution. It is recommended that future research comparing these acute physiological and hemodynamic responses (muscle and cerebral) between novice subjects and experienced industrial workers be designed to evaluate whether there are any inherent differences between these populations. As well, replication of these findings by independent researchers is important to increase the impact of these findings.

Another limitation of the present findings could be the measurements obtained from the NRS instrumentation. The large variance in the muscle and cerebral hemodynamic responses in the present research [Table 2.3 in Chapter 2, Table 3.2 in Chapter 3, Table 5.3 in Chapter 5, and Table 6.2 in Chapter 6] is similar to that previously reported (Bhambhani et al. 1998, 2000, and 2001, Rundell et al. 1997). Whether this variance is an inherent nature of NIRS measurements is still not clear. It could be due to new (and may be relevant) hemodynamic behavior not identifiable by the existing oxygenation and blood volume measurements. Giller et al. (2000) suggested a similar explanation for the high variance in cerebral hemodynamic responses measured by transcranial Doppler ultrasound during rhythmic handgrip contractions. Using a larger sample size in these studies may have reduced the large variance in the NIRS measurements obtained in the present research. It is suggested that sample sizes for future studies, which incorporate both cardiorespiratory, and tissue hemodynamic measurements be calculated on the basis of statistical power that can be obtained with the NIRS variables of interest.

In the workplace, employees are exposed to a variety of environmental factors that can affect their work performance and the associated physiological responses. The current observations under controlled laboratory conditions can mask the true nature of job demands of workers who are exposed to whole body vibration or pushing/pulling in conjunction with other extraneous variables at the workplace. Keyserling (2000) suggested that laboratory studies are "generally incapable of proving a relationship between exposure and injury". Further, the subjects participating in these laboratory studies were instructed to maintain specific postures to suit the experimental testing procedures. However, in the real world there usually is considerable flexibility in the job demands and workplace design that allows workers to adopt postures that suit their comfort, which could influence the physiological responses during these tasks. Nevertheless, Keyserling (2000) stressed the importance of laboratory studies for providing valuable scientific insights into how the human body responds to risk factors in the workplace.

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APPENDIX A

CONSENT FORMS
AND
INFORMATION SHEETS

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CONSENT FORM

Part 1 (to be completed by the Principal Investigator):

Title: Dose Response Effects of Whole Body Vibration on Acute Physiological Responses in Healthy Men and Women

Principal Investigator(s): Dr. Yagesh Bhambhani

Co-Investigator(s): Ram Maikala, Ph.D Student, Faculty of Rehabilitation Medicine; 7248

Part 2 (to be completed by the research subject):

Do you understand that you have been asked to be in a research study?	Yes	No
Have you read and received a copy of the attached Information Sheet?	Yes	No
Do you understand the benefits and risks involved in taking part in this research study?	Yes	No
Have you had an opportunity to ask questions and discuss this study?	Yes	No
Do you understand that you are free to refuse to participate or withdraw from the study at any time? You do not have to give a reason and it will not affect your care. *(Use wording appropriate to your subject group)*	Yes	No
Has the issue of confidentiality been explained to you? Do you understand who will have access to your records?	Yes	No
Do you want the investigator(s) to inform your family doctor that you are participating in this research study? *If so, please provide your doctor's name:* ______________________ *(N.B. This question is optional).*	Yes	No

This study was explained to me by: ______________________

I agree to take part in this study.

______________________ ______________

Signature of Research Participant   Date   Witness

____

Printed Name   Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

______________________ ______________

Signature of Investigator or Designee   Date

THE INFORMATION SHEET MUST BE ATTACHED TO THIS CONSENT FORM AND A COPY GIVEN TO THE RESEARCH SUBJECT

Faculty of Rehabilitation Medicine

2-64 Corbett Hall • University of Alberta • Edmonton • Canada • T6G 2G4
Telephone: (780) 492-2499 • Fax: (780) 492-1626

UNIVERSITY OF ALBERTA

INFORMATION SHEET

Project Title: Dose Response Effects of Whole Body Vibration on Acute Physiological Responses in Healthy Men and Women

Investigator(s):

Dr. Y. Bhambhani, Professor
3-73 Corbett Hall
Department of Occupational Therapy
University of Alberta
Tel: 492 – 7248

Rammohan V. Maikala, PhD Candidate
1-94 Corbett Hall
Work Physiology Lab
University of Alberta
Tel: 492 – 0404

(1) Purpose

Vibration is movement of the body that occurs when a person sits in a car or bus. A dose of vibration may cause pleasure, pain, or motion sickness. This depends on the type of motion and activities of the person. It can also depend on other things in the environment. Small doses of vibration increase the physiological stress on the body in the same way as walking or jogging. Exposure to vibration for several years may cause physical and mental changes.

Some researchers think that the body's response to vibration may depend upon the person's physical fitness. Others feel that vibration affects men and women differently. However, there are no studies that have tested these theories.

In this study, we will test: a) the effects of vibration on the oxygen levels of the back muscles and brain in healthy males and females, and b) examine the relationship of these changes with the aerobic fitness levels of the subjects.

(2) Study Requirements

This study will last two weeks. During this time you will be tested four times. **Each test will last approximately 45 minutes.** These tests will tell us how well your heart, lungs, arm muscles and brain are working. The four tests are: arm cranking till exhaustion, 16 minutes of seated vibration at 3 Hz, 4.5 Hz and 6 Hz with rest in between vibration. During vibration, you will be asked to squeeze a grip strength instrument with your right hand for one minute. You will be also asked to do a deep breathing for 15 seconds during these vibration tests. You will be shown how the testing is done by a research assistant before you volunteer for the study.

(b) Testing Methodology

In the first test, you will be asked to exercise with arms for approximately 12 to 15 minutes. The test will be started with no load for two minutes. After that, the load will be increased every two minutes until you are tired and cannot exercise any more. After the test, you will be asked to continue exercising with no load for two minutes and then rest for four minutes. **You can stop exercising at any time during the test if you feel you cannot continue or do not want to continue.**

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In the next three tests you will be asked to sit on a vibrating chair for 15 minutes. The chair will be vibrated at three different levels (3 Hz, 4.5 Hz or 6 Hz). These levels are similar to that you feel while sitting in a car or truck that is going over a bumpy road at a slow speed. During all the exercise tests we will place a sterilized rubber tube in your mouth. This is like a snorkel that is used for underwater swimming. Your nose will be closed with a nose clip. The tube will be connected to a machine that will measure how hard you are breathing and how much oxygen you are using. We will place four sticky pieces of tape on your chest. These tapes will be connected with some wires to a machine. This will tell us how your heart is working during the exercise tests. We will also place a cuff around your left arm to measure your blood pressure while you are exercising. We will place elastic bandages around the lower back and forehead. These elastic bandages have a light source in them. They will measure how fast the muscles and brain utilize oxygen.

All these machines have been checked and they are working properly. Only a research assistant who knows how to use them will test you. If we see anything unusual while you are being tested we will stop the test immediately.

(4) Risks

During the arm cranking test you will: feel tired, have difficulty in breathing, and sweat. You may feel nauseous and dizzy during or after the exercise tests. This usually happen when a person exercises and will last for a few minutes. During any maximal exercise test, there is a possibility that you may have a problem with the heart. In this study, you will be allowed to volunteer only if you pass the screening process. During the tests, your responses will be continuously monitored. If anything unusual is observed the test will be stopped immediately. Over the last 10 years, we have safely conducted approximately 500 exercise tests using this procedure.

Studies that have examined the effects of vibration at these levels have shown no harm. During the vibration tests, your heart rate and breathing will increase as it does while walking at a comfortable speed.

Research studies that have tested volunteers during arm exercise and vibration have shown that they can be safely tested using these procedures.

(5) Benefits

If you volunteer for this study, you will get important information on the fitness level of the heart, lungs and muscles. This study will help us understand how vibration affects the brain, heart, lungs, and muscles in healthy men and women.

(6) Confidentiality

All information will be held confidential except when professional codes of ethics and/or legislation require reporting. Any report published as a result of this study will not identify you by name. The study data will be kept for at least seven years after the study is completed in a secure area accessible only by research team.

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Telephone: (780) 492-2499 • Fax: (780) 492-1626

(7) Freedom to Withdraw

You are free to withdraw from the research study at any time. If any knowledge gained from this or any other study becomes available which could influence your decision to continue in this study, you will be promptly informed.

(8) Additional Contact

If you have any questions or concerns about this study, please contact Dr. Paul Hagler, Associate Dean of Graduate Studies, Faculty of Rehabilitation Medicine; Tel: 492-0841, email: paul.hagler@ualberta.ca.

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CONSENT FORM

Part 1 (to be completed by the Principal Investigator):

Title: Tissue Oxygenation and Metabolism Comparisons during Incremental Pushing and Pulling and Arm Cranking

Principal Investigator(s): Dr. Yagesh Bhambhani

Co-Investigator(s): Ram Maikala, Ph.D Student, Faculty of Rehabilitation Medicine; 7248

Part 2 (to be completed by the research subject):

Do you understand that you have been asked to be in a research study?	**Yes**	**No**
Have you read and received a copy of the attached Information Sheet?	**Yes**	**No**
Do you understand the benefits and risks involved in taking part in this research study?	**Yes**	**No**
Have you had an opportunity to ask questions and discuss this study?	**Yes**	**No**
Do you understand that you are free to refuse to participate or withdraw from the study at any time? You do not have to give a reason and it will not affect your care. ***(Use wording appropriate to your subject group)***	**Yes**	**No**
Has the issue of confidentiality been explained to you? Do you understand who will have access to your records?	**Yes**	**No**
Do you want the investigator(s) to inform your family doctor that you are participating in this research study? If so, please provide your doctor's name: ______________________ ***(N.B. This question is optional).***	**Yes**	**No**

This study was explained to me by: ______________________

I agree to take part in this study.

______________________ ______________

Signature of Research Participant **Date** **Witness**

____

Printed Name **Printed Name**

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

______________________ ______________

Signature of Investigator or Designee **Date**

THE INFORMATION SHEET MUST BE ATTACHED TO THIS CONSENT FORM AND A COPY GIVEN TO THE RESEARCH SUBJECT

Faculty of Rehabilitation Medicine

2-64 Corbett Hall • University of Alberta • Edmonton • Canada • T6G 2G4
Telephone: (780) 492-2499 • Fax: (780) 492-1626

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INFORMATION SHEET

Project Title: Tissue Oxygenation and Metabolism Comparisons during Incremental Pushing and Pulling and Arm Cranking

Investigator(s):

Dr. Y. Bhambhani, Professor
3-73 Corbett Hall
Department of Occupational Therapy
University of Alberta
Tel: 492 – 7248

Ram Maikala
PhD Candidate
1-94 Corbett Hall
University of Alberta
Tel: 432-7943/ 492-0404

(1) Purpose

Pushing and pulling is moving any material without walking for some distance. It can be one hand or two-handed werk like shoveling snow. Some researchers think that the body's response to pushing and pulling may depend upon the person's physical fitness. Others feel that pushing and pulling affects men and women differently. However, there are no studies that have tested these theories.

In this study, we will test: a) the effects of pushing and pulling and arm cranking on the oxygen levels of the back and arm muscles in healthy males and females.

(2) Study Requirements

This study will last three weeks. During this time you will be tested three times. Each test will last approximately 45 minutes. You will be tested for your back muscle endurance on the first day. This test will tell you how long you can hold your back when your upper body is unsupported. For this test, you will be asked to lye on your stomach on a bed for 2 minutes. A weight attached to a rope will be lowered to touch the portion between your shoulders. At the end of 2 minutes, a portion of the bed supporting your upper body is lowered. You will be asked to hold your arms across the chest and keep in contact with the weight as long as you can. When you are unable to be in contact with the rope, test will be stopped and your upper body will be supported for 4 minutes. Next two tests will tell us how well your heart, lungs, arm and back muscles working. These two tests are: arm cranking till exhaustion, and one hand pulling and pushing till exhaustion. You will be shown how the testing is done by a research assistant before you volunteer for the study.

During the first test, a blood pressure cuff will be folded around your dominant hand and blood flow will be stopped for a brief period. You will be asked to sit in a chair during this blood pressure test. This test will be useful for finding your minimum and maximum oxygen values in the arm at rest.

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(b) Testing Methodology

In the first test, you will be asked to exercise with arms for approximately 8 to 12 minutes. The test will be started with no load for two minutes. After that, the load will be increased every two minutes until you are tired and cannot exercise any more. After the test, you will be asked to continue exercising with no load for two minutes and then rest for four minutes. **You can stop exercising at any time during the test if you feel you cannot continue or do not want to continue.**

In the next four tests you will be asked to push and pull an attachment on the work simulator at your comfortable height using your dominant hand. The work simulator is adjustable for any height. During all the exercise tests we will place a sterilized rubber tube in your mouth. This is like a snorkel that is used for underwater swimming. Your nose will be closed with a nose clip. A tube will be connected to a machine that will measure how hard you are breathing and how much oxygen you are using. We will place four sticky pieces of tape on your chest. These tapes will be connected with some wires to a machine. This will tell us how your heart is working during the exercise tests. We will place elastic bandages around the lower back and forearm. These elastic bandages have a light source in them. They will measure how fast the muscles and utilize oxygen. For measuring your back endurance, you will be asked to rest your body on a couch with lower half of your body strapped to the couch. When instructed, you are asked to raise your upper body horizontal to the couch as long as you can.

All these machines have been checked and they are working properly. Only a research assistant who knows how to use them will test you. If we see anything unusual while you are being tested we will stop the test immediately.

(4) Risks

During the arm cranking test you will: feel tired, have difficulty in breathing, and sweat. You may feel nauseous and dizzy during or after the exercise tests. This usually happen when a person exercises and will last for a few minutes. During any maximal exercise test, there is a possibility that you may have a problem with the heart. In this study, you will be allowed to volunteer only if you pass the screening process. During the tests, your responses will be continuously monitored. If anything unusual is observed the test will be stopped immediately. Over the last 10 years, we have safely conducted approximately 500 exercise tests using this procedure. During the blood pressure cuff test, you may feel dizzy for few minutes but will go away as soon as the cuff is opened.

Research studies that have tested volunteers during arm exercise and pushing and pulling have shown that they can be safely tested using these procedures.

(5) Benefits

If you volunteer for this study, you will get important information on the fitness level of the heart, lungs and muscles. This study will help us understand how pushing and pulling affects the heart, lungs, and muscles in healthy men and women.

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(6) Confidentiality

All information will be held confidential except when professional codes of ethics and/or legislation requir . reporting. Any report published as a result of this study will not identify you by name. The study data will be kept for at least seven years after the study is completed in a secure area accessible only by research team.

(7) Freedom to Withdraw

You are free to withdraw from the research study at any time. If any knowledge gained from this or any other study becomes available which could influence your decision to continue in this study, you will be promptly informed.

(8) Additional Contact

If you have any questions or concerns about this study, please contact Dr. Paul Hagler, Associate Dean of Graduate Studies, Faculty of Rehabilitation Medicine; Tel: 492-0841, email: paul.hagler@ualberta.ca.

Physical Activity Readiness Questionnaire - PAR-Q (revised 1994)

PAR - Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	1.	Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
☐	☐	2.	Do you feel pain in your chest when you do physical activity?
☐	☐	3.	In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4.	Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5.	Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	6.	Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
☐	☐	7.	Do you know of <u>any other reason</u> why you should not do physical activity?

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to <u>all</u> PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

[illegible]

<u>Informed Use of the PAR-Q</u>: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

You are encouraged to copy the PAR-Q but only if you use the entire form

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction.

NAME ______________________________

SIGNATURE ______________________________ DATE ______________

SIGNATURE OF PARENT ______________________________ WITNESS ______________
or GUARDIAN (for participants under the age of majority)

Supported by: Health Canada Santé Canada

APPENDIX B

BONFERRONI ADJUSTMENTS

APPENDIX B.1

Chapter 2

Table 2.2: Postural and acceleration differences during WBV at different doses in healthy men and women

∝ = 0.05 ÷ by 4 (# of comparisons) = 0.0125 level ≈ 0.01[Ψ]

Table 2.3: Cerebral Oxygenation and Blood Volume differences during WBV at different doses in healthy men and women

∝ = 0.05 ÷ by 4 (# of comparisons) = 0.0125 level ≈ 0.01[Ψ]

APPENDIX B.2

Chapter 3

Table 3.2: Erector Spinae Oxygenation and Blood Volume values

∝ = 0.05 ÷ by 4 (# of comparisons) = 0.0125 level ≈ 0.01[Ψ]

APPENDIX B.3

Chapter 4

Table 4.2: Metabolic and Respiratory responses during Whole-body Vibration

∝ = 0.05 ÷ by 7 (# of comparisons) = 0.007 level ≈ 0.01[Ψ]

Table 4.3: Cardiovascular responses during Whole-body Vibration

∝ = 0.05 ÷ by 4 (# of comparisons) = 0.0125 level ≈ 0.01[Ψ]

APPENDIX B.4

Chapter 5

Table 5.2: Peak Physiological, Perceptual and Biomechanical Responses during Incremental Pushing-Pulling and Incremental Arm Cranking in Healthy Men and Women

∝ = 0.05 ÷ by 13 (# of comparisons) = 0.003 level ≈ 0.01[Ψ]

Table 5.3: Biceps Brachii Oxygenation and Blood Volume responses

∝ = 0.05 ÷ by 7 (# of comparisons) = 0.007 level ≈ 0.01[Ψ]

APPENDIX B.5

Chapter 6

Table 6.2: Erector Spinae Oxygenation and Blood Volume responses during Incremental Pushing-Pulling and Incremental Arm Cranking in Healthy Men and Women

$\propto$ = 0.05 ÷ by 7 (# of comparisons) = 0.007 level ≈ 0.01[Ψ]

[Ψ] **For multiple comparisons, any $\propto$ value obtained less than $\propto$=0.01 [for a smaller sample size] can be approximated to $\propto$ = 0.01 *(Personal Communication, Dr. Todd Rogers, Director, Centre for Research in Applied Measurement and Evaluation, University of Alberta, Edmonton, CANADA).***