NOTE TO USERS

THE UNIVERSITY OF ALBERTA

COMPARISON BETWEEN HEALTHY AND LOW BACK PAIN SUBJECTS DURING STATIC AND DYNAMIC CONTRACTIONS OF THE ERECTOR SPINAE MUSCLE

By

Robert Thomas Kell

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Faculty of Physical Education and Recreation

Edmonton Alberta

Spring 2005

Your file Votre référence
ISBN: 0-494-08258-5
Our file Notre référence
ISBN: 0-494-08258-5

DEDICATION

TO MY WIFE AND FAMILY

ABSTRACT

The purpose of this thesis was to compare healthy and non-specific low back pain (LBP) subjects on three different tests: (1) Biering-Sorensen muscular endurance (BSME) test, (2) repetitive incremental lifting and lowering (RILL) test, and (3) psychophysical evaluation of the maximal acceptable weight (MAW) of lift in order to determine differences and relationships between groups on cardiorespiratory, muscle blood volume (Mbv) and oxygenation (Mox) variables. It was hypothesized that differences and relationships between the variables of interest could be used to determine if a lower fitness level existed in the LBP subjects, and which variables can be used to determine this. A sample size of 50 LBP subjects age matched with healthy controls (case control in a cross-sectional design) was used in each test: BSME 60 (30 · group^{-1}), RILL 68 (34 · group $^{-1}$), and psychophysical evaluation 24 (12 · group^{-1}) with different subjects in each test. The procedure for all tests was as follows: 2-min resting baseline, the *"test"*, and 4-min recovery period. The results indicated that during all studies the erector spinae Mbv and Mox trends were similar on the left and right sides and similar between the groups. However, some inter-subject variation in Mbv and Mox was noted in study three. The theory of a reduced fitness level in the LBP subjects was supported as important cardiorespiratory variables were lower at peak and at ventilatory threshold (VT) during the peak RILL test. Additionally, during the submaximal psychophysical test the LBP subjects demonstrated greater cardiorespiratory stress, working above their individual VT. The LBP subjects showed reduced erector spinae Mbv and Mox changes during the BSME and the peak RILL test, but not the submaximal psychophysical test. It was concluded that LBP subjects might have reduced ability to deliver and extract

oxygen to/from the working muscles, and these differences may be the result of a reduced fitness level stemming from a lower level of physical activity.

ACKNOWLEDGEMENTS

I would like to thank all of the subjects, who made the study possible, as well as my advisors and committee members who gave me guidance through the process. Funding for this research project from the Alberta Workers' Compensation Board is acknowledged.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER TWO (Study one)

CHAPTER THREE (Study two)

CHAPTER FOUR (Study three)

LIST OF FIGURES

CHAPTER TWO (Study one)

CHAPTER THREE (Study two)

CHAPTER FOUR (Study three)

NOMENCLATURE

½ recovery time (½ rec) – is calculated as the time taken to reach 50% of the post-exercise maximal value (change in amplitude).

Arteriovenous oxygen difference (a-vO_2diff) – is the amount of oxygen released by hemoglobin during circulation to the tissues of interest (muscle), and is calculated as the difference between the quantities of oxygen carried in arterial blood minus the amount of oxygen returning in venous blood ($ml \cdot dl^{-1}$).

Carbon dioxide produced (VCO_2) – the volume of carbon dioxide produced by the body ($L \cdot min^{-1}$).

Central fatigue – perception of stress associated with the cardiorespiratory system as indicated on the Borg Scale for ratings of perceived exertion.

Chronic non-specific low back pain (LBP) – back pain in the lumbar region (≥3 months in duration) that is musculoskeletal (soft tissue) in nature.

Dynamic contraction – is a muscle contraction during which the force exerted fluctuates as the muscle shortens to accommodate change in muscle length and/or joint angle throughout the range of motion while moving a constant external load.

Fatigue – The inability to maintain the desired power output due to a transient loss of physical capacity resulting from the preceding physical work.

Heart rate (HR) – is the number of cardiac cycles or beats of the heart per minute (beats $\cdot min^{-1}$)

Manual Materials Handling (MMH) – are tasks (jobs) that require the movement (carrying, lifting, lowering, pushing, pulling) of materials common to a manual labour type work environment (e.g., construction, masonry).

Maximum acceptable weight (MAW) – is the selection of a maximum weight of load according to the subject's perception of effort. As the subject lifts and lowers a basket from the floor to a waist height table he/she adds and removes weight from the basket, while avoiding overexertion or excessive fatigue. The selected weight is then classified as the maximum acceptable weight.

Mbv - muscle blood volume as measured by Near Infrared Spectroscopy (NIRS) (optical density).

Mbv-delta - is the change in Mbv, in either a positive or negative direction, measured from the last 20-sec of resting baseline to the lowest or highest Mbv value during exercise (optical density).

Mbv-max - the maximum Mbv value achieved during exercise (optical density).

Mbv-min - the minimum Mbv value achieved during exercise (optical density).

Mbv-range - is the change in Mbv from the highest value during exercise to the lowest Mbv value during recovery (optical density).

Minute ventilation expired (V_E) – is the volume of air expired each minute and can be determined as tidal volume times breathing frequency ($L \cdot min^{-1}$).

Mox - muscle oxygen volume as measured by NIRS (optical density).

Mox-delta – is the change in Mox, in either a positive or negative direction, as measured from the last 20-sec of resting baseline to the lowest or highest Mox value during exercise (optical density).

Mox-min - the minimum Mox value achieved during exercise (optical density).

Mox-max - the maximum Mox value achieved during exercise (optical density).

Mox-range - is the change in Mox from the lowest value during exercise to the highest Mox value during recovery (optical density).

Muscular endurance – the ability of a muscle or group of muscles to repeatedly exert a force against a given resistance.

NIRS – Continuous wave near infrared spectroscopy, with associated wavelengths of deoxygenated hemoglobin 760 nm and the oxygenated hemoglobin 850 nm.

Oxygen consumption (VO_2) – the amount of oxygen consumed and utilized by the body ($L \cdot min^{-1}$).

Peripheral fatigue – perception of stress associated with the arms/shoulders and low back, as indicated on the Borg Scale for ratings of perceived exertion.

Respiratory exchange ratio (RER) – the ratio between the VCO_2 produced and VO_2 consumed.

Static contraction – is a contraction of a muscle that produces an increase in muscle tension, but does not cause meaningful limb displacement and therefore does not result in movement of the skeleton.

Ventilatory Threshold (VT) – is the point where the linear rise in V_E becomes curvilinear, VCO_2 becomes curvilinear and VO_2 remains linear. VT can be determined via ventilatory equivalents (V_E/VO_2) method or the V-slope methods (VCO_2 by VO_2).

More specifically, the intent was to stress the cardiorespiratory and musculoskeletal system maximally in an attempt to attain the following criteria for VO_{2max}: (1) a levelling off (increase of less than 100 ml · min^{-1}) or a decrease in the oxygen consumption (VO_2) with increasing workload, (2) age predicted maximal HR, calculated as (220 – age), and (3) a respiratory exchange ratio >1.10.

VO_{2max} – the maximum amount of oxygen that can be utilized by the body, usually under exercise conditions (L · min^{-1} or ml · kg^{-1} · min^{-1}).

VO_{2peak} – the largest amount of oxygen that can be consumed and utilized by the body during a particular exercise (e.g., lifting and lowering, cycling) (L · min^{-1} or ml · kg^{-1} · min^{-1}).

VO_{2peak} (L · min^{-1}) – is the largest amount of oxygen that can be consumed per minute (absolute).

VO_{2peak} (ml · kg^{-1} · min^{-1}) – is the largest amount of oxygen that can be consumed per kilogram of body weight per minute (relative).

Volitional fatigue – the point at which the subject is unable to meet the exercise instructions set out by the researcher and self-terminates the exercise test due to a transient loss of physical capacity.

CHAPTER ONE

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Seventy percent of individuals will suffer from chronic (≥3-months) low back pain (LBP) during their lifetime [1], with LBP being responsible for ~21% of compensable work injuries [23]. Low back pain has been shown to be influenced by both physiological and psychological stress [23], and may arise from various activities of daily living, with many occurring during manual materials handling (MMH) in the occupational setting [21]. During MMH both static (isometric) and dynamic muscle contractions are used in order to complete the necessary duties. Two situations that have been associated with an increased risk of LBP are prolonged static contractions or repetitive dynamic contractions of the erector spinae muscles [3, 22].

Prolonged static contractions can result in fatigue predisposing a person to injury and LBP [3]. Low back pain due to static contraction has been found in occupational settings [2, 24, 26]. Muscular pain or injury associated with static contractions likely occurs as a result of fatigue from holding the body in one position for long periods [24], which has been suspected to cause muscle imbalance and ischemia [28]. Alternatively, repetitive lifting has been associated with back pain complaints, thought to be a result of repetitive, rapid loading causing cyclic changes in spinal compression [22]. In 60% of LBP injury reports, overexertion was noted as the primary cause of which 66% involved repetitive lifting [21, 22]. Research on prolonged static and/or repetitive dynamic contractions of the erector spinae muscles has shown an increased risk of muscle fatigue, which may result in injury to the low back and consequently LBP [22, 28].

Some common explanations for low back muscle fatigue and injury have been abnormal erector spinae muscle vasculature [6] and variation in muscle fiber type

characteristics [13], both of which may influence the onset rate of erector spinae muscle fatigue. However, recently reduced fitness level was purported to be associated with LBP [17, 22]. Additionally, lower physical activity levels were found in LBP subjects [19, 27], resulting in reduced cardiorespiratory function [17, 29]. The result of the reduced fitness level may be earlier whole body (cardiorespiratory) and/or site-specific fatigue (peripheral) diminishing work capacity during MMH and increasing the risk of injury.

Consequently, to investigate the presence of a reduced fitness level the LBP subjects were sub-divided based on activity level (LBP-sedentary: exercised <3 d/wk, <30 min/day; LBP-active: exercised ≥3 d/wk, ≥30-min/d). The cardiorespiratory, erector spinae muscle blood volume (Mbv) and oxygenation (Mox) responses in the LBP subjects were measured during physical activity to examine the possibility of a reduced central and peripheral fitness level. Cardiorespiratory (central) measures have been made during many forms of activity, including weight lifting [5], cycling [30], running and box lifting [18]. However, the use of near infrared spectroscopy (NIRS) provided a non-invasive and continuous method of examining relative changes in Mbv and Mox levels in the arterioles, venules, and capillaries of the erector spinae muscle (peripheral) [4]. Monitoring changes in Mbv and Mox trend and amplitude provided an index of oxygen supply and extraction in the muscle of interest [4]. Near infrared spectroscopy has been demonstrated to be a valid [12] and reliable (Appendix B) [8] measure of Mbv and Mox. The application of NIRS to the erector spinae muscles of health subjects during both static (Appendix B) [8, 31] and dynamic (Appendix C) [7, 14] contractions has been studied. However, the application of NIRS to both static [11, 16] and dynamic [10] erector spinae muscle contraction in LBP subjects is relatively novel. However, the limited research

agrees that NIRS can differentiate between healthy and LBP subjects [10, 11, 16]. Together the cardiorespiratory, Mbv and Mox responses were used to determine the interplay between potential central (cardiorespiratory) and peripheral (Mbv and Mox) fatigue in the LBP subjects during both static and dynamic contractions and the possibility of whole body and/or site specific reductions in fitness level.

It is important that the testing modes be as similar as possible in movement to those found in manual materials handling (MMH), in order to allow a better comparison to the work place. Typical laboratory testing modes use treadmill running or cycle ergometry, but the physiological responses differ in magnitude from that of static contractions and repetitive lifting [20, 25]. Thus, the assessment modes selected for the present study were the: (1) Biering-Sorensen muscular endurance (BSME) test, (2) repetitive incremental lifting and lowering (RILL) test, and (3) psychophysical evaluation of maximal acceptable weight (MAW) of lift. The BSME examines erector spinae muscle response to a prolonged submaximal static contraction [9], similar to that which may be used in standing or sitting for long periods [3]. The RILL test uses dynamic contractions of the erector spinae, arm and leg muscles in a repetitive and incremental fashion [25], which stresses both the cardiorespiratory and peripheral muscles [7]. The psychophysical evaluation examined the subject's perception and their physical response to a MAW during prolonged submaximal (8-hours) lifting and lowering [15]. For further information regarding LBP and the tests employed in this thesis please refer to Appendix A.

PURPOSES OF THE RESEARCH

Study One:

Purposes

1) Compare Mbv and Mox responses to erector spinae static muscle contraction in healthy, LBP, LBP-active and LBP-sedentary subjects.
2) Determine if any correlations exist between BSME time, Mbv and Mox.

Hypotheses

1) The healthy subjects will show significantly greater change in erector spinae Mbv and Mox as compared to the LBP subjects.
2) The BSME time will be significantly correlated with changes in Mbv and Mox.

Study Two:

Purposes

1) Compare the peak cardiorespiratory, Mbv and Mox changes in the healthy, LBP, LBP-active, and LBP-sedentary groups during the RILL test.
2) Determine which factors, central and/or peripheral, will best predict each group's VO_{2peak}.

Hypotheses

1) The LBP and LBP-sedentary subjects will demonstrate a significantly reduced cardiorespiratory response as compared to the healthy subjects.

2) The LBP and LBP-sedentary subjects will demonstrate significantly lower changes in amplitude in Mbv and Mox variables.
3) Muscle blood volume and Mox changes will be more strongly correlated in LBP and LBP-sedentary groups than LBP-active and healthy subjects.
4) The LBP-active subjects will show a significantly greater peak cardiorespiratory response in comparison to the LBP-sedentary subjects.

Study Three:

Purposes

1) Compare the ventilatory (lactate) threshold (i.e., VT) during incremental lifting and lowering in healthy and LBP subjects.
2) Examine the relationship of pertinent physiological variables at VT and the psychophysically determined MAW in the healthy and LBP subjects.
3) Examine the Mbv and Mox responses during the MAW protocol in the healthy and LBP subjects.

Hypotheses

1) The LBP subjects will show a significantly lower VO_2 at VT in comparison to the healthy subjects.
2) There will be a significant relationship between the VO_2 values at VT and the MAW.
3) The LBP subjects will demonstrate significantly lower localized Mox as compared to the healthy subjects.

REFERENCES

1. Andersson, G. B. Epidemiologic aspects on low-back pain in industry. *Spine.* 6:53-60., 1981.
2. Burdorf, A. and H. Zondervan. An epidemiological study of low-back pain in crane operators. *Ergonomics.* 33:981-987, 1990.
3. Callaghan, J. P. and S. M. McGill. Low back joint loading and kinematics during standing and unsupported sitting. *Ergonomics.* 44:280-294, 2001.
4. Chance, B., M. Dait, C. Zhang, T. Hamaoka, and F. Hagerman. Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. *Am J Physiol.* 262:C766-C775, 1992.
5. Collins, M. A., K. J. Cureton, D. W. Hill, and C. A. Ray. Relationship of heart rate to oxygen uptake during weight lifting exercise. *Med Sci Sports Exerc.* 23:636-640, 1991.
6. Kauppila, L. I. Prevalence of stenotic changes in arteries supplying the lumbar spine. A postmortem angiographic study on 140 subjects. *Ann Rheum Dis.* 56:591-595, 1997.
7. Kell, R. T. and Y. Bhambhani. Cardiorespiratory & Hemodynamic Responses during Repetitive Incremental Lifting & Lowering in Healthy Males & Females. *Eur J Appl Physiol.* 90:1-9, 2003.
8. Kell, R. T., M. Farag, and Y. Bhambhani. Reliability of erector spinae oxygenation and blood volume responses using near-infrared spectroscopy in healthy males. *Eur J Appl Physiol.* 91:499-507, 2004.

9. Koumantakis, G. A., F. Arnall, R. G. Cooper, and J. A. Oldham. Paraspinal muscle EMG fatigue testing with two methods in healthy volunteers. Reliability in the context of clinical applications. *Clinical Biomechanics (Bristol, Avon).* 16:263-266., 2001.

10. Kovacs, K. M., W. S. Marras, A. S. Litsk, P. Gupta, and S. A. Ferguson. Localized oxygen use of healthy and low back pain individuals during controlled trunk movements. *J Spinal Disord.* 14:150-158, 2001.

11. Kunimune, Y., Y. Harada, Y. Kabuto, K. Takeuchi, M. Senda, and H. Inoue. Recovery from exercise-induced desaturation in the paraspinal muscles in idiopathic scoliosis. *Spine.* 24:2019-2024, 1999.

12. Mancini, D., L. Bolinger, L. Li, K. Kendrick, B. Chance, and J. Wilson. Validation of near-infrared spectroscopy in humans. *J Appl Physiol.* 77:2740-2745, 1994.

13. Mannion, A. F. Fibre type characteristics and function of the human paraspinal muscles: normal values and changes in association with low back pain. *J Electromyogr Kinesiol.* 9:363-377, 1999.

14. Maronitis, A. B., K. M. Kovacs, R. E. Splittstoesser, and W. S. Marras. The effectiveness of whole body localized measures of fatigue. In *HFES*: Proceedings of the IEA, pp. 5-91-95-94, 2000.

15. Mital, A. The psychophysical approach in manual lifting--a verification study. *Hum Factors.* 25:485-491., 1983.

16. Miyake, M., Y. Harada, M. Senda, K. Oda, and H. Inoue. Oxygen dynamics at paraspinal muscles during exertion using near-infrared spectroscopy in patients with degenerative lumbar scoliosis. *J Orthop Sci.* 81:187-191, 2003.

17. Nielens, H. and L. Plaghki. Cardiorespiratory fitness, physical activity level, and chronic pain: are men more affected than women? *Clin J Pain.* 17:129-137, 2001.

18. Nindl, B. C., M. A. Sharp, R. P. Mello, V. J. Rice, M. M. Murphy, and J. F. Patton. Gender comparison of peak oxygen uptake: repetitive box lifting versus treadmill running. *Eur J Appl Physiol Occup Physiol.* 77:112-117, 1998.

19. Payne, N., N. Gledhill, P. T. Katzmarzyk, and V. Jamnik. Health-related fitness, physical activity and history of back pain. *Can J Appl Physiol.* 24:236-249, 2000.

20. Petrofsky, J. S. and A. R. Lind. Comparison of metabolic and ventilatory responses of men to various lifting tasks and bicycle ergometry. *J Appl Physiol.* 45:60-63, 1978.

21. Pope, M. H. Occupational Hazards for Low Back Pain. In: *Low Back Pain: A scientific and clinical overview.* J. N. Weinstein and S. L. Gordon (Eds.) Rosemont: American Academy of Orthopaedic Surgeons, 1996, pp. 333-345.

22. Pope, M. H. Risk indicators in low back pain. *Ann Med.* 21:387-392., 1989.

23. Pope, M. H., K. L. Goh, and M. L. Magnusson. Spine ergonomics. *Annu Rev Biomed Eng.* 4:49-68, 2002.

24. Ratzon, N. Z., T. Yaros, A. Mizlik, and T. Kanner. Musculoskeletal symptoms among dentists in relation to work posture. *Work.* 15:153-158, 2000.

25. Sharp, M. A., E. Harman, J. A. Vogol, J. J. Knapik, and S. J. Legg. Maximal aerobic capacity for repetitive lifting: comparison with three standard exercise tests and modes. *Eur J Appl Physiol Occup Physiol.* 57:753-760, 1988.

26. Skov, T., V. Borg, and E. Orhede. Psychosocial and physical risk factors for musculoskeletal disorders of the neck, shoulders, and lower back in salespeople. *Occup Environ Med.* 53:351-356, 1996.

27. Spenkelink, C. D., M. M. Hutten, H. J. Hermens, and B. O. Greitemann. Assessment of activities of daily living with an ambulatory monitoring system: a comparative study in patients with chronic low back pain and nonsymptomatic controls. *Clin Rehabil.* 16:16-26, 2002.

28. Valachi, B. and K. Valachi. Mechanisms leading to musculoskeletal disorders in dentistry. *J Am Dent Assoc.* 134:1344-1350, 2003.

29. van der Velde, G. and D. Mierau. The effect of exercise on percentile rank aerobic capacity, pain, and self-rated disability in patients with chronic low-back pain: a retrospective chart review. *Arch Phys Med Rehabil.* 81:1457-1463, 2000.

30. Weston, S. B., A. B. Gray, D. A. Schneider, and G. C. Gass. Effect of ramp slope on ventilation thresholds and VO2peak in male cyclists. *Int J Sports Med.* 23:22-27, 2002.

31. Yoshitake, Y., H. Ue, M. Miyazaki, and T. Moritani. Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. *Eur J Appl Physiol.* 84:174-179, 2001.

CHAPTER TWO (Study One)

RELATIONSHIP BETWEEN ERECTOR SPINAE STATIC ENDURANCE AND MUSCLE OXYGENATION-BLOOD VOLUME CHANGES IN HEALTHY AND LOW BACK PAIN SUBJECTS

INTRODUCTION

Poor back muscle fitness is believed to be associated with back pain and dysfunction regardless of gender and age [23, 36, 46]. The Biering-Sorensen isometric endurance (BSME) test is a simple, low cost, back muscle static endurance test that is thought to be able to discriminate between subjects with and without LBP. Cross-sectional studies suggest that endurance time on the BSME was capable of discriminating between subjects with and without low back pain or injury [23, 27, 36, 43, 46]. Longitudinal research has demonstrated that a shorter BSME time denotes an increased risk of developing LBP [7-9]. Alternatively, other research has found that endurance time on the BSME was not sufficiently sensitive to predict the future occurrence of LBP [1, 54]. In saying that, it is generally accepted that a shorter BSME time is associated with LBP [23, 27, 36, 43], and temporally associated with the development of LBP [7-9].

Near infrared spectroscopy (NIRS) has been used to monitor erector spinae muscle blood volume (Mbv) and oxygenation (Mox) changes during static contraction in healthy subjects [3, 25, 32, 33, 37, 41, 57], (see Appendix B and C for related manuscripts) and compare regional changes in Mbv and Mox of healthy and LBP subjects [34, 35, 42]. Near infrared spectroscopy detects changes in Mbv and Mox at the level of the arterioles, capillaries and venules from a single reference point during static and isotonic muscle contractions [22, 51]. It is a non-invasive technique based on the differential absorption properties of hemoglobin (Hb) and myoglobin (Mb) in the near infrared range of 700 to 1000 nm. At 760 nm these chromophores (light absorbing compounds), are in a deoxygenated state, while at 850 nm they are in an oxygenated state. The difference in

absorbency between these two wavelengths indicates the change in oxygenation, whereas the sum signal indicates the change in blood volume.

The rationale for using NIRS was that localized Mbv and Mox changes are known to be a factor in the cessation of muscle contraction as a result of fatigue [57]. Fatigue is accelerated during sustained static muscle contraction due to: (1) increased metabolism of the working muscle and (2) increased intramuscular pressure (IMP), which may restrict blood flow and oxygen delivery to the working muscles [5]. High intensity muscular contraction is associated with fatigue and the accumulation of fatigue by-products (e.g., hydrogen ions) due to increased metabolic rate and greater need for oxygen [19]. The BSME elicits a muscular contraction of ~45 to 55% of maximal volitional contraction (MVC) [39, 52], which reduces or occludes erector spinae muscle blood supply [24, 26]. Several studies have used NIRS to examine the regional erector spinae Mbv and Mox during static contraction [3, 25, 33, 41, 57], as well as test-retest reliability in monitoring erector spinae Mbv and Mox changes during exercise [33, 37]. Research indicates that NIRS is suitable for detecting differences in Mbv and Mox between healthy and LBP subjects [34, 35, 42].

In an effort to determine if a reduced fitness level, regardless of LBP, influences erector spinae regional Mbv and Mox trends, the present study separated the LBP subjects into sedentary and active subject groups based on recreational activity level. Research has demonstrated that subjects with LBP have a reduced overall fitness level as compared to healthy subjects [44, 56], which may be related to a reduced physical activity level [46, 53]. Related research has found metabolic indicators of reduced fitness level in LBP subjects; for example, an increased glycolytic and reduced oxidative profile in the erector spinae muscles of LBP as compared to healthy subjects [40]. Therefore, the

purposes of this study were to: (1) compare Mbv and Mox responses of the erector spinae muscles during static muscle contractions in healthy, LBP, LBP-A and LBP-S subjects, and (2) determine if any correlations exist between BSME time, Mbv and Mox. The hypotheses were: (1) there would be significant differences between the healthy and LBP subjects in the degree of erector spinae Mbv and Mox response, and (2) the BSME time would be significantly correlated with changes in Mbv and Mox.

METHODS

Subjects

Written informed consent (see Appendix D) was obtained from: (1) 30 healthy (15 male, 15 female) subjects who were recruited from the students and staff at the University of Alberta, Edmonton; (2) 30 subjects with low back pain (LBP) who were recruited from the following sources: Millard Health (n=1), the Chronic Pain Clinic at the University of Alberta Hospital, Edmonton (N = 2), Edmonton Garrison (N = 1), and advertisements in the Edmonton Journal newspaper (N = 26). The criteria for subject inclusion were males and females between the ages of 18 and 50-years that had LBP for $\geq 3 \cdot$ months. Potential subjects were excluded via telephone interview if they acknowledged having: pain below the knee, spinal stenosis, a herniated or ruptured disc, slipping of the disc bodies (spondylolithesis), infection in the lumbosacral area, tumours, scoliosis, a rheumatologic disorder, osteoporosis, or previous back surgery. A visual analogue scale (VAS) rating of 2 (mild pain) or less on the 11-point scale was used for exclusion from the study (personal communication with Dr. Crites-Battié). To determine each LBP subject's VSA rating the subjects were asked to "rate their average pain during

a typical week". The VAS has been established as a valid index of chronic LBP [17, 20]. The subjects were required to complete a Physical Activity Readiness Questionnaire [12] (see Appendix E). Any subjects with known history of metabolic, cardiovascular, respiratory or neurological disorders were excluded. Of the subjects that were contacted regarding participation approximately 25 did not meet one or more of the inclusion criteria listed above, and were not included in the study.

Two groups were initially formed based on the above criteria and the absence or presence of low back pain, 1) healthy (N = 30; 15 male and 15 female) and 2) LBP (N = 30; 15 male and 15 female). The LBP group was then further subdivided [LBP-active (A) and LBP-sedentary (S)] based on activity level. The criteria used to subdivide the LBP subjects was based on their level of recreational physical activity via their response to a physical activity questionnaire: (1) LBP-S (N = 18; 11 male and 7 female) group consisted of subjects that answered (a) *"Not physically active"* or (b) *"Vigorous activity less than 30-min 3-days a week"* to their level of level of recreational physical activity over the past 6 months, and (2) the LBP-A (N = 12; 4 male and 8 female) group consisted of subjects that answered (c) *"Vigorous activity for 30-min 3-day a week"* or (d) *"Vigorous activity greater than 30-min 3-days a week"* to their level of recreational physical activity over the past 6-months (see Appendix F). Additionally, the activity level of the healthy group was (13 sedentary and 17 active) comparable to the distribution of the LBP group. Thus, a total of 4 groups were present (healthy, LBP, LBP-A and LBP-A). The guidelines used to establish the research questionnaire were based on information from the "The Canadian Physical Activity, Fitness, and Lifestyle Appraisal" [12] and the "Resources Manual for Guidelines for Exercise Testing and Prescription" [4],

which indicated that aerobic activity 3-5 days/week between 60 and 90% of age predicted maximum heart rate would maintain or improve cardiovascular fitness. The healthy and LBP subjects were matched based on age and sex (healthy: 15 male, 15 female; LBP: 15 male, 15 female) using a random numbers table. The study was conducted in accordance with the procedures approved by the Health Research Ethics Board at this institution.

PROCEDURES

Physical Characteristics

The subject's age (yrs), standing height (m), and body mass (kg) were measured in accordance with standardized procedures [12]. Height and body mass were measured using a calibrated Detecto-Medic beam scale (Detecto Scales Inc., Brooklyn, NY, USA). The Body Mass Index (BMI) was calculated as the ratio between body mass and height^2.

Skinfold thickness (SF) was measured with Lange calipers (Beta Technology Inc., Santa Cruz, CA, USA) at the following body sites in sequence: biceps, triceps, suprailiac and subscapularis. Each body site was measured 3-times and the average values was calculated to the nearest 0.5 mm. The subject's percent (%) body fat (BF) was predicted using charts established by Durnin and Womersley [18]. A linear regression equation was used to calculate body density [18]. The SF-right (Rt) and-left (Lt) at the NIRS probe sites was measured 3-cm to the Rt and Lt of the 3rd lumbar vertebrae (L3), respectively. This value was halved (½ skinfold thickness) to denote the thickness of the subcutaneous tissue that the near infrared light passed through prior to reaching the small vessels in the erector spinae muscle.

Borg Scale (RPE)

The Borg scale [11] for rating perceived exertion (RPE) was explained to each subject to allow them to rate their peripheral effort at the completion of the BSME (see Appendix G). The validity and reliability of the Borg scale in measuring perceived physical stress during isoinertial loading of the paraspinal muscles was previously documented [30]. The RPE scale has been used in exercise and occupational studies [13, 47, 49] and for the measurement of differences in fatigue based on body region [6, 45].

Near Infrared Spectroscopy (NIRS)

Clear plastic shrink-wrap was placed over each probe to reduce the accumulation of sweat on the diodes and minimize distortion of the NIRS signal. The two NIRS probes were then positioned on the subject's erector spinae muscle. The NIRS probes were placed bilaterally 3 cm to the Lt and Rt of L3, identified through manual palpation in either a standing or prone position. The probes were secured with a tensor bandage to block out all background light without occluding blood flow. Blood flow occlusion would have been recognized as a systematic decline in Mbv during resting baseline, but this trend was not evident.

The NIRS probe has one tungsten light source located at a distance of 3.5 cm from the silicone diodes, which absorb the reflected light at 760 and 850 nm. The penetration depth was approximately 60% of the optode distance or 2.1-cm. The NIRS unit was calibrated using the NIRCOM software provided with the instrument (Microrunman, NIM Inc., PA). The reliability of the NIRCOM NIRS unit has been previously verified [33, 37]. The light intensity during calibration and testing ranged

between 100-and 150-mV. The relative change in optical density (OD) at 760 and 850 nm was calculated from the raw NIRS data using the modified Beer-Lambert law as follows [14, 38]:

$$OD = a \times c \times d \times B + G$$

accordingly a is the absorption coefficient of the tissue, c is the concentration of the tissue, d is the distance between optodes on the measuring probe, B is the differential path length factor of the tissue, and G is the geometry of the tissue. Relative change in muscle Mbv was calculated as the sum of the change in OD at 760 nm (deoxy-Hb) and 850 nm (oxy-Hb), while the relative change in Mox was calculated as the difference between the 760 nm - 850 nm signals. The values of interest were Mbv-and Mox-range and Mbv-and Mox-delta. The Mbv-range and Mox-range were calculated as the change (difference) from the lowest value during exercise to the highest value during recovery. The Mbv-delta and Mox-delta were calculated as the change in either a positive or negative direction during the last 20-secs of resting baseline to the largest or smallest value during exercise. The Mbv and Mox ½ recovery times (½ rec) were calculated as the time taken to reach 50% of the post-BSME maximal value, with the Mox ½ rec time used as an index of intramuscular oxygen dynamics [14]. The raw NIRS data were averaged over 5-sec intervals during each phase of the test protocol.

Biering-Sorensen Muscular Endurance (BSME) Test

The BSME test was used to assess low back static muscular endurance according to the procedures described by Latimer et al. [36], Jorgensen and Nicolaison [27] and Kell et al. [33]. The subject was moved into a prone position on the plinth so as the iliac crest was

at the breakpoint of the upper body support. Two straps, one at ankle and one at gluteal level were lightly fastened around the plinth and the subject. Towels were positioned beneath the ankle and gluteus straps to reduce the strain on the muscle surface and any discomfort. The subject rested with their upper body on the plinth and their head on a padded stool while the 2-min resting baseline data were collected (Appendix H).

Approximately 30-sec prior to the start of the BSME test the straps were tightened in order to safely fasten the subject to the plinth, following which the upper body support of the plinth and stool were removed to start the BSME. The subject was forced to support their upper body weight with their arms folded across their chest (Appendix H). A horizontal neutral position was maintained by contracting the musculature of the low back (i.e., erector spinae). A wooden adjustable marker was suspended from the ceiling to indicate the neutral position. The trends in $\dot{M}bv$ and Mox were recorded bilaterally at L3 while the subject maintained the neutral position for the longest duration possible with no rotation or lateral shifting.

Verbal encouragement was given during the BSME, but the subject was not informed of the elapsed time. The subject was allowed to terminate the test at any time due to pain or volitional fatigue. Once the subject was incapable of maintaining the neutral position, the upper portion of the plinth and stool were replaced and the subject rested in the prone position for the 4-min recovery period. The subject was asked for their RPE at the completion of the BSME test. Once the recovery data were collected, the investigator asked the subject their reason for terminating the test.

Statistical Analysis

The data in this study was analyzed in its raw form. Analysis of variance (ANOVA) was used to examine the differences in the anthropometric characteristics amongst the healthy, LBP, LBP-A and LBP-S subjects. Comparisons between: 1) healthy and LBP, 2) healthy and LBP-A, 3) healthy and LBP-S, and 4) LBP-A and LBP-S were made to determine if significant differences existed, but no comparison was made between LBP and LBP-A or LBP-S, as it would have been a violation of one of the assumptions (independent groups) of ANOVA. A 2-way analysis of covariance (2-way ANCOVA) with repeated measures was used to examine the difference between the means of the groups and the right and left sides for the pertinent NIRS variables. If no significant differences were present between the right and left sides, the sides were collapsed (averaged) for further comparison. The ½ skinfold thickness of the right and left sides were averaged and used as a covariate as this has been reported to influence the NIRS variables [55]. Significant *F* ratios were subjected to a Scheffé post hoc analysis in order to identify differences between the groups and sides. The alpha level was set at ≤ 0.05 ($P \leq .05$). Pearson correlations were used to examine the relationship between BSME time and pertinent NIRS variables. Statistical analyses were performed using the Statistica 6.1 (Statsoft, Inc. '2003 Edition, Tulsa, OK) computer package.

RESULTS

Physical characteristics

It is evident from Table 2.1 that the LBP subjects had significantly greater SF-Rt and-Lt, and less LBM (kg) than the healthy subjects. The LBP-S subjects showed

significantly greater SF-Rt and-Lt side thickness, %BF, and FM than the healthy subjects. Additionally, LBP-S subjects demonstrated significantly greater SF-Rt and-Lt, and %BF than LBP-A subjects. In general, the three subject groups were similar anthropometrically, but the LBP subjects demonstrated slightly greater SF thicknesses over the NIRS probe sites and greater %BF than the healthy subjects. No statistically significant difference was noted between the LBP-A (4.2) and LBP-S (4.8) subjects in level of low back pain as indicated by the VAS.

Comparison of BSME Time Among Groups

Table 2.2 displays the BSME times for the healthy and LBP subjects. Contrary to most research, the present study found no significant differences between the healthy (141.5-sec), LBP-A (147.5-sec) and LBP-S (122.9-sec) subjects in BSME time.

Muscle Blood Volume and Oxygenation Trends

Figures 2.1 to 2.4 show right and left side erector spinae Mbv and Mox trends for a typical healthy and LBP subject. The trends were similar among groups and sides, with considerable variation in the magnitude of change within each variable. Similar baseline trends for Mbv and Mox were found on both the Rt and Lt side erector spinae muscle for all subjects. At the start of the BSME there was an initial increase in Mbv in ~84% of the cases, followed by a systematic increase in ~94% of the cases. In ~69% of the cases a short (~45-sec) plateau occurred just prior to termination of the BSME. At termination there was a systematic decrease toward baseline during the initial 2-min in ~87% of the

cases (Figures 2.1 and 2.3). In recovery Mbv was at or near baseline level during the final 2-min.

Muscle oxygenation had two distinct trends: (1) an initial increase (~47% of cases) followed by a systematic decrease (93% of cases) until BSME termination, and (2) an initial decrease (~63% of cases) followed by a systematic decrease (~93% of cases) until termination. A short plateau occurred about ~30-sec prior to the termination of the BSME in ~68% of the cases. At BSME termination Mox systematically returned to baseline in the initial 2-min in 93% of the cases. During the latter 2-min of the BSME recovery Mox stabilized remaining at or near baseline level.

Comparison of NIRS Variables between Groups and Sides

The results of the ANCOVA indicated no significant two-way interaction for any of the NIRS variables examined. This implies that the response on the right and left sides was similar in both the healthy and LBP subjects (Figure 2.5 to 2.10). The mean values and post hoc comparisons of the NIRS variables are summarized in Table 2.2. The healthy subjects demonstrated significantly greater Mbv-delta-Lt than the LBP subjects, and as well significantly greater Mox-range-Rt than both the LBP and LBP-S subjects. The larger change in Mbv-range and Mox-delta values in the healthy subjects indicate a greater overall change in the Mbv and Mox response as compared to the LBP subjects. As well, the healthy subjects showed a significantly shorter ½ rec Mox-Lt than all LBP groups (LBP, LBP-A and LBP-S).

Correlations Between BSME Time and NIRS Variables

No significant correlations were found in the healthy subject group for BSME time and any of the Mbv or Mox variables with the sides pooled (see Table 2.3). However, significant correlations were revealed for the LBP and LBP-A subjects between the BSME time and Mox-range ($r = 0.55$ and $r = 0.64$, respectively) and Mox-delta ($r = 0.51$ and $r = 0.63$, respectively). Additionally, no significant correlations were noted between the BSME time and Mbv ½ rec time or Mox ½ rec time.

DISCUSSION

The purposes of this study were to: (1) compare Mbv and Mox responses to erector spinae static muscle contraction in healthy, LBP-A and LBP-S subjects, and (2) determine the relationships between BSME time, Mbv and Mox. The hypotheses were that there would be: (1) significant differences between the healthy and LBP subjects in the degree of erector spinae Mbv and Mox response, and (2) a significant correlation between the BSME time and changes in Mbv and Mox. The present findings indicated similar trends in Mbv and Mox in the healthy and LBP subjects with significant differences between the two groups on certain Mbv and Mox variables. Selected correlations between the BSME test, Mbv and Mox variables were significant in the LBP subjects, but not in the healthy subjects. The results suggest that a lower fitness level may be present in LBP subjects, which was detectable with NIRS technology.

Muscle Blood Volume and Oxygenation Trends

The Mbv and Mox trends were similar across right and left sides, which has been found in other NIRS research [3], and thus will be discussed together. The Mbv response in the present study was similar to that of Albert et al. [3], whose findings indicated an initial increase in Mbv followed by a plateau, and a decrease to baseline at the termination of the BSME. In contrast, a study by Yoshitake et al. [57] showed an initial decrease in the Mbv followed by a plateau and a return to baseline upon termination. The difference in Mbv response between these studies is likely due in part to methodology. Yoshitake et al. [57] used a fixed test duration of 60-sec and back angles of 0° and 15° with reference to the horizontal plane.

The validity of the initial increase followed by a plateau in Mbv is supported by the work of Jorgensen and Nicolaisen [27]. The relative contraction level during the BSME can be calculated as [27]:

% MVC = gravitational torque on the trunk / maximal volitional torque at L4-L5

In their study of 53 male postal workers the % of MVC required to maintain the BSME position was 37% [27]. Erector spinae muscle blood flow is maximal at 20% MVC and occluded at 40% of MVC [10]. Therefore, it is reasonable to believe that the initial increase in Mbv at the onset off the BSME was associated with muscle blood flow that was still present at the beginning of the BSME and possibly throughout the BSME. Additionally, the initial increase in Mbv was supported by localized redistribution of blood to, and within, the working motor units. Redistribution of blood is driven by the working motor units oxygen requirement and sympatholysis within the working muscle(s) [16].

Sympatholysis occurs as a result of local tissue factors, such as nitric oxide and adenosine, which override the vasoconstriction associated with the sympathetic nervous output [16, 48]. Simultaneous to the sympatholysis within the working motor units, is vasoconstriction within the nonworking motor units and a concomitant cardiovascular response, which increases heart rate, cardiac output, and blood pressure [21]. At asymptote, blood redistributed to working motor units may have ceased and become trapped as a result of increased IMP, a theory also suggested by Albert et al. [3]. Once IMP equalizes intravascular pressure further vasodilation is not possible [50]. At the cessation of the BSME, the IMP and the requirement for oxygen by the working motor unit were reduced, and as a consequence Mbv declined toward baseline level.

The systematic decrease in Mox during the BSME was due to: (1) increased cellular oxygen uptake by mitochondria due to increased metabolism of the working motor units [25, 41], and (2) increased intramuscular pressure (IMP) reducing muscle blood supply and oxygen delivery to the active motor units [25, 41]. The findings of previous NIRS studies [3, 25, 37, 41, 42, 57] that have evaluated erector spinae Mox trends in static positions in healthy subjects and individuals with low back disorders are summarized in Table 2.4. In general, the current findings are in agreement with those of the studies reviewed in this table.

The Mox plateau ~20-to 30-sec prior to BSME termination suggests that the small blood vessels of the active motor units reached maximum desaturation [25]. The systematic Mox increase upon BSME termination shows that both Mbv and Mox returned promptly to baseline or near baseline level to re-establish homeostasis within the motor units. The reoxygenation may be an indication of the re-establishment of blood supply to the erector

spinae muscle post contraction [37]. The reoxygenation phase during recovery was driven by the need to resaturate Hb and Mb, restore depleted phosphocreatine (PC) and ATP, as well as eliminate the metabolites accumulated during exercise [14].

Comparison of NIRS Variables

The healthy subjects demonstrated a larger change in Mbv-delta Lt and Mox-range Rt as compared to the LBP subjects. The smaller change in Mbv-delta in the LBP subjects may have been a consequence of reduced capillarization [31], as a result of a reduced fitness level due to a lower physical activity level [44, 46, 53]. The consequence of reduced capillarization may manifest itself as a decreased ability to deliver blood to the erector spinae. Additionally, the healthy and LBP subjects in the present study had similar body mass and height, and it is likely that the upper body mass supported during the BSME would be similar. If the erector spinae muscles of the LBP subjects were weaker [2], possibly due to a reduced fitness level [44, 56], then the LBP subjects would have exerted a greater % of MVC to support their upper body mass, which may have led to an earlier occlusion of erector spinae blood flow. It was speculated that a decreased erector spinae capillarization and an increase in the % of MVC necessary during the BSME might be evident as a reduced change in amplitude in Mbv in the LBP subjects.

The Mox response was used as an index of the change in erector spinae muscle oxygen extraction, as Mox is influenced by the capacity of the regional muscle mitochondria to consume and utilize oxygen [14]. A greater change in Mox-range Rt implies that the erector spinae muscle of the healthy subjects had a greater ability to extract and utilize the oxygen than the LBP or LBP-S subjects. Also, this would

necessitate greater muscle blood supply for oxidative metabolism, supporting the current findings of a greater Mbv-delta Lt response in the healthy subjects. A further index of oxygen demand and delivery is Mox ½ rec time from exercise, which is a marker of aerobic resaturation of exercise-desaturated Hb and Mb [14]. The longer Mox ½ rec time Lt side found in the LBP and LBP-S subjects agrees with previous research that noted a longer Mox ½ rec time in chronic LBP and scoliosis subjects [35, 42]. The above results suggest that the erector spinae muscles of the LBP and LBP-S subjects displayed a compromised ability to deliver and utilize oxygen.

The findings of decreased change in Mbv-delta Lt, Mox-range Rt and slower Mox ½ rec time support the theory of a reduced fitness level in the LBP and LBP-S subjects [44, 56], as these same differences were absent between the healthy and LBP-A subjects. A reduction in fitness level may occur within a few weeks of the cessation of training, decreasing oxidative capacity as a result of diminished muscle mitochondrial enzyme activity (e.g., citrate synthase) [15]. The Mox-range Rt and Mox ½ rec time variables may reflect a lower oxidative capacity as a result of a reduced fitness level. A decline in muscle mitochondrial enzyme activity would negatively influence the replenishment of high-energy phosphates (e.g., ATP) and the removal of metabolic by-products (e.g., hydrogen ions) post-contraction [14]. Thus, the findings of the present study extends the current body of research suggesting that LBP subjects display a reduced oxidative potential as indicated by smaller changes in Mox, Mbv and a longer Mox ½ rec time as compared to the healthy subjects, which may suggest a reduced peripheral fitness in the LBP subjects.

Correlations between BSME time and NIRS Variables

The present study found no significant difference in BSME time between the groups [27]. Gender was likely an influencing factor in the present study, as the number of males and females in the healthy and LBP groups were the same, and similar between the LBP-A and LBP-S. Additionally, Jorgensen & Nicolaisen [27] also found no significant difference in endurance time between healthy, LBP subjects able to work, and LBP subjects unable to work due to pain. Alternatively, other research has found significant differences between healthy and LBP subjects [23, 36, 46]. The variability in this research may be related to methodological, and/or other physical characteristics aside from erector spinae muscular endurance. Factors such as age, body mass, BMI, back muscle strength, and the strength and activation level of other synergistic muscle groups all have been determined to influence BSME time [28, 29]. As a result, BSME times may be similar between groups, but physiological differences in the erector spinae muscle may still be present due to the multifactorial nature of the influences on BSME test duration.

In contrast, significant correlations were noted between BSME time and NIRS variables (range and delta) in the LBP and LBP-A, and in the LBP-S subjects. This indicates a relationship between erector spinae muscle endurance and regional changes in Mbv and Mox in the LBP subjects. Perhaps the healthy subjects BSME time was limited more by the failure of other synergistic muscle groups when compared to LBP subjects. Again, the lack of significant relationship between BSME time and NIRS variables in the healthy subjects was likely related to the fact that other variables influence BSME time [28, 29], while the significant relationship in the LBP subjects may be related to an overall lower fitness level noted as reduced blood flow and oxygen supply during moderate

intensity static contractions (BSME). Nonetheless, the present results reiterate the somewhat unpredictable nature of both BSME time and its relationship with other physiological variables.

Conclusion

There was no significant difference between healthy and LBP subjects for BSME time. However, the healthy subjects demonstrated a greater change in Mbv and Mox values on the left and right sides respectively and equal or a faster Mox ½ rec time as compared to LBP and LBP-S subjects. These differences in peripheral oxygenation between the subjects may have been due to a diminished fitness level associated with a lower activity level. There were no significant correlations between the BSME time and any of the NIRS variables in the healthy subjects. However, BSME time was significantly correlated with Mox-range and Mox-delta in the LBP subjects, implying that localized muscle oxygenation plays an important role in determining low back static muscle endurance in this population.

Table 2.1. Physical characteristics of the healthy, LBP, LBP-A and LBP-S subjects. Values are mean (±SD).

	Groups			
Variable	**Healthy (N=30) 15 Male 15 Female**	**LBP (N=30) 15 Male 15 Female**	**LBP-A (N=18) 11 Male 7 Female**	**LBP-S (N=12) 4 Male 8 Female**
Age (yrs)	32.0(8.06)	33.6(6.06)	32.7(5.87)	35.1(6.32)
Skinfold left (mm)	4.50(1.57)[ab]	5.85(2.17)	4.95(1.54)[c]	7.17(2.34)
Skinfold right (mm)	4.25(1.55)[ab]	5.85(2.12)	5.00(1.45)[c]	7.20(2.33)
BF (%)	22.2(4.3)[b]	27.2(7.0)	24.5(6.1)[c]	31.4(6.4)
Height (m)	1.71(0.08)	1.71(0.08)	1.74(0.07)	1.67(0.07)
Body mass (kg)	76.2(13.87)	76.6(13.44)	76.1(13.60)	77.3(13.78
Fat mass (kg)	18.5(5.97)[b]	21.0(6.87)	18.8(6.03)	24.3(6.94)
Lean body mass (kg)	63.5(10.76)[a]	55.6(10.42)	57.3(10.49)	53.0(10.19)
BMI	26.0(3.18)	26.0(3.43)	24.9(3.11)	27.5(3.45)

[a] indicates a significant difference between healthy and LBP.

[b] indicates a significant difference between healthy and LBP-S.

[c] indicates a significant difference between LBP-A and LBP-S.

Table 2.2. BSME time, Borg scale, skinfolds, and NIRS (optical density) variables with the sides compared for the healthy, LBP, LBP-A and LBP-S subjects. Values are mean (±SD).

	Groups							
	Healthy (N=30)		**LBP (N=30)**		**LBP-A (N=18)**		**LBP-S (N=12)**	
Variable	**15 Male 15 Female**		**15 Male 15 Female**		**11 Male 7 Female**		**4 Male 8 Female**	
Side	Lt	Rt	Lt	Rt	Lt	Rt	Lt	Rt
BSME time (sec)	141.5(35.0)		137.6(52.8)		147.5(80.5)		122.9(35.7)	
Borg Scale (6-20)	17.5(1.1)		16.8(1.5)		16.8(1.7)		16.8(1.2)	
½ Skinfold (mm)	4.5	4.25	5.84	5.84	4.9	5.0	7.15	7.2
Mbv-range	0.197(0.124)	0.154(0.120)	0.157(0.070)	0.159(0.090)	0.166(0.078)	0.172(0.092)	0.143(0.058)	0.140(0.087)
Mbv-delta	0. 163(0.122)[a]	0.132(0.125)	0.107(0.070)	0.123(0.084)	0.126(0.045)	0.139(0.088)	0.080(0.052)	0.098(0.073)
Mox-range	0.075(0.057)	0.067(0.048)[ac]	0.055(0.028)	0.046(0.026)	0.065(0.031)	0.056(0.027)	0.039(0.015)	0.031(0.013)
Mox-delta	0.063(0.058)	0.051(0.050)	0.041(0.027)	0.039(0.023)	0.051(0.030)	0.046(0.025)	0.026(0.014)	0.027(0.013)
½ rec Mbv	34.17(32.7)	36.92(31.5)	30.75(28.7)	28.50(29.8)	37.9(34.5)	30.83(32.4)	20.00(10.9)	25.0(26.5)
½ rec Mox	51.17(29.8)[abc]	58.42(37.1)	76.68(30.4)	58.75(33.1)	76.8(31.2)	61.9(35.1)	76.5(30.6)	54.0(30.5)

[a] indicates a significant difference between healthy and LBP.

[b] indicates a significant difference between healthy and LBP-A.

[c] indicates a significant difference between healthy and LBP-S.

Table 2.3. Pearson's correlation coefficients (r) between BSME time and Mbv and Mox variables for the healthy, LBP, LBP-A and LBP-S subjects with sides pooled.

	Groups			
Variables	**Healthy (N=30) 15 Male 15 Female**	**LBP (N=30) 15 Male 15 Female**	**LBP-A (N=18) 11 Male 7 Female**	**LBP-S (N=12) 4 Male 8 Female**
Mbv-range	0.08	0.27	0.36	-0.18
Mbv-delta	0.03	0.23	0.25	-0.14
Mox-range	-0.04	0.55[a]	0.64[a]	-0.30
Mox-delta	0.02	0.51[a]	0.63[a]	-0.53
½ rec Mbv	0.00	0.01	0.00	-0.30
½ rec Mox	0.12	-0.02	-0.16	0.41

[a] indicates a significant correlation (r) at $P \leq 0.05$

Table 2.4. Comparison of NIRS research examining the erector spinae during static contraction.

Variable	Studies											
	Miyake et al. (2003)		**Yoshitake et al. (2001)**	**Maikala et al. (2000)**	**McGill et al. (2000)**		**Kunimune et al. (1999)**		**Jensen et al. (1999)**			
Gender	Male	Female	Male	Male	Male	Female	Male	Female	Male			
Subjects (N)	N=7	N=37	N=8	N=16	N=5	N=3	N=8	N=28	N=9			
Condition	Scoliosis & 11 healthy controls		Healthy	Healthy	Healthy		Scoliosis & 20 healthy controls		Healthy			
NIRS manufacturer	Omron, Heo-200		Omron Heo-100	Runman, NIM Inc.	Runman, CWS-2000		Omron Heo-200		Runman, NIM, Inc.			
Probe Placement	Right and left side L3		L3 (side?)	Right side L3	Right side L3		Right and left side L3		Right side L4			
BSME angle (∠) or Body position	Standing position with forward flexion at waist		0 and 15 degrees	Sitting and standing	Sitting		Standing position with forward flexion at waist		Standing			
Contraction Time (sec)	30-sec		60-sec	2-min	30-sec		30-sec		30-sec			
Contraction intensity	NA		45-to-55% MVC	Maximal Movement	2, 5, 10, 20, 30% MVC		NA		5, 20, 40, 60, 80% MVC and maximal			
NIRS trend	Dec. Mox		Dec. Mox and dec. Mbv at both angles	Dec. Mox and dec. Mbv in both positions	Dec. Mox		Two trends: (1) gradual dec. Mox, (2) initial inc., then gradual dec. in Mox		Dec. Mox with increasing isometric contraction intensity			
½ rec Time	Significantly slower ½ rec time in scoliosis gp on convex side, with no difference on concave side. No gender difference.		NA	NA	NA		Significantly slower ½ rec time in scoliosis gp on convex side, with difference on concave side. No gender difference.		NA			
Comments	The authors consider ½ rec time to be indicative of back muscle stress, but found no relationship between ½ rec time and pain.		NIRS may be useful in examining reduced Mbv due to increased intramuscular pressure during isometric contraction.	High intersession reliability suggests that NIRS can be successfully applied to back muscle to study fatigue.	NIRS has implication in the study of prolonged postural work, where isometric contractions are held for hours.							

∠ - indicates the angle with reference to the horizontal plane

L - indicates lumbar region, e.g., L3 indicates 3rd lumbar vertebrae region

NA – not applicable

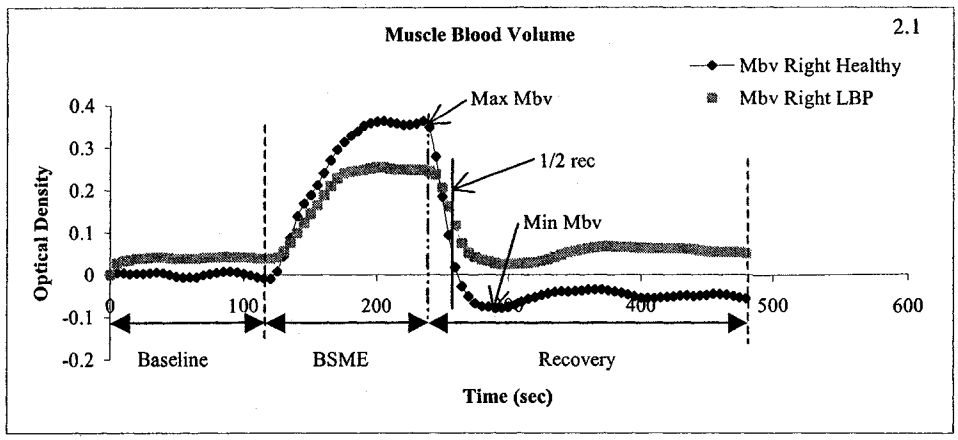


Figure 2.1. An example of muscle blood volume trends on the right side of a typical healthy and LBP subject during the BSME test. The healthy subject demonstrates the maximum and minimum values and ½ rec time markers.

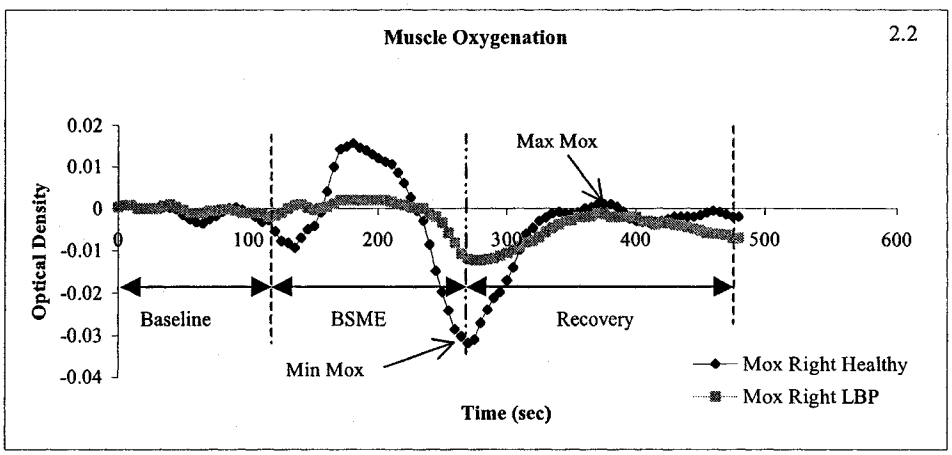


Figure 2.2. An example of muscle oxygenation trends on the right side of a typical healthy and LBP subject during the BSME test.

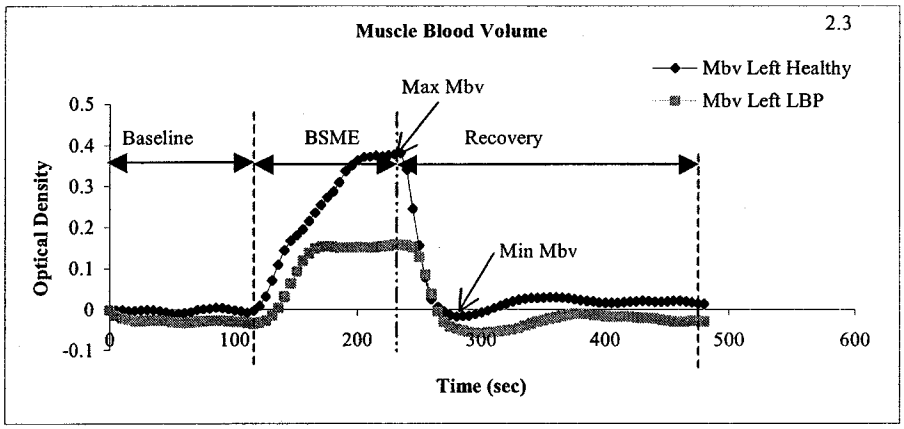


Figure 2.3. An example of muscle blood volume trends on the left side of a typical healthy and LBP subject during the BSME test.

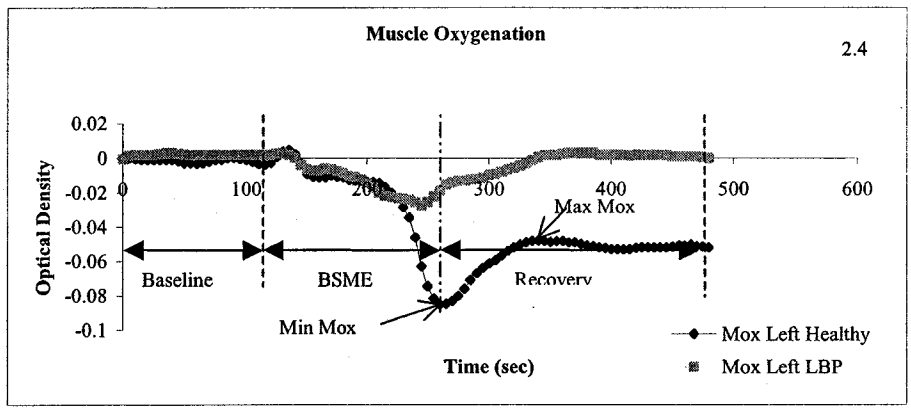


Figure 2.4. An example of muscle oxygenation trends on the left side of a typical healthy and LBP subject during the BSME test.

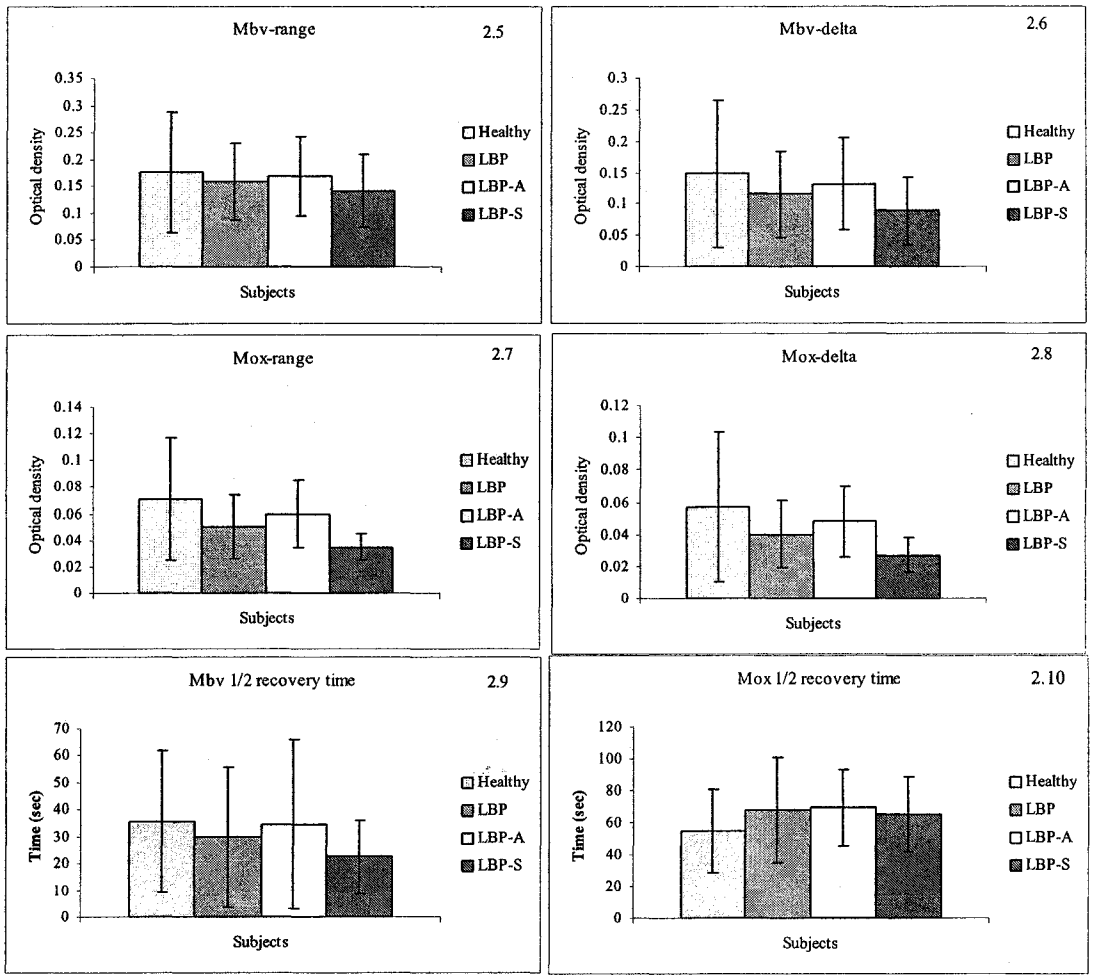


Figure 2.5 - 2.10. Are an index of Mbv-range and-delta, Mox-range and-delta, and Mbv and Mox ½ rec times during the BSME test in the healthy, LBP, LBP-S, and LBP-A subjects. No significant differences were detected between any of the subject groups on the Mbv or the Mox variables.

REFERENCES

1. Adams, M. A., A. F. Mannion, and P. Dolan. Personal risk factors for first-time low back pain. *Spine*. 24:2497-2505, 1999.
2. Addison, R. and A. Schultz. Trunk strength in patients seeking hospitalization for chronic low-back disorders. *Spine*. 5:539-544, 1980.
3. Albert, W. J., G. G. Sleivert, J. P. Neary, and Y. N. Bhambhani. Monitoring individual erector spinae fatigue responses using electromyography and near infrared spectroscopy. *Can J Appl Physiol*. 29:363-379, 2004.
4. American College of Sports Medicine. *Resource Manual for Guidelines for Exercise Testing and Prescription*. Fourth ed. Philadelphia: Lippincott Williams & Wilkins, 2001
5. Barnes, W. S. The relationship between maximum isometric strength and intramuscular circulatory occlusion. *Ergonomics*. 23:351-357, 1980.
6. Bhambhani, Y., R. Maikala, and S. Buckley. Muscle oxygenation during incremental arm and leg exercise in men and women. *Eur J Appl Physiol Occup Physiol*. 78:422-431., 1998.
7. Biering-Sorensen, F. A one-year prospective study of low back trouble in a general population. The prognostic value of low back history and physical measurements. *Danish Medical Bulletin*. 31:362-375., 1984.
8. Biering-Sorensen, F. Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine*. 9:106-119, 1984.
9. Biering-Sorensen, F., C. E. Thomsen, and J. Hilden. Risk indicators for low back trouble. *Scand J Rehab Med*. 21:151-157, 1989.

10. Bonde-Petersen, F., A. L. MØrk, and E. Nielsen. Local muscle blood flow and sustained isometric contractions of human arm and back muscles. *Eur J Appl Physiol.* 34:43-50, 1975.

11. Borg, G. and B. Noble. Perceived exertion. *Exerc Sport Sci Rev.* 2:131-153, 1974.

12. Canadian Society for Exercise Physiology. *The Canadian Physical Activity, Fitness & Lifestyle Appraisal Manual.* Ottawa: The Canadian Society for Exercise Physiology, 1996.

13. Capodaglio, P. The use of subjective rating of exertion in Ergonomics. *G Ital Med Lav Ergon.* 24:84-89, 2002.

14. Chance, B., M. Dait, C. Zhang, T. Hamaoka, and F. Hagerman. Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. *Am J Physiol.* 262:C766-C775, 1992.

15. Coyle, E. F., W. H. Martin, 3rd, D. R. Sinacore, M. J. Joyner, J. M. Hagberg, and J. O. Holloszy. Time course of loss of adaptations after stopping prolonged intense endurance training. *J Appl Physiol.* 57:1857-1864, 1984.

16. DeLorey, D. S., S. S. Wang, and J. K. Shoemaker. Evidence for sympatholysis at the onset of forearm exercise. *J Appl Physiol.* 93:555-560, 2002.

17. Dickens, C., M. Jayson, and F. Creed. Psychological correlates of pain behavior in patients with chronic low back pain. *Psychosomatics.* 43:42-48, 2002.

18. Durnin, J. V. G. A. and J. Womersley. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutri.* 32:77-97, 1974.

19. Fitts, R. H. Cellular Mechanisms of Muscle Fatigue. *Physiological Reviews.* 71:49-93, 1994.

20. Fritzell, P., O. Hagg, P. Wessberg, and A. Nordwall. Chronic low back pain and fusion: a comparison of three surgical techniques: a prospective multicenter randomized study from the Swedish lumbar spine study group. *Spine.* 27:1131-1141, 2002.

21. Gaffney, F. A., G. Sjogaard, and B. Saltin. Cardiovascular and metabolic responses to static contraction in man. *Acta Physiol Scand.* 138:249-258, 1990.

22. Hamaoka, T., T. Katsumura, N. Murase, S. Nishio, T. Osada, T. Sako, H. Higuchi, Y. Kurosawa, and T. Shimomitsu. Quantification of ischemic muscle deoxygenation by near infrared time-resolved spectroscopy. *J Biomed Opt.* 5:102-105, 2000.

23. Hölmstrom, E., U. Moritz, and M. Andersson. Trunk muscle strength and back muscle endurance in construction workers with and without low back disorders. *Scand J Rehab Med.* 24:3-10, 1992.

24. Humphreys, P. W. and A. R. Lind. The blood flow through active and inactive muscles of the forearm during sustained handgrip contractions. *J Physiol.* 166:120-135, 1962.

25. Jensen, B. R., K. Jorgensen, A. R. Hargens, P. K. Nielsen, and T. Nicolaisen. Physiological response to submaximal isometric contractions of the paravertebral muscles. *Spine.* 24:2332-2338, 1999.

26. Jørgensen, K. Human trunk extensor muscles physiology and ergonomics. *Acta Physiol Scand.* 160:5-58, 1997.

27. Jørgensen, K. and T. Nicolaisen. Trunk extensor endurance: determination and relation to low-back trouble. *Ergonomics*. 30:259-267, 1987.

28. Jørgensen, K. and T. Nicolaisen. Two methods for determining trunk extensor endurance: A comparative study. *Eur J Appl Physiol*. 55:639-644, 1986.

29. Kankaanpaa, M., D. Laaksonen, S. Taimela, S. M. Kokko, O. Airaksinen, and O. Hanninen. Age, sex, and body mass index as determinants of back and hip extensor fatigue in the isometric Sorensen back endurance test. *Arch Phys Med Rehabil*. 79:1069-1075., 1998.

30. Kankaanpaa, M., S. Taimela, C. J. Webber, O. Airaksinen, and O. Hanninen. Lumbar paraspinal muscle fatigability in repetitive isoinertial loading: EMG spectral indicies, Borg scale and endurance time. *Eur J Appl Physiol*. 76:236-242, 1997.

31. Kauppila, L. I. Prevalence of stenotic changes in arteries supplying the lumbar spine. A postmortem angiographic study on 140 subjects. *Ann Rheum Dis*. 56:591-595, 1997.

32. Kell, R. T., M. Farag, and Y. Bhambhani. Relationship between Erector Spinae Hemodynamics and Static Back Endurance in Healthy Males Edmonton, 2002, pp. 1-22 (unpublished).

33. Kell, R. T., M. Farag, and Y. Bhambhani. Reliability of erector spinae oxygenation and blood volume responses using near-infrared spectroscopy in healthy males. *Eur J Appl Physiol*. 91:499-507, 2004.

34. Kovacs, K. M., W. S. Marras, A. S. Litsk, P. Gupta, and S. A. Ferguson. Localized oxygen use of healthy and low back pain individuals during controlled trunk movements. *J Spinal Disord.* 14:150-158, 2001.

35. Kunimune, Y., Y. Harada, Y. Kabuto, K. Takeuchi, M. Senda, and H. Inoue. Recovery from exercise-induced desaturation in the paraspinal muscles in idiopathic scoliosis. *Spine.* 24:2019-2024, 1999.

36. Latimer, J., C. G. Maher, K. Refshauge, and I. Colaco. The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. *Spine.* 24:2085-2089; discussion 2090., 1999.

37. Maikala, R. and Y. Bhambhani. Low-back muscle oxygenation trends during simple postural variations-intersession reliability using near infra-red spectroscopy. In *IEA2000/HFES Congress*, pp. 5-9 to 9-12, 2000.

38. Mancini, D., L. Bolinger, L. Li, K. Kendrick, B. Chance, and J. Wilson. Validation of near-infrared spectroscopy in humans. *J Appl Physiol.* 77:2740-2745, 1994.

39. Mannion, A. F. and P. Dolan. Electromyographic median frequency changes during isometric contraction of the back extensors to fatigue. *Spine.* 19:1223-1229, 1994.

40. Mannion, A. F., L. Kaser, E. Weber, A. Rhyner, J. Dvorak, and M. Muntener. Influence of age and duration of symptoms on fibre type distribution and size of the back muscles in chronic low back pain patients. *Eur Spine J.* 9:273-281, 2000.

41. McGill, S. M., R. L. Hughson, and K. Parks. Lumbar erector spinae oxygenation during prolonged contractions: implications for prolonged work. *Ergonomics*. 43:486-493., 2000.

42. Miyake, M., Y. Harada, M. Senda, K. Oda, and H. Inoue. Oxygen dynamics at paraspinal muscles during exertion using near-infrared spectroscopy in patients with degenerative lumbar scoliosis. *J Orthop Sci*. 81:187-191, 2003.

43. Nicolaisen, T. and K. Jorgensen. Trunk strength, back muscle endurance and low-back trouble. *Scand J Rehab Med*. 17:121-127, 1985.

44. Nielens, H. and L. Plaghki. Cardiorespiratory fitness, physical activity level, and chronic pain: are men more affected than women? *Clin J Pain*. 17:129-137, 2001.

45. Pandolf, K. B., D. S. Billings, L. L. Drolet, N. A. Pimental, and M. N. Sawka. Differential ratings of perceived exertion and various physiological responses during prolonged upper and lower body exercise. *Eur J Appl Physiol Occup Physiol*. 53:5-11, 1984.

46. Payne, N., N. Gledhill, P. T. Katzmarzyk, and V. Jamnik. Health-related fitness, physical activity and history of back pain. *Can J Appl Physiol*. 24:236-249, 2000.

47. Perez-Landaluce, J., B. Fernandez-Garcia, M. Rodriguez-Alonso, F. Garcia-Herrero, P. Garcia-Zapico, A. M. Patterson, and N. Terrados. Physiological differences and rating of perceived exertion (RPE) in professional, amateur and young cyclists. *J Sports Med Phys Fitness*. 42:389-395, 2002.

48. Radegran, G. and Y. Hellsten. Adenosine and nitric oxide in exercise-induced human skeletal muscle vasodilatation. *Acta Physiol Scand*. 168:575-591., 2000.

49. Rittweger, J., H. Schiessl, and D. Felsenberg. Oxygen uptake during whole-body vibration exercise: comparison with squatting as a slow voluntary movement. *Eur J Appl Physiol.* 86:169-173, 2001.

50. Sadamoto, T., F. Bonde-Petersen, and Y. Suzuki. Skeletal muscle tension, flow, pressure, and EMG during sustained isometric contractions in humans. *Eur J Appl Physiol Occup Physiol.* 51:395-408, 1983.

51. Sako, T., T. Hamaoka, H. Higuchi, Y. Kurosawa, and T. Katsumura. Validity of NIR specroscopy for quantitatively measuring muscle oxidative metabolic rate in exercise. *J Appl Physiol.* 90:338-344, 2001.

52. Smidt, G. L. and P. R. Blanpied. Analysis of strength tests and resistive exercises commonly used for low-back disorders. *Spine.* 12:1025-1031, 1987.

53. Spenkelink, C. D., M. M. Hutten, H. J. Hermens, and B. O. Greitemann. Assessment of activities of daily living with an ambulatory monitoring system: a comparative study in patients with chronic low back pain and nonsymptomatic controls. *Clin Rehabil.* 16:16-26, 2002.

54. Takala, E. and E. Juntura. Do functional tests predict low back pain? *Spine.* 25:2126-2132, 2000.

55. van Beekvelt, M. C., M. S. Borghuis, B. G. van Engelen, R. A. Wevers, and W. N. Colier. Adipose tissue thickness affects in vivo quantitative near-IR spectroscopy in human skeletal muscle. *Clin Sci.* 101:21-28., 2001.

56. van der Velde, G. and D. Mierau. The effect of exercise on percentile rank aerobic capacity, pain, and self-rated disability in patients with chronic low-back pain: a retrospective chart review. *Arch Phys Med Rehabil.* 81:1457-1463, 2000.

57. Yoshitake, Y., H. Ue, M. Miyazaki, and T. Moritani. Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. *Eur J Appl Physiol.* 84:174-179, 2001.

CHAPTER THREE (Study Two)

CARDIORESPIRATORY & ERECTOR SPINAE BLOOD VOLUME & OXYGENATION RESPONSES DURING REPETITIVE INCREMENTAL LIFTING & LOWERING IN HEALTHY AND LOW BACK PAIN SUBJECTS

INTRODUCTION

Occupationally functional testing has been used to determine an employee's readiness to return to manual materials handling (MMH) type work following injury [1], as well as prevention strategies for reducing the risk of low back injury in the work place [20]. Repetitive lifting and lowering is an integral part of many MMH occupations [38]. The Work Practices Guide for Manual Lifting published by the National Institute for Occupational Safety and Health (NIOSH), suggests that to avoid undue fatigue during an 8-hour workday the time weighted average energy expenditure should not exceed one-third of an individual's maximal aerobic capacity (VO_{2max}) [38]. However, the exercise mode for the determination of the VO_{2max} was not specified in their recommendation. Researchers have suggested that fitness assessment protocols should be specific to the occupational demands in order to maximize the validity of the assessment. As a result, several studies have evaluated the VO_{2max} during incremental lifting and compared it with other modes of exercise [44, 50]. The findings clearly indicate that the VO_{2max} during incremental lifting is significantly lower than that attained during incremental cycling or treadmill running [44, 50]. Recently a repetitive incremental lifting and lowering study [28] demonstrated that the criteria for attaining VO_{2max} was not met as the subjects did not achieve their age predicted maximal heart rate (220 – age) [28], implying that central circulation was a limiting factor during repetitive incremental lifting and lowering (RILL). Consequently, the term peak VO_2 (VO_{2peak}) has been used instead of VO_{2max}.

Chronic non-specific low back pain (LBP) is prevalent in today's society, and occupations involving repetitive lifting tasks [46] and extensive MMH have been implicated in LBP. Yet, many individuals with LBP continue to work in these occupations.

Research suggests that individuals with LBP may demonstrate reduced physical activity [42, 51], which could lead to reduced fitness [39, 55], thereby exacerbating their condition. Reduced levels of physical activity can compromise the ability of the central circulation to transport oxygen and reduce peripheral oxygen extraction [13]. Research has also demonstrated that the aerobic capacity of the erector spinae muscles in individuals with LBP was reduced because of alterations in the vasculature [27] and oxidative capacity [32]. As well, these muscles have a greater preponderance of the fast fatigable motor units in individuals with LBP [33]. These observations suggest that peripheral oxygen extraction would likely be lower in LBP subjects, and more strongly associated with reduced VO_{2peak} than in healthy subjects.

Recently there has been considerable interest in the application of near infrared spectroscopy (NIRS) in examining the changes in erector spinae muscle blood volume (Mbv) and oxygenation (Mox) during static and dynamic exercise [34, 57]. Near infrared spectroscopy is a non-invasive optical technique that has been used to examine the relative changes in muscle blood volume and oxygenation during a variety of exercise modes [3, 10, 18]. In an earlier investigation [28], which documented the relative VO_{2peak} during RILL in healthy males and females, it was reported that fat mass explained 40% of the common variance between the two variables, while the peak heart rate and the left side oxygenation and blood volume measured by NIRS explained approximately 16% and 18% of the common variance respectively (see Appendix C). A comparison between healthy and LBP subjects using NIRS during RILL has not been reported. In light of the findings that the peripheral vasculature and oxidative capacity of the erector spinae muscles may be compromised in patients with LBP, the current study was designed to

compare the following responses during RILL in healthy and LBP subjects: (1) the VO_{2peak} and associated cardiorespiratory variables, (2) the changes in erector spinae Mbv and Mox, and (3) the central and peripheral factors that would best predict their VO_{2peak}. It was hypothesized that in comparison with the healthy subjects, the LBP subjects would demonstrate a significantly: (1) lower relative VO_{2peak}, (2) lower changes in Mbv and Mox, and (3) stronger correlation with the Mbv and Mox changes measured by NIRS. A secondary objective of the study was to compare the peak cardiorespiratory and Mbv and Mox changes during the RILL protocol between LBP subjects who were active (LBP-A) and sedentary (LBP-S). It was hypothesized that there would be significant differences between these two sub-groups for each of the variables examined.

METHODS

Subjects

Written informed consent (see Appendix D) outlining the possible risks and benefits of participating in this study was obtained from two groups of subjects: (1) thirty four healthy (17 male and 17 female) subjects were recruited from the students and staff at the University of Alberta; (2) fifty subjects with low back pain (LBP) were recruited from the following sources: metropolitan Edmonton area via advertisements placed in the Edmonton Journal (N = 42), Chronic Pain Clinic at the University of Alberta Hospital (N = 4), Edmonton Garrison (N = 3), and Millard Health (N = 1).

The criteria for subject inclusion were males and females with chronic LBP ($\geq$3 months) between the ages of 18 and 50-years. Potential subjects were interviewed via telephone, and excluded if they had: pain below the knee, spinal stenosis, a herniated or

ruptured disc, slipping of the disc bodies (Spondylolithesis), infection in the lumbosacral area, tumours, scoliosis, a rheumatologic disorder, osteoporosis, previous back surgery. A visual analogue scale (VAS) rating of 2 (mild pain) or less on the 11-point scale was ground for exclusion from the study (personal communication with Dr. Crites-Battié). The VAS has been validated as an index for chronic LBP [16, 19]. Any subjects with known history of metabolic, cardiovascular, respiratory or neurological disorders were excluded. Approximately 25 potential subjects did not meet one or more of the inclusion criteria, and as a result were excluded from the study. The subjects were required to complete a Physical Activity Readiness Questionnaire [8] (see Appendix E). Of these 50 LBP subjects, 34 (17 male and 17 female) were age and sex matched with the healthy (N = 34; 17 male and 17 female) group. The two groups initially formed based on the above criteria were: 1) healthy and 2) LBP. The LBP group was then further subdivided based on activity level [LBP-active (A) and LBP-sedentary (S)]. The LBP-S group (N = 15; 6 male, 9 female) consisted of subjects that answered (a) *"Not physically active"* or (b) *"Vigorous activity less than 30-min 3-days a week"* to their level of recreational physical activity over the past 6 months. The LBP-A group (N = 19; 11 male, 8 female) consisted of subjects that answered (c) *"Vigorous activity for 30-min 3-days a week"* or (d) *"Vigorous activity greater than 30-min 3-days a week"* to their level of recreational physical activity over the past 6-months (see Appendix F). Of note, the level of physical activity of the healthy group was (13 sedentary and 21 active) was similar to that of the LBP group. The study was conducted in accordance with the procedures approved by the Health Research Ethics Board at this institution.

Physical Characteristics

Physical characteristics are summarized in Table 3.1. Age (yrs), standing height (m), body mass (kg), and body mass index (BMI) were measured following standardized procedures [8]. Height and body mass were measured using a calibrated Detecto-Medic beam scale (Detecto Scales Inc., Brooklyn, NY, USA). The percent (%) body fat (BF) and ½ skinfold thickness (SF)-Left (SF-Lt; mm), SF-Right (Rt) (mm) were measured and recorded as follows (see Appendix F). Skinfold thickness was measured with Lang calipers (Beta Technology Inc., Santa Cruz, CA, USA) on the right side of the body at the following four sites: biceps, triceps, suprailiac and subscapularis. Measurements were undertaken three times in the same sequence and the average of the three trials was recorded (nearest 0.5 mm). The subject's % BF was predicted using charts established by Durnin and Womersley [17]. A linear regression equation was used to estimate body density [17]. The SF-Rt and-Lt at the NIRS probe site was measured 3-cm to the Rt and Lt of the 3rd lumbar vertebrae (L3). This value was halved in order to denote the thickness of the subcutaneous tissue that the near infrared light penetrated prior to reaching the vasculature within the erector spinae.

Repetitive Incremental Lifting and Lowering (RILL) Protocol

Each subject was asked to demonstrate a safe lifting and lowering technique prior to starting the RILL test. If the technique chosen by the subject was deemed unsafe, e.g., lifting with straight legs, then a safe lifting technique was demonstrated and recommended for use. Once the subject demonstrated that the task could be performed safely, the metabolic equipment was properly fitted for cardiorespiratory measurements

(see Appendix J). The subject sat in an upright posture against the backrest of the chair placed adjacent to the lifting table while 2-min resting baseline data were collected. A computerized metronome (Raney Day Productions, Mike's Metronome) set at 10 beats · min^{-1} was started. Thereafter the subject approached the weight basket (5 kg; 33 cm x 33 cm x 29 cm) that was resting on the floor ~45 cm in front of the lifting table. The basket was fitted with handles on both sides for bilateral load carriage.

The subject self-selected a metronome beat to begin lifting and lowering the basket to-and-from the floor to the waist height table (ht = 76 cm). The load was increased 2.25 kg · min^{-1} continuously until voluntary fatigue (see Appendix K). At the 30 sec mark of each stage the subject was asked to rate their perceived exertion (RPE) using the Borg Scale [6] (see Appendix G). The RPE was segmented as follows [41]: (1) central – sensations in the heart and lungs, (2) local – sensations in the arms/shoulder, and (3) local – sensations in the lower back (L3 region). Towards the end of each RILL stage the subject was asked if he/she could continue with the test. If the response was "yes", the load was increased by 2.25 kg. If the response was "no", the subject was asked to increase the lifting frequency as much as possible until voluntary fatigue. The intent was to stress the cardiorespiratory and musculoskeletal system maximally in an attempt to attain the following criteria [2] for VO_{2max}: (1) a levelling off (increase of less than 100 ml · min^{-1}) or a decrease in the oxygen consumption (VO_2) with increasing workload, (2) age predicted maximal HR, calculated as (220 – age), and (3) a respiratory exchange ratio >1.10. At the termination of the RILL protocol the subject sat quietly on a chair while 4-min of recovery data were collected. The investigator then asked the subject the reason for terminating the test.

Cardiorespiratory Measurements

A previously validated portable wireless metabolic analyzer (Vmax*ST* system, SensorMedics Corp., Yorba Linda, CA, USA) was used to measure the cardiorespiratory responses during RILL on a breath-by-breath basis [47]. The 570 gm, battery operated metabolic analyzer was fitted snugly about the subject's chest and shoulders using a breathable Velcro shoulder mount (see Appendix K). The unit contained a volume transducer, O_2 and CO_2 analyzers, a temperature sensor and a pressure transducer. The O_2 and CO_2 analyzers were calibrated using commercially available precision gases (16% O_2, 4% CO_2, balance N_2; SensorMedics Corp., CA) prior to and at the completion of each test in order to ensure data accuracy. The flowmeter was calibrated via injection of a 3-L syringe of air. Heart rate was recorded via a wireless chest monitor (Sport tester) interfaced with the portable metabolic unit. The breath-by-breath data were averaged over 20-sec intervals for subsequent analysis.

Near Infrared Spectroscopy (NIRS) Procedures

The NIRS probe had one tungsten light source located at a distance of 3.5 cm from the silicone diodes, which absorb the reflected light at 760 nm and 850 nm. The penetration depth was approximately 60% of the optode distance or 2.1-cm. The NIRS probes were placed at the third lumbar vertebra (L3), 3-cm to the Rt and Lt of the spine. The exact location was determined through manual palpation in either a standing or prone position. The probes were secured with a tensor bandage without occluding the muscle blood flow. Blood flow occlusion would have been visible as a gradual decline in muscle Mbv trend as indicated by NIRS, during the resting baseline phase, but was not evident.

A piece of clear plastic wrap was placed over the probe so as to minimize the accumulation of sweat on the diodes, which could distort the NIRS signal. The NIRS unit was calibrated using the NIRCOM software provided with the instrument (Microrunman, NIM Inc., PA). The light intensity ranging between 100-and 150-mV was applied during calibration and testing. The reliability of the NIRCOM system in examining Mbv and Mox responses of the erector spinae muscles has been verified [29, 30].

NIRS Data Analysis

The relative change in optical density (OD) at 760 nm and 850 nm was calculated using the raw NIRS data and a modification of the Beer-Lambert law [10, 31]:

$$OD = a \times c \times d \times B + G$$

where a = the absorption coefficient of the tissue, c = the concentration of the tissue, d = the distance in between optodes on the measuring probe, B = the differential path length factor of the tissue, and G = the geometry of the tissue. The relative change in Mbv was calculated as the sum of the change in OD at the two wavelengths (deoxy-Hb at 760 nm and oxy-Hb at 850 nm). The relative change in Mox was calculated as the difference between the two signals (850 nm - 760 nm). The raw NIRS data were averaged over 20 sec intervals during each phase of the test protocol. The NIRS values of interest were Mbv-and Mox-range and-delta. The range was calculated as the change in Mbv or Mox from the lowest value during exercise to the highest value during recovery. The delta value was calculated as the change in Mbv or Mox (either positive or negative) from the last 20 secs of resting baseline to the lowest or greatest value during exercise. The ½ recovery time (½ rec) for Mbv and Mox was calculated as the time taken to reach 50% of

the maximal recovery value (Figure 3.1). Half recovery time was considered an index for intramuscular oxygen dynamics (resaturation of exercise-desaturated haemoglobin and myoglobin) [10].

Visual Analogue Scale (VAS) and Borg Scale (RPE)

The VAS has been used to indicate the level of pain in previous chronic low back pain studies [16, 19]. The current study used the VAS to obtain an average baseline pain value for each LBP subject. The VAS has produced repeatable results in the study of low back pain subjects [52]. The Borg scale [6] was used to obtain the RPE of the subjects during and at the completion of the RILL. The validity of the Borg scale during isoinertial loading of the paraspinal muscles has been previously documented [26]. The RPE scale has been used for both exercise and occupational related studies [9, 43, 48], as well as for measuring differences in fatigue based on body region [4, 41].

Statistical Analysis

All data was analyzed in its raw form, as no normalization of the data was made. A one-way analysis of variance (ANOVA) was used to examine the differences in the anthropometric characteristics amongst the healthy, LBP, LBP-A and LBP-S subjects. Comparisons were made between: 1) healthy and LBP, 2) healthy and LBP-A, 3) healthy and LBP-S, and 4) LBP-A and LBP-S to determine if significant differences existed, but no comparison was made between LBP and LBP-A or LBP-S, as it would have been a violation of ANOVA (assumption of independent groups) of. A 2-way analysis of covariance (2-way ANCOVA) with repeated measures was used to examine the

difference between the means of the groups and the two sides (Rt and Lt) for the pertinent NIRS variables. If no significant differences were found between the Rt and Lt sides then the sides were pooled (averaged) for further analysis. The average ½ skinfold thickness of the Rt and Lt sides was used as the covariate as this variable has been reported to influence the NIRS variables [54]. Significant *F* ratios were subjected to post hoc analysis using the Scheffé procedure to identify differences between the groups and sides. Forward stepwise multiple regression analysis was used to identify the variables that would best predict the absolute and relative peak VO_2 during the RILL in the healthy and LBP subjects. Because of the smaller number of subjects in the LBP-A and LBP-S sub-groups, the prediction was done for only the entire LBP subjects. Statistical analyses were performed using the Statistica 6.1 (Statsoft, Inc. '2003 Edition, Tulsa, OK) computer package. The alpha level was set at 0.05 ($P \leq .05$).

RESULTS

Physical Characteristics

The physical characteristics of the healthy, LBP, LBP-S, and LBP-A subjects are listed in Table 3.1. No statistically significant differences were observed between the healthy and LBP subjects for age, standing height, body mass, % BF, SF-Rt and BMI. The LBP subjects had a significantly greater SF-Lt than the healthy subjects. The LBP-A subjects were significantly taller and had significantly lower SF-Lt, SF-Rt, and % BF and BMI values than the LBP-S subjects. Additionally, no significant difference was found between the LBP-S (4.9) and LBP-A (4.2) subjects in degree of low back pain as determined by the VAS.

Cardiorespiratory and Perceptual Responses

Table 3.2 lists the peak values of the mass lifted and the associated cardiorespiratory and perceptual (RPE) responses of the healthy, LBP, LBP-A and LBP-S subjects during the RILL protocol. Each subject completed the RILL protocol to voluntary fatigue. None of the subjects attained the criteria defined in the methods for VO_{2max}, thus from this point forward the term VO_{2peak} will be used to indicate the highest oxygen uptake achieved by the subjects.

No significant mean differences were observed between the healthy and LBP subjects for peak values of absolute VO_2, HR, V_E, and O_2 pulse during the RILL protocol. However, the healthy subjects demonstrated significantly greater mean responses than the LBP subjects for peak values of mass lifted, test duration, relative VO_2, B*f*, but the healthy subjects had a significantly lower mean RER. No significant mean differences were noted between healthy and LBP-S subjects for peak values of HR and respiratory exchange ratio (RER). Yet, the healthy subjects showed significantly greater mean responses as compared to the LBP-S subjects for peak values of mass lifted, test duration, absolute and relative VO_2, B*f*, V_E, and O_2 pulse. Comparison between the LBP-A and LBP-S groups indicated no significant mean differences for the peak values of test duration, mass lifted, HR and O_2 pulse. However, the LBP-A subjects demonstrated significantly greater peak values for absolute and relative VO_2 and V_E than the LBP-S group. In all subject groups the highest localized RPE values were observed for the lower back, followed by the heart/lungs and arm/shoulder areas. However, no significant differences were observed between the healthy, LBP, LBP-S or LBP-A subjects for these responses.

NIRS Trends During RILL

The Mbv and Mox trends for the right and left side erector spinae muscles of a healthy and LBP subject are illustrated in Figure 3.1 to 3.4 respectively. The Mbv trends were similar in the healthy and LBP subjects on both sides with the primary variation being test duration. At the onset of the RILL test there was a rapid decrease in Mbv on both the right and left sides in ~75% of the subjects, with the remaining 25% demonstrating an initial increase followed by a rapid decrease. Thereafter Mbv systematically increased (~14%), decreased (~73%), or levelled off (~14%) for the remainder of the test duration. At the cessation of the RILL test there was a rapid increase in Mbv towards the resting baseline on both the right and left sides.

Muscle oxygenation changes were also very similar in the healthy and LBP subjects on both sides. At the onset of RILL there was a sharp decrease in Mox on both the right and left sides in all the subjects. Thereafter, there was a systematic decrease in the Mox with increasing mass lifted, with a slight increase, levelling off, or a sharp decline as the maximal load was attained. Upon termination of the RILL, ~78% of the healthy subjects showed a rapid recovery in Mox towards the baseline, while ~48% of the LBP subjects demonstrated this rapid response. In the remaining healthy and LBP subjects, the recovery was more gradual. The recovery process was typically complete within the first 2-min and was followed by a levelling off near or above the resting baseline level. In ~50% of the cases, both Mbv (hyperemia) and Mox exceeded the resting baseline value observed prior to the onset of lifting.

Comparison of NIRS Variables Between Healthy and Low Back Pain Subjects

No significant difference was observed between the right and left sides for any of the NIRS variables in the healthy and LBP subjects. Therefore, the values for the two sides were pooled and used for analysis. A comparison of the means of the NIRS variables between the healthy and LBP subjects, and the LBP-A and LBP-S subjects are provided in Figures 3.5, 3.6, 3.7, and 3.8. No significant differences were observed between the healthy and LBP groups for the Mbv-delta and Mbv-range. However, the Mox-delta and Mox-range were significantly greater in the healthy subjects compared to the LBP subjects. As well, the ½ rec Mbv and ½ rec Mox were significantly faster in the healthy subjects compared to the LBP subjects (see Figures 3.9 and 3.10). Comparison between the LBP-A and LBP-S subjects indicated no significant difference between the two groups except for the Mox-delta, which was significantly lower in the LBP-S group.

Prediction of Peak Oxygen Uptake

The results of the forward stepwise regression analysis to predict the absolute and relative VO_{2peak} in the healthy and LBP subjects are provided in Tables 3.3 and 3.4, respectively. For the absolute VO_{2peak} in the healthy subjects, peak O_2 pulse explained ~69% of the common variance (r = 0.83), while HR_{peak} contributed an additional 29% to the common variance (r = 0.99). In the LBP subjects, ~72% of the common variance (r = 0.85) was predicted by V_{Epeak}, ~14% (r = 0.93) was predicted by O_2 pulse, and ~10% (r = 0.98) was explained by HR_{peak}. The regression equations for predicting the absolute VO_{2peak} in the healthy and LBP subjects are given in equations (Eq.) 1 and 2, respectively:

$$VO_{2peak}\ (L \cdot min^{-1}) = -2.40 + 0.147(O_2\ pulse) + 0.015(HR_{peak}) \quad \text{[Eq.1]}$$

$$VO_{2peak}\ (L \cdot min^{-1}) = -2.14 + 0.003(V_{Epeak}) + 0.150(O_2\ pulse) + 0.012(HR_{peak}) \quad \text{[Eq. 2]}$$

The predictors for the relative VO_{2peak} in the healthy and LBP subjects differed from those for the absolute value. In the healthy subjects ~35% of the common variance ($r = 0.59$) was predicted by HR_{peak} with an additional ~21% ($r = 0.75$) predicted by peak O_2 pulse. The total variance predicted by these two variables was 56%.

However, in the LBP subjects, ~29% of the common variance ($r = 0.54$) in relative VO_{2peak} was predicted by HR_{peak}, while an additional 19% ($r = 0.69$) was explained by Mox-delta, and a further 7% ($r = 0.74$) by O_2 pulse. The total variance predicted by these three variables was 55%. The regression equations for predicting the relative VO_{2peak} in the healthy and LBP subjects are given in Eq. 3 and 4, respectively:

$$VO_{2peak}\ (ml \cdot kg^{-1} \cdot min^{-1}) = -16.59 + 0.218(HR_{peak}) + 0.765(O_2\ pulse_{peak}) \quad \text{[Eq.3]}$$

$$VO_{2peak}\ (ml \cdot kg^{-1} \cdot min^{-1}) = -11.83 + 0.168(HR_{peak}) + 51.855(Mox\text{-}delta) + 0.588(O_2\ pulse) \quad \text{[Eq. 4]}$$

It is interesting to note that: (1) peak values of heart rate and O_2 pulse were the most consistent variables in determining the common variance for both absolute and

relative VO_{2peak} in the healthy and LBP subjects, and (2) Mox-delta was included as the second variable that predicted the relative VO_{2peak} in the LBP subjects.

DISCUSSION

The primary purposes of this study were to compare healthy and LBP subjects during RILL on: (1) VO_{2peak} and related cardiorespiratory variables, (2) changes in erector spinae Mbv and Mox, (3) the central and peripheral factors that would best predict their VO_{2peak}. The secondary purpose of this study was to compare these responses between active and sedentary subjects with LBP (LBP-A and LBP-S, respectively). It was hypothesized that in contrast with the healthy subjects, the LBP subjects would demonstrate significantly: (1) lower relative VO_{2peak} values, (2) lower changes in muscle oxygenation and blood volume, (3) stronger correlations between the Mbv and Mox changes in the prediction of VO_{2peak}. It was also hypothesized that there would be significant differences between the LBP-A and LBP-S subgroups for each of the variables examined.

Cardiorespiratory and Perceptual Responses during RILL

The results of this study support previous observations [44, 45, 50] that subjects did not attain the criteria for a true VO_{2max} [2]. Of note, all subjects terminated the RILL due to volitional fatigue, not due to pain. In this study, the HR_{peak} of the healthy and LBP subjects corresponded to only 90% and 86% (LBP-A 87% and LBP-S 86%) respectively, of their age predicted maximum HR, which was consistent with previous observations [21, 50]. As well, the RER was below the criterion of 1.10 in most of the subjects, indicating

that the metabolic stress was not maximal. The absolute and relative values of the subjects VO_{2peak} were similar to values reported for other males and females [40]. Thus, performance during the RILL may have been limited by muscular fatigue of the erector spinae [44, 50], resulting in a significant cardiovascular reserve at the end of the test.

Additionally, the lower V_E values obtained during the RILL as compared to treadmill running [50] may have been due to a Valsalva maneuver and the increased work of the respiratory muscles. It is possible that a Valsalva maneuver occurred during RILL, as the load became greater, acting to increase intra-abdominal and intrathoracic pressure to stabilize the spine [15]. Increased work of breathing, which is similar in effect to a Valsalva maneuver, reduces performance during strenuous aerobic exercise [23]. Research has shown [22, 23] a decrement in the time to volitional fatigue during near maximal (~90% VO_{2max}) aerobic activity when the work of breathing was increased (graded resistive loads). Also, when a graded resistive load was added concurrently with maximal cycle ergometer exercise a reduction in leg muscle blood flow was found which was likely associated with vasoconstriction in the leg musculature in attempts to maintain respiratory muscle blood flow due to the increased work of ventilation [22]. In RILL the primary muscles used during the movement were the legs and lower back, if a reduction in erector spinae muscle blood flow occurred the result may be early fatigue, without inducing pain.

To date, the peak cardiorespiratory responses during RILL have not been reported in LBP subjects. In the present study, significantly lower peak mass, absolute and relative VO_{2peak}, V_{Epeak}, breathing frequency (Bf), and O_2 pulse was detected in the LBP and/or LBP-S subjects. There are two likely explanations for the diminished

cardiorespiratory values in the LBP subjects, (1) a prolonged Valsalva maneuver to stabilize the spine and/or (2) a lower fitness level. As previously mentioned, during RILL the Valsalva maneuver was probably greater in all subjects as compared to cycle ergometry work, but the Valsalva maneuver may have been accentuated in LBP subjects. A prolonged Valsalva maneuver might have been used to assist the diaphragm in maintaining truncal stability to reduce the risk of further injury [11]. Research has shown that the duration of the Valsalva maneuver was longer in LBP subjects [53]. The fact that the LBP subjects demonstrated significantly lower cardiorespiratory measures has important implications for endurance performance in jobs that require extensive MMH [12, 38, 45].

The LBP and LBP-S demonstrated a reduced level of cardiorespiratory fitness [39, 55], likely associated with a reduced level of physical activity [51]. Decreases in cardiovascular function have been reported with reduced physical activity in healthy subjects [13]. The reduced level of physical activity, which leads to a reduced fitness level, may be related to the LBP subjects fear and avoidance of pain [56]. The chief point is that the diminished cardiorespiratory function noted in the LBP and LBP-S, but not the LBP-A subjects, was a strong indicator of either fear of further injury and/or a reduced fitness level [39, 55] based on reduced physical activity level [51], may negatively influence the successful completion of MMH tasks.

NIRS Trends During RILL

The general trends for Mbv and Mox during RILL were similar in both the healthy and LBP subjects (see Figures 3.1 to 3.4). The Mox trend observed was

comparable to that reported for the vastus lateralis muscle during incremental cycling [3, 4], rowing [10] and submaximal lifting [34]. The systematic decrease in Mox during the RILL was attributed to the increased cellular metabolism in the mitochondria for aerobic energy production. The plateau in the latter stages of RILL suggested that the oxyhemoglobin in the small blood vessels had attained their maximum level of desaturation at this intensity [10].

Examination of the Mbv trend during RILL indicated that it was opposite to that reported during other modes of dynamic activity, e.g. cycling, walking and running [24]. The present study found that Mbv reduced rapidly at onset of exercise, and then declined systematically throughout the remainder of RILL. The difference in the Mbv response between RILL and other dynamic exercise modes was most likely due to the considerable isometric activity of the erector spinae muscles during lifting and lowering [44]. Research indicated that muscle blood flow was reduced at ~20% maximal volitional contraction (MVC) during intermittent and sustained isometric contractions [25, 36] and occluded at ≥40% MVC [5, 49] due to increased intramuscular pressure (IMP). The progressive decline in Mbv during RILL was likely associated with a progressive increase in IMP during the protocol due to the elongation of the isometric contraction as the load became progressively heavier and the lifting and lowering movements became extended. Additionally, the periods of standing and squatting at the top and bottom of each movement would require contraction of the erector spinae muscles to maintain the posture [7]. Thus a state of relaxation of the erector spinae muscle would not occur until the completion of the RILL test, which would result in an increase in Mbv as is evident in Figure 3.1.

Recently, Maronitis et al. [34] reported that during 60-min of steady state submaximal lifting Mbv increased systematically throughout the test with no signs of levelling off. The discrepancy between the studies was likely the effect of differences in the protocol and test duration. The present study used a continuous incremental lifting and lowering protocol to voluntary fatigue, whereas Maronitis et al. (2000) used a submaximal lifting only protocol (30 lbs) separated into three 20-min segments. The test duration of the current study ranged between 7:00-and 11:00-min (Maronitis = 60-min). The differences in test duration may have influenced intramuscular temperature and the accumulation of vasodilator metabolites (e.g., adenosine, carbon dioxide) [35], both of which could have influenced localized Mbv as measured by NIRS.

The rapid increase in Mox during the early stages of recovery reflected reestablishment of muscle blood and oxygen supply, and reduced cellular oxygen uptake at the cessation of exercise [10]. The initial reoxygenation during recovery was driven by the need to replenish two-phosphate groups, phosphocreatine (PCr) and adenosine triphosphate (ATP) [10]. The latter phase of reoxygenation was likely a result of the need to oxidize metabolites such as lactate that accumulate during the exercise phase [35]. The rapid increase in Mox was more prevalent within the healthy than the LBP subjects. The difference between the subjects in reoxygenation might have been related to differences in erector spinae vasculature [27], and changes in mitochondrial density and enzyme levels associated with a lower level of fitness [14].

Comparison of NIRS Variables Between Healthy and Low Back Pain Subjects

During exercise, the Mox-delta value indicates the degree of deoxygenation that occurs at the level of the small blood vessels and is dependent upon the balance between oxygen delivery and extraction [10]. In the current study, the Mox-delta was significantly greater in the healthy compared to the LBP subjects, implying greater oxygen extraction in the healthy group. It was suggested that the ½ rec time measured by NIRS was an index of the oxidative capacity of the exercising muscle [10]. The current findings indicated that the ½ rec times for Mbv and Mox were significantly faster in the healthy compared to the LBP subjects (see Figures 3.9 and 3.10). This may have been due to either reduced fitness in the LBP subjects or inherent pathology of their lower back musculature.

Research on individuals with a reduced level of fitness indicated that decreases in mitochondrial enzyme activity (citrate synthase and succinate dehydrogenase), take place within a few weeks of the cessation of training [14]. The fact that the ½ rec times were faster in the healthy subjects compared to the LBP subjects suggests that a reduced fitness level was most likely a factor (see Figures 3.9 and 3.10). Additionally, the LBP-A subjects displayed a faster Mbv ½ rec time as compared to the LBP-S subjects. A delay in muscle ½ rec time in LBP subjects was reflective of reductions in capillary density, myoglobin concentration, mitochondrial density, oxidative enzyme activity, and oxygen transport capacity [37], all of which would compromise the ability to restore oxygen supply to the erector spinae muscles during recovery from the RILL protocol. The slower ½ rec time in LBP subjects was directly related to reduced blood supply, and thus reduced oxygen supply to the recovering muscle, due to increased IMP [37]. As well, it was reported that the erector spinae muscle fiber characteristics of LBP subjects were

different from those of healthy subjects. The LBP subjects tended to have a greater proportion of fast fatiguing motor units as compared to healthy subjects [33]. A significant (P = .015) negative relationship was reported between the proportions of Type I (oxidative) muscle fibers present in the erector spinae and the duration of low back pain [32].

Prediction of VO_{2peak}

In the current study, the stepwise regression analysis indicated that the significant predictors for absolute VO_{2peak} in the healthy subjects were the peak values of O_2 pulse and HR. Collectively, these two variables explained 98% of the common variance. In the LBP subjects three predictors, namely, the peak values of the V_E, O_2 pulse and HR explained 96% of the common variance. It should be noted that none of the NIRS variables contributed significantly to the prediction of absolute VO_{2peak} in either the healthy or LBP subjects. However, upon examining the predictive model for the relative VO_{2peak}, it was interesting to note that Mox-delta emerged as the second significant predictor of the VO_{2peak} in the LBP subjects. This variable significantly increased the predictability of relative VO_{2peak} from 54% attributed to the HR_{peak} to 69%, an increase of 15%. These findings suggest that intramuscular factors that influence the capacity of the erector spinae muscles to extract oxygen play an important role in determining the VO_{2peak} in LBP subjects. Group differences in the variables that predicted VO_{2peak} might have been due in whole, or in part, to a reduced fitness level or other factors discussed above that influence the oxidative capacity of the erector spinae muscles.

Conclusion

The results of this study indicated no significant differences in absolute VO_{2peak} between the healthy and LBP subjects, but significantly lower values in absolute and relative VO_{2peak} values in LBP-S compared to healthy subjects. In the LBP subjects the degree of erector spinae muscle deoxygenation during RILL was significantly reduced and the ½ rec time, an index of muscle oxidative capacity, was slower. This difference between the healthy and LBP-S subjects was likely the result of a lower level of fitness associated with physical inactivity in the LBP-S subjects, and/or the inherent pathology of the low back musculature that was previously reported in LBP subjects. Regression analysis indicated that in the healthy subjects, peak values of HR and O_2 pulse explained 35% and 21% respectively of the relative VO_{2peak} during incremental lifting an lowering. However, in the LBP subjects, these two variables accounted or 29% and 7% respectively of the relative VO_{2peak}, while Mox accounted for 19% of the prediction. The latter findings suggest that the capacity of the localized musculature to extract oxygen during incremental lifting and lowering is a factor limiting the VO_{2peak} in individuals with LBP.

Table 3.1. Physical characteristics of healthy, LBP, LBP-A, and LBP-S subject groups. Values are mean (±SD).

	Groups			
Variable	Healthy (N=34) 17 Male 17 Female	LBP (N=34) 17 Male 17 Female	LBP-A (N=19) 11 Male 8 Female	LBP-S (N=15) 6 Male 9 Female
Age (yrs)	31.79(8.55)	34.62(6.31)	33.16(6.09)	36.47(6.29)
Height (m)	1.71(0.09)	1.71(0.08)	1.73(0.08)[c]	1.67(0.07)
Body mass (kg)	75.59(14.06)	76.70(14.18)	74.69(14.56)	79.23(13.75)
½ Skinfold Left (mm)	4.72(1.71)[ab]	5.99(2.43)	4.79(1.62)[c]	7.52(2.46)
½ Skinfold Right (mm)	5.05(2.11)[b]	6.02(2.29)	4.88(1.52)[c]	7.47(2.32)
BF (%)	24.93(6.70)[b]	27.84(7.35)	24.57(5.98)[c]	31.97(6.96)
FM (kg)	18.66(5.30)[b]	21.59(7.73)	18.45(6.01)[c]	25.57(8.00)
LBM (kg)	59.63(12.47)[b]	55.11(10.47)	56.24(11.25)	53.67(9.57)
BMI	25.80(3.13)	26.23(3.98)	24.64(3.30)[c]	28.28(3.93)

[a] indicates a significant difference between healthy and LBP

[b] indicates a significant difference between healthy and LBP-S

[c] indicates a significant difference between LBP-A and LBP-S

Table 3.2. Peak cardiorespiratory responses of all subjects during the RILL test. Values are mean (±SD).

	Groups			
	Healthy (N=34)	**LBP (N=34)**	**LBP-A (N=19)**	**LBP-S (N=15)**
Variable	**17 Male 17 Female**	**17 Male 17 Female**	**11 Male 8 Female**	**6 Male 9 Female**
Peak Mass Lifted (kg)	25.85(9.69)[ac]	21.08(6.79)	23.36(6.76)	18.20(5.82)
Test Duration (min:sec)	11:00(4:32)[ac]	8:39(3:09)	9:45(3:13)	7:16(2:31)
VO_{2peak} ($L \cdot min^{-1}$)	2.54(0.58)[c]	2.29(0.52)	2.48(0.56)[d]	2.06(0.36)
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	34.39(6.67)[ac]	29.85(6.16)	32.94(5.88)[d]	25.94(3.97)
VO_{2peak} ($ml \cdot kg_{LBM}^{-1} \cdot min^{-1}$)	45.16(7.99)[ac]	40.98(6.55)	43.33(6.39)	38.00(5.60)
HR_{peak} ($beats \cdot min^{-1}$)	170.94(19.74)	161.49(21.97)	164.2(25.33)	158.41(17.81)
Bf ($breaths \cdot min^{-1}$)	42.52(9.17)[ac]	37.81(7.94)	39.54(8.23)	35.62(7.25)
% Age Predicted HRpeak	90.78(9.63)	86.93(11.56)	87.51(13.56)	86.27(9.22)
V_{Epeak} ($L \cdot min^{-1}$)	78.84(22.98)[c]	71.64(24.43)	80.15(28.40)[d]	60.87(12.14)
RER_{peak}	1.02(0.08)[ab]	1.09(0.07)	1.09(0.06)	1.07(0.08)
O_2 Pulse ($ml \cdot beat^{-1}$)	15.24(3.41)[c]	14.46(2.76)	15.20(3.04)	13.51(2.13)
RPE Arms/shoulder	15.06(2.81)	15.5(2.88)	15.21(3.21)	15.87(2.47)
RPE Back	17.94(1.89)	18.15(1.76)	17.95(1.87)	18.40(1.64)
RPE Cardiorespiratory	16.71(1.98)	16.38(2.49)	16.47(2.57)	16.27(2.46)

[a] indicates a significant difference between healthy and LBP

[b] indicates a significant difference between healthy and LBP-A

[c] indicates a significant difference between healthy and LBP-S

[d] indicates a significant difference between LBP-A and LBP-S

Table 3.3. Summary of the forward stepwise regression analysis for absolute VO_{2peak} in healthy and LBP subjects.

Healthy	Step in/out	Multiple R	Multiple R-squared	R-square Change	p-level
O_2 Pulse	1	0.832863	0.693661	0.693661	0.000000
HR_{peak}	2	0.988876	0.977875	0.284214	0.000000

LBP	Step in/out	Multiple R	Multiple R-squared	R-square Change	p-level
V_{Epeak}	1	0.850374	0.723136	0.723136	0.000000
O_2 Pulse	2	0.927576	0.860397	0.137261	0.000005
HR_{peak}	3	0.978299	0.957069	0.096671	0.000000

Table 3.4. Summary of the forward stepwise regression analysis for relative VO_{2peak} in healthy and LBP subjects.

Healthy	Step in/out	Multiple R	Multiple R-squared	R-square Change	p-level
HR_{peak}	1	0.589890	0.347970	0.347970	0.000241
O_2 Pulse	2	0.748056	0.559588	0.211618	0.000539

LBP	Step in/out	Multiple R	Multiple R-squared	R-square Change	p-level
HR_{peak}	1	0.537121	0.288499	0.288499	0.001055
Mox-delta	2	0.690982	0.477456	0.188957	0.002147
O_2 Pulse	3	0.742111	0.550729	0.073273	0.034727

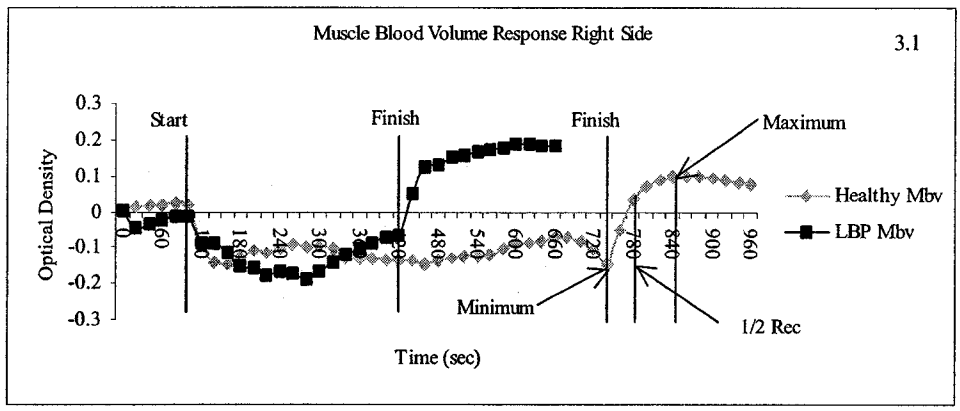


Figure 3.1. Muscle blood volume trends on the right side for a typical healthy and LBP subject during the RILL test. The healthy subject demonstrates the maximum and minimum values and ½ rec time markers.

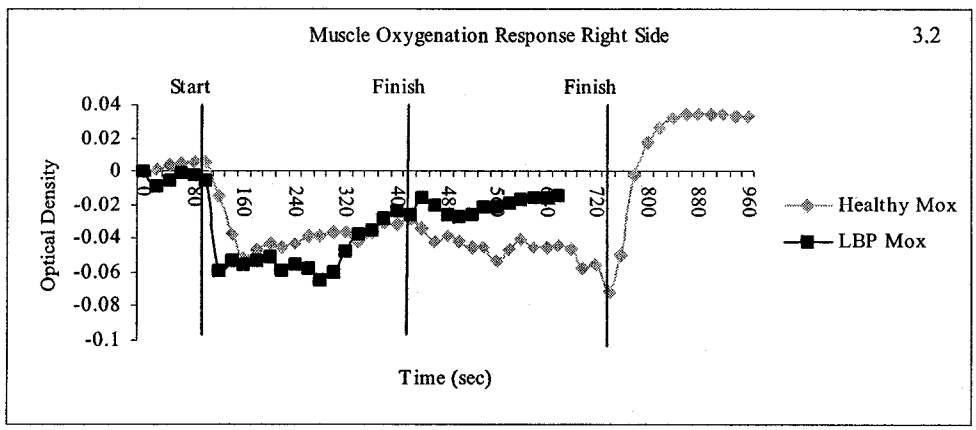


Figure 3.2. Muscle oxygenation trends on the right side for a typical healthy and LBP subject during the RILL test.

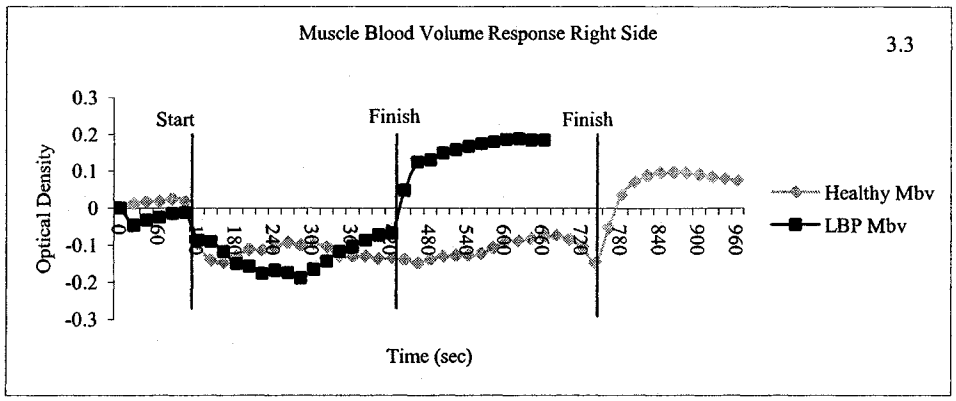


Figure 3.3. Muscle blood volume trends on the left side for a typical healthy and LBP subject during the RILL test.

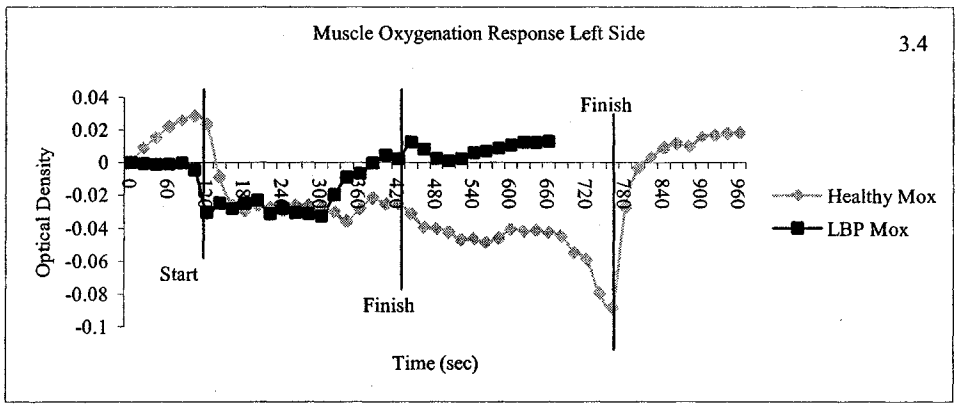


Figure 3.4. Muscle oxygenation trends on the left side for a typical healthy and LBP subject during the RILL test.

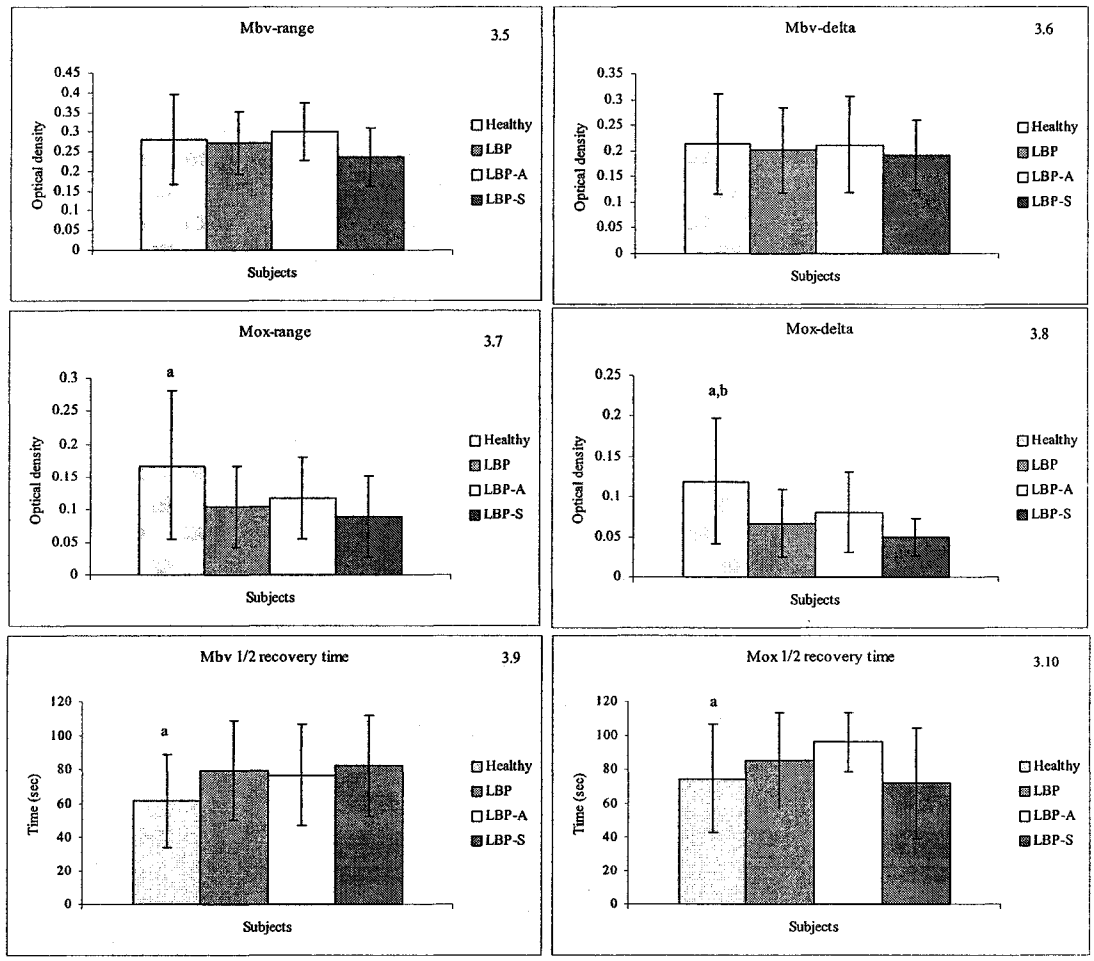


Figure 3.5 - 3.10. A comparison of Mbv-range and-delta, Mox-range and-delta, and Mbv and Mox ½ rec times during the RILL test in the healthy, LBP, LBP-S, and LBP-A subjects. [a] indicates a significant difference between healthy and LBP, [b] indicates a significant difference between healthy and LBP-S.

REFERENCES

1. Abdel-Moty, E., D. A. Fishbain, T. M. Khalil, S. Sadek, R. Cutler, R. S. Rosomoff, and H. L. Rosomoff. Functional capacity and residual functional capacity and their utility in measuring work capacity. *Clin J Pain.* 9:168-173., 1993.
2. American College of Sports Medicine. *Resource Manual for Guidelines for Exercise Testing and Prescription.* Fourth ed. Philadelphia: Lippincott Williams & Wilkins, 2001
3. Belardinelli, R., T. Barstow, J. Porsasz, and K. Wasserman. Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. *Eur J Appl Physiol.* 70:487-492, 1995.
4. Bhambhani, Y., R. Maikala, and S. Buckley. Muscle oxygenation during incremental arm and leg exercise in men and women. *Eur J Appl Physiol Occup Physiol.* 78:422-431., 1998.
5. Bonde-Petersen, F., A. L. MØrk, and E. Nielsen. Local muscle blood flow and sustained isometric contractions of human arm and back muscles. *Eur J Appl Physiol.* 34:43-50, 1975.
6. Borg, G. and B. Noble. Perceived exertion. *Exerc Sport Sci Rev.* 2:131-153, 1974.
7. Callaghan, J. P. and S. M. McGill. Low back joint loading and kinematics during standing and unsupported sitting. *Ergonomics.* 44:280-294, 2001.
8. Canadian Society for Exercise Physiology. *The Canadian Physical Activity, Fitness & Lifestyle Appraisal Manual.* Ottawa: The Canadian Society for Exercise Physiology, 1996.

9. Capodaglio, P. The use of subjective rating of exertion in Ergonomics. *G Ital Med Lav Ergon.* 24:84-89, 2002.

10. Chance, B., M. Dait, C. Zhang, T. Hamaoka, and F. Hagerman. Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. *Am J Physiol.* 262:C766-C775, 1992.

11. Cholewicki, J., K. Juluru, A. Radebold, M. M. Panjabi, and S. M. McGill. Lumbar spine stability can be augmented with an abdominal belt and/or increased intra-abdominal pressure. *Eur Spine J.* 8:388-395, 1999.

12. Costill, D. L., H. Thomason, and E. Roberts. Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports.* 5:248-252, 1973.

13. Coyle, E. F., M. K. Hemmert, and A. R. Coggan. Effects of detraining on cardiovascular responses to exercise: role of blood volume. *J Appl Physiol.* 60:95-99, 1986.

14. Coyle, E. F., W. H. Martin, 3rd, D. R. Sinacore, M. J. Joyner, J. M. Hagberg, and J. O. Holloszy. Time course of loss of adaptations after stopping prolonged intense endurance training. *J Appl Physiol.* 57:1857-1864, 1984.

15. Cresswell, A. G. and A. Thorstensson. Changes in intra-abdominal pressure, trunk muscle activation and force during isokinetic lifting and lowering. *Eur J Appl Physiol.* 68:315-321, 1994.

16. Dickens, C., M. Jayson, and F. Creed. Psychological correlates of pain behavior in patients with chronic low back pain. *Psychosomatics.* 43:42-48, 2002.

17. Durnin, J. V. G. A. and J. Womersley. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutri.* 32:77-97, 1974.

18. Foster, C., K.W. Rundell, A.C. Snyder, J. Stray-Gundersen, G. Kemkers, N. Thometz J. Broker, E. Knapp. Evidence for restricted muscle blood flow during speed skating. *Med Sci Sports Exerc.* 31:1433-1440, 1999.

19. Fritzell, P., O. Hagg, P. Wessberg, and A. Nordwall. Chronic low back pain and fusion: a comparison of three surgical techniques: a prospective multicenter randomized study from the Swedish lumbar spine study group. *Spine.* 27:1131-1141, 2002.

20. Garg, A. and J. S. Moore. Prevention strategies and the low back in industry. *Occup Med.* 7:629-640., 1992.

21. Hagen, K. B., J. Hallen, and K. Harms-Ringdahl. Physiological and subjective responses to maximal repetitive lifting employing stoop and squat technique. *Eur J Appl Physiol Occup Physiol.* 67:291-297, 1993.

22. Harms, C. A., M. A. Babcock, S. R. McClaran, D. F. Pegelow, G. A. Nickele, W. B. Nelson, and J. A. Dempsey. Respiratory muscle work compromises leg blood flow during maximal exercise. *J Appl Physiol.* 82:1573-1583, 1997.

23. Harms, C. A., T. J. Wetter, C. M. St Croix, D. F. Pegelow, and J. A. Dempsey. Effects of respiratory muscle work on exercise performance. *J Appl Physiol.* 89:131-138, 2000.

24. Hiroyuki, H., T. Hamaoka, T. Sako, S. Nishio, R. Kime, M. Murakami, and T. Katsumura. Oxygenation in vastus lateralis and lateral head of gastrocnemius

during treadmill walking and running in humans. *Eur J Appl Physiol.* 87:343-349, 2002.

25. Jensen, B. R., K. Jorgensen, A. R. Hargens, P. K. Nielsen, and T. Nicolaisen. Physiological response to submaximal isometric contractions of the paravertebral muscles. *Spine.* 24:2332-2338, 1999.

26. Kankaanpaa, M., S. Taimela, C. J. Webber, O. Airaksinen, and O. Hanninen. Lumbar paraspinal muscle fatigability in repetitive isoinertial loading: EMG spectral indicies, Borg scale and endurance time. *Eur J Appl Physiol.* 76:236-242, 1997.

27. Kauppila, L. I. Prevalence of stenotic changes in arteries supplying the lumbar spine. A postmortem angiographic study on 140 subjects. *Ann Rheum Dis.* 56:591-595, 1997.

28. Kell, R. T. and Y. Bhambhani. Cardiorespiratory & Hemodynamic Responses during Repetitive Incremental Lifting & Lowering in Healthy Males & Females. *Eur J Appl Physiol.* 90:1-9, 2003.

29. Kell, R. T., M. Farag, and Y. Bhambhani. Reliability of erector spinae oxygenation and blood volume responses using near-infrared spectroscopy in healthy males. *Eur J Appl Physiol.* 91:499-507, 2004.

30. Maikala, R. and Y. Bhambhani. Low-back muscle oxygenation trends during simple postural variations-intersession reliability using near infra-red spectroscopy. In *IEA2000/HFES Congress*, pp. 5-9 to 9-12, 2000.

31. Mancini, D., L. Bolinger, L. Li, K. Kendrick, B. Chance, and J. Wilson. Validation of near-infrared spectroscopy in humans. *J Appl Physiol.* 77:2740-2745, 1994.

32. Mannion, A. F., L. Kaser, E. Weber, A. Rhyner, J. Dvorak, and M. Muntener. Influence of age and duration of symptoms on fibre type distribution and size of the back muscles in chronic low back pain patients. *Eur Spine J.* 9:273-281, 2000.

33. Mannion, A. F., B. R. Weber, J. Dvorak, D. Grob, and M. Muntener. Fibre type characteristics of the lumbar paraspinal muscles in normal healthy subjects and in patients with low back pain. *J Orthop Res.* 15:881-887, 1997.

34. Maronitis, A. B., K. M. Kovacs, R. E. Splittstoesser, and W. S. Marras. The effectiveness of whole body localized measures of fatigue. In *HFES*: Proceedings of the IEA, pp. 5-91-95-94, 2000.

35. McArdle, W. D., F. I. Katch, and V. L. Katch. *Exercise Physiology: Energy, Nutrition, and Human Performance.* 5th ed. New York: Lippincott, Williams & Wilkins, 2001

36. McGill, S. M., R. L. Hughson, and K. Parks. Lumbar erector spinae oxygenation during prolonged contractions: implications for prolonged work. *Ergonomics.* 43:486-493., 2000.

37. Miyake, M., Y. Harada, M. Senda, K. Oda, and H. Inoue. Oxygen dynamics at paraspinal muscles during exertion using near-infrared spectroscopy in patients with degenerative lumbar scoliosis. *J Orthop Sci.* 81:187-191, 2003.

38. National Institute for Occupational Safety and Health. *Work Practices Guide for Manual Lifting*. Washington: U.S. Government Printing Office. DHHS Pub. No. 81-122, 1981.

39. Nielens, H. and L. Plaghki. Cardiorespiratory fitness, physical activity level, and chronic pain: are men more affected than women? *Clin J Pain*. 17:129-137, 2001.

40. Nindl, B. C., M. A. Sharp, R. P. Mello, V. J. Rice, M. M. Murphy, and J. F. Patton. Gender comparison of peak oxygen uptake: repetitive box lifting versus treadmill running. *Eur J Appl Physiol Occup Physiol*. 77:112-117, 1998.

41. Pandolf, K. B., D. S. Billings, L. L. Drolet, N. A. Pimental, and M. N. Sawka. Differential ratings of perceived exertion and various physiological responses during prolonged upper and lower body exercise. *Eur J Appl Physiol Occup Physiol*. 53:5-11, 1984.

42. Payne, N., N. Gledhill, P. T. Katzmarzyk, and V. Jamnik. Health-related fitness, physical activity and history of back pain. *Can J Appl Physiol*. 24:236-249, 2000.

43. Perez-Landaluce, J., B. Fernandez-Garcia, M. Rodriguez-Alonso, F. Garcia-Herrero, P. Garcia-Zapico, A. M. Patterson, and N. Terrados. Physiological differences and rating of perceived exertion (RPE) in professional, amateur and young cyclists. *J Sports Med Phys Fitness*. 42:389-395, 2002.

44. Petrofsky, J. S. and A. R. Lind. Comparison of metabolic and ventilatory responses of men to various lifting tasks and bicycle ergometry. *J Appl Physiol*. 45:60-63, 1978.

45. Petrofsky, J. S. and A. R. Lind. Metabolic, cardiovascular, and respiratory factors in the development of fatigue in lifting tasks. *J Appl Physiol*. 45:64-68., 1978.

46. Pope, M. H. Occupational Hazards for Low Back Pain. In: *Low Back Pain: A scientific and clinical overview*. J. N. Weinstein and S. L. Gordon (Eds.) Rosemont: American Academy of Orthopaedic Surgeons, 1996, pp. 333-345.

47. Prieur, F., J. Castells, and C. Denis. A methodology to assess the accuracy of a portable metabolic system (VmaxST). *Med Sci Sports Exerc.* 35:879-885, 2003.

48. Rittweger, J., H. Schiessl, and D. Felsenberg. Oxygen uptake during whole-body vibration exercise: comparison with squatting as a slow voluntary movement. *Eur J Appl Physiol.* 86:169-173, 2001.

49. Sadamoto, T., F. Bonde-Petersen, and Y. Suzuki. Skeletal muscle tension, flow, pressure, and EMG during sustained isometric contractions in humans. *Eur J Appl Physiol Occup Physiol.* 51:395-408, 1983.

50. Sharp, M. A., E. Harman, J. A. Vogol, J. J. Knapik, and S. J. Legg. Maximal aerobic capacity for repetitive lifting: comparison with three standard exercise tests and modes. *Eur J Appl Physiol Occup Physiol.* 57:753-760, 1988.

51. Spenkelink, C. D., M. M. Hutten, H. J. Hermens, and B. O. Greitemann. Assessment of activities of daily living with an ambulatory monitoring system: a comparative study in patients with chronic low back pain and nonsymptomatic controls. *Clin Rehabil.* 16:16-26, 2002.

52. Staes, F., K. Stappaerts, H. Vertommen, and G. Nuyens. Visual analogue scale for the perceived influence of exertion and movements/positions on low back problems in surveys of adolescents. *Acta Paediatr.* 89:713-716, 2000.

53. Troup, J. D., T. P. J. Leskinen, H. R. Stalhammar, and I. A. A. Kuorinka. A comparison of intra-abdominal pressure increase, hip torque, and lumbar vertebral compression in different lifitngtechniques. *Human Factors*. 25:517-525, 1983.

54. van Beekvelt, M. C., M. S. Borghuis, B. G. van Engelen, R. A. Wevers, and W. N. Colier. Adipose tissue thickness affects in vivo quantitative near-IR spectroscopy in human skeletal muscle. *Clin Sci.* 101:21-28., 2001.

55. van der Velde, G. and D. Mierau. The effect of exercise on percentile rank aerobic capacity, pain, and self-rated disability in patients with chronic low-back pain: a retrospective chart review. *Arch Phys Med Rehabil.* 81:1457-1463, 2000.

56. Verbunt, J. A., H. A. Seelen, J. W. Vlaeyen, G. J. van de Heijden, P. H. Heuts, K. Pons, and J. Andre Knottnerus. Disuse and deconditioning in chronic low back pain: concepts and hypotheses on contributing mechanisms. *Eur J Pain.* 7:9-21, 2003.

57. Yoshitake, Y., H. Ue, M. Miyazaki, and T. Moritani. Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. *Eur J Appl Physiol.* 84:174-179, 2001.

CHAPTER FOUR (Study Three)

CARDIORESPIRATORY AND ERECTOR SPINAE MUSCLE BLOOD VOLUME AND OXYGENATION RESPONSES DURING A PSYCHOPHYSICAL EVALUATION OF LIFTING AND LOWERING CAPACITY

INTRODUCTION

Physiological factors associated with endurance capacity have been extensively studied during a variety of exercise modes. There is considerable evidence indicating that the maximal aerobic power (VO_{2max}), defined as the maximum amount of oxygen that can be utilized per unit time, is closely related to endurance performance during activities such as running and cycling in healthy individuals [9, 10]. As well, evidence indicates that the lactate (anaerobic) threshold (LT), defined as the exercise intensity at which the rate of lactate production exceeds the rate of lactate removal, is a good predictor of endurance capacity during these exercise modes [2]. It is generally accepted that if the exercise intensity is below the LT, work can be performed for extended periods [40]. However, when the exercise intensity exceeds the LT, endurance capacity is severely curtailed [40]. In the occupational environment, repetitive lifting and lowering of loads are routinely performed during manual material handling (MMH) tasks [35]. Although several studies [37, 39, 43] have documented the peak physiological responses during repetitive lifting and lowering in healthy males and females, the LT was not evaluated in any of these studies.

Psychophysics is a branch of psychology that examines the relationships between stimuli and the resulting sensations. During the last three decades, ergonomists have extensively used a psychophysical approach to develop guidelines for MMH tasks so as to minimize fatigue, reduce the incidence of injury, and increase worker productivity [44]. One common procedure used in the psychophysical approach is to determine the maximal acceptable weight (MAW) that one can lift repeatedly for an extended period of time without excessive fatigue. These findings led to the recommendation that a healthy person can sustain ~33% of VO_{2max} for whole-body repetitive lifting tasks for a duration

between 2-and 8-hours [33, 35]. This recommendation, however, did not take the LT into consideration. A previous study that measured arterial lactate concentrations during repetitive lifting indicated that a work intensity ≤40% of the peak volume of oxygen consumed (VO_{2peak}), with an upper limit of 50%, was suitable for an 8-hour workday with minimal signs of fatigue [40]. Research demonstrated that when individuals ran for extended periods on a treadmill: (1) they self selected a running velocity that was just below the LT, and (2) there was a strong positive correlation between the oxygen uptake at the self-selected running velocity and the LT during running [16]. If these observations can be applied to prolonged repetitive lifting, it can be hypothesized that the oxygen uptake during the MAW will be just below and significantly correlated with the LT during incremental lifting and lowering.

Epidemiological evidence has indicated that individuals whose jobs involve extensive MMH are at an increased risk for chronic non-specific low back pain (LBP) [19]. Although the exact etiology has not yet been elucidated [8], it has been suggested that a reduction in the oxidative capacity of the localized musculature could be a causative factor [21]. This could be due to a decrease in the slow (oxidative) motor units, diminished cross-sectional area [31] and reduced vasculature of the paravertebral muscles [21]. Diminished aerobic capacity has been found in LBP subjects [36, 49], which has been associated with a reduced level of physical activity [38, 47]. It is generally accepted that the accumulation of significant amounts of lactate during incremental exercise (i.e., the LT) is due to an imbalance between oxygen supply by the central circulation and the oxygen demand by the exercising musculature. Theoretically, if a reduction in aerobic capacity of the exercising musculature due to reduced physical activity [36, 49] is implicated in LBP,

then it is logical to hypothesize that: (1) the LT would occur at a lower exercise intensity in subjects with LBP when compared to healthy subjects, and (2) localized muscle oxygenation would also be lower in the subjects with LBP. Therefore, the purposes of this study were to: (1) compare the LT during incremental lifting and lowering in healthy and chronic LBP subjects, (2) examine the relationship of pertinent physiological variables at the LT and the psychophysically determined MAW in these two groups of subjects, and (3) examine the muscle blood volume (Mbv) and muscle oxygenation (Mox) responses during the MAW protocol in these two groups of subjects.

METHODS

Subjects

Written informed consent (see Appendix D) was obtained from all subjects. Specifically, 12 healthy (6 male and 6 female) subjects were recruited from the students and staff at the University of Alberta and 12 subjects (6 male and 6 female) with non-specific chronic LBP were recruited from the following sources: advertisements in the Edmonton Journal newspaper (N = 10), Millard Health Centre (N = 1) and Edmonton Garrison (N = 1). The criteria for subject inclusion were males and females with LBP for ≥3 months between the ages of 18 and 50 years. Potential subjects were excluded through self-reporting via telephone interview if they had pain below the knee, spinal stenosis, a herniated or ruptured disc, slipping of the disc bodies (Spondylolithesis), infection in the lumbosacral area, tumours, scoliosis, a rheumatologic disorder, osteoporosis or have had previous back surgery. Based on the above criteria two groups were formed for the study, healthy and LBP.

The visual analogue scale (VAS) has been used in previous chronic low back pain studies [14, 18] and was used to provide an indication of the level of low back pain [14, 18]. A VAS rating of 2 (mild pain) or less on the 11-point scale was used as a criterion for exclusion from the study (personal communication with Dr. Crites-Battié). Subjects with a known history of metabolic, cardiovascular, respiratory or neurological disorders were also excluded. As a result of the above exclusion criteria approximately 25 potential subjects were not approved to participate in the study. All study subjects completed a Physical Activity Readiness Questionnaire [6] (see Appendix E). Each of the two groups of subjects was comprised of six males and six females who were matched for age. This study was conducted in accordance with the University of Alberta's Health Research Ethics Board.

Session 1: Anthropometric Measurements and Repetitive Incremental Lifting and Lowering (RILL) Test

In session one, the subject's age (yrs), standing height (m), body mass (kg), and body mass index (BMI) were recorded according to standardized procedures developed by the Canadian Society for Exercise Physiology [6]. A calibrated Detecto-Medic beam scale (Detecto Scales Inc., Brooklyn, NY, USA) was used to record standing height and body mass. One complete round of skinfold thickness (SF) (Beta Technology Inc., Santa Cruz, CA, USA) was recorded (nearest 0.5 mm), followed by two rounds in the same order (see Appendix F). The average of the three values was used for analysis. Percent (%) body fat (BF) was predicted from charts developed by Durnin and Womersley [15] based on right side biceps, triceps, suprailiac, and subscapularis skinfold thicknesses.

The linear regression equation for the estimate of body density developed by these authors was: *density* = $c - m \times log\ skinfold$ [15]. The ½ SF-right side (Rt) and-left side (Lt) was used as an estimate of the tissue thickness that the near infrared light needed to penetrate prior to reaching the tissue of interest, the erector spinae muscle, to monitor the changes in muscle blood volume (Mbv) and oxygenation (Mox). The subject's anthropometric characteristics are summarized in Table 4.1.

Procedures for the repetitive incremental lifting and lowering (RILL) protocol have been previously described [22]. Briefly, after two minutes of seated rest, the subject bilaterally lifted and lowered a 1.5-kg basket (33 cm × 33 cm × 29 cm) from the floor to a tabletop (at a height of 76 cm). The lifting frequency was set at 10 lifts/min and was regulated via a metronome (Raney Day Productions, Mike's Metronome). The weight was increased by 2.25 kg every minute until voluntary fatigue or the attainment of one or more of the following criteria for VO_{2max}: (1) an asymptote or decrease in VO_2 with increasing workload, (2) age predicted maximum heart rate (HR) calculated as (220 – age, yrs), or (3) a respiratory exchange ratio (RER) >1.10. If the subject indicated that they were unable to tolerate another increase in the workload, the lifting frequency was increased so as to obtain a maximal effort. Typically, a RILL test is terminated as a result of localized fatigue of the erector spinae muscle, and therefore, subjects do not achieve their age predicted maximal HR (220 – age) and maximal cardiac output [22]. As a result, true VO_{2max} values are not attained during this exercise mode, and therefore, the term peak VO_2 (VO_{2peak}) is typically used in the literature.

Session 2: Psychophysical test (8-hour workday weight estimate procedures)

Snook and Ciriello [45] have previously described the development and methodology of the psychophysical evaluation in detail. The psychophysical instructions that were used in the current study were similar to those used by Ayoub and Dempsey [1]. Briefly, standardized instructions were read to each subject who was then given the opportunity to ask any questions (see Appendix F). The procedure allowed the subjects to freely adjust the amount of weight in the basket by either adding or removing weight so as to obtain the MAW that they could lift and lower repeatedly for an 8-hour workday, without excessive fatigue. The experimental set up used for the psychophysical determination was the same as that used for the RILL protocol.

The NIRS probes and metabolic equipment were placed on the subject as previously described [22]. Testing started with a 2-min resting baseline (seated), psychophysical (20-min) evaluation and a 4-min seated recovery. Subjects were seated, as it was easier to maintain consistency in posture within and between subjects. The subject started the test with an empty basket weighing 1.5 kg, which was placed on the floor in front of the waist height table. The lifting frequency was set at 10 lifts/min, matching that which was used during the RILL. At no time was external motivation given. The subjects used the full 20-min time period to subjectively estimate the MAW that they felt they were capable of managing for an 8-hour workday. The psychophysical cardiorespiratory and NIRS responses were compared to the peak values achieved during the RILL test and were expressed as a percentage.

Cardiorespiratory Measurements

A portable wireless metabolic analyzer (Vmax*ST* system, SensorMedics Corp., Yorba Linda, CA, USA) was used to measure the cardiorespiratory responses on a breath-by-breath basis during the RILL and psychophysical evaluation. The metabolic system (570 gm) was fitted securely about the subject's chest and shoulders using a breathable Velcro shoulder mount (see Appendix J). The unit contained a volume transducer, oxygen (O_2) and carbon dioxide (CO_2) analyzers, a temperature sensor and a pressure transducer. The O_2 and CO_2 analyzers were calibrated using commercially available precision gases of known concentrations (16% O_2, 4% CO_2, balance N_2; SensorMedics Corp., CA) prior to and at the completion of each test in order to ensure data accuracy. The flowmeter was calibrated using a 3-L syringe. Heart rate was recorded via a wireless chest monitor (Sport tester) that was interfaced with the portable metabolic unit. Metabolic data were collected breath-by-breath and averaged over 20-second (sec) intervals for subsequent analysis. For the RILL, the peak 20-sec value was considered the VO_{2peak}, whereas for the psychophysical evaluation, the average VO_2 for the last five minutes was used for analysis.

Detection of the Ventilatory Threshold

In this study, the LT was not detected using blood lactate analysis, but rather it was estimated indirectly from the respiratory gas exchange data obtained during the RILL test. Therefore, the term ventilatory threshold (VT) will be used hereafter in reference to this point. The criteria used to detect the VT were: a systematic increase in the ventilatory equivalent for oxygen (V_E/VO_2 ratio) without a concomitant increase in the

ventilatory equivalent for carbon dioxide (V_E/VCO_2 ratio). The VT was detected using software available with the metabolic system. The validity of these criteria against blood lactate measurements during cycle ergometry has been previously reported [50]. Once the VT was identified, the weight lifted and the cardiorespiratory responses corresponding to workloads at VT were determined from the test data for each subject.

Near Infrared Spectroscopy (NIRS) Procedures

Near infrared spectroscopy (NIRS) was used to non-invasively determine the Mbv and Mox of the erector spinae muscles during the RILL and psychophysical tests. NIRS is based on the differential absorption properties of hemoglobin (Hb) and myoglobin (Mb) in the near infrared range. At a wavelength of 760 nm, Hb/Mb occur in the deoxygenated form whereas at 850 nm, the chromophores occur in the oxygenated state (HbO_2/MbO_2). The difference in absorbency between these two wavelengths indicates the relative change in Mox, while the sum signal provides an index of Mbv. The validity of NIRS in evaluating changes in Mox has been previously documented during forearm exercise [30], while the reliability has been demonstrated during cuff-ischemia in the biceps [5] and isometric contraction of the erector spinae [23, 29]. However, reliability has not been demonstrated for erector spinae muscle during dynamic movement.

The NIRS probes were placed bilaterally at L3, which was located using manual palpation with the subject in either an erect or prone position. The probes were secured with a tensor bandage to minimize background light without occluding blood flow. The two probes were calibrated prior to each test using the NIRCOM software provided with the instrument (MicroRunman, NIM Inc., PA). The NIRS probe has one tungsten light

source located at a distance of 3.5 cm from the silicone diodes, which absorb reflected light at 760 nm and 850 nm. The penetration depth was approximately 60% of the optode distance, or 2.1 cm. A moderate penetration depth with the light intensity ranging between 100 and 150 (millivolt) mV was applied during calibration and testing.

From the raw NIRS data, the relative change in optical density (OD) at 760 nm and 850 nm was calculated with the modified Beer-Lambert law as follows [7, 30]:

$$OD = a \times c \times d \times B + G$$

where a was the absorption coefficient of the tissue, c was the chromophore concentration of the tissue, d was the distance between optodes on the measuring probe, B was the differential path length factor of the tissue, and G was the geometry of the tissue. The relative change in Mbv was calculated as the sum of the change in OD at the two wavelengths (760 nm + 850 nm), while the relative change in Mox was calculated as the difference in OD between the two wavelengths (850 nm - 760 nm). The raw NIRS data were averaged over 20-sec intervals during each phase of the test protocol. The NIRS values used for analysis were: the Mbv-and Mox-min, Mbv-and Mox-max, Mbv-and Mox-range and Mbv-and Mox-delta. The range was calculated as the change in Mbv or Mox from the lowest value during exercise to the highest value during recovery. Delta change was calculated as the change in Mbv or Mox (either positive or negative) from the last 20-sec of resting baseline to the lowest or greatest value during exercise. Changes in Mbv-range and-delta do not indicate direction of change, but specifically the amplitude of change. The half recovery time (½ rec time) for Mbv and Mox was defined as the time taken to reach 50% of the post-psychophysical maximal value. This variable was considered an index of intramuscular oxygen dynamics (i.e., resaturation of exercise-

desaturated hemoglobin and myoglobin) and reflects oxidative capacity of the localized musculature [7].

Statistical Analysis

Data collected in this study was analyzed in its raw form. Independent t-tests were used to compare differences between the mean values of the anthropometric characteristics in the healthy and LBP subjects. A two-way (group by intensity) analysis of variance (ANOVA) was used to examine the differences between mean values of pertinent responses between the VT and psychophysical measures in the healthy and LBP subjects. For NIRS variables, a three-way (group by intensity by side) analysis of covariance (ANCOVA) was used to examine the difference between the means of the two groups and the two sides (right and left) at the VT and psychophysical MAW. If no significant differences were found between the Rt and Lt sides the sides were then pooled (averaged) for further analysis. The average ½ skinfold thickness of the Rt and Lt sides was used as the covariate as this variable has been reported to influence Mbv and Mox measurement [48]. Significant *F*-ratios were subjected to post hoc analysis using the Scheffé procedure to identify differences between the groups and sides. Pearson correlations were used to examine the interrelationships at the peak, VT and psychophysical loads for pertinent cardiorespiratory and NIRS responses. The alpha level was considered significant at 0.05 ($p \leq 0.05$). Statistical analyses were performed using Statistica 6.1 (Statsoft, Inc. '2003 Edition, Tulsa, OK).

RESULTS

Physical Characteristics

The subjects were similar in physical make-up as suggested by their physical characteristics (see Table 4.1). No significant differences were noted between the healthy and LBP subjects for age, standing height, body mass, FM, LBM, or BMI. However, the healthy subjects had significantly lower % BF than the LBP subjects.

Cardiorespiratory Responses During Repetitive Incremental Lifting and Lowering

The cardiorespiratory responses at VT and VO_{2peak} during the RILL test are summarized in Table 4.2. No significant differences were found between groups for the peak cardiorespiratory responses during the RILL test. Although the peak mass lifted by the healthy subjects was 31% higher than that lifted by the LBP subjects, this difference was not statistically significant. The mean values of the peak HR and RER indicated that neither group met the criteria for VO_{2max} during the RILL test. At the VT, the following values were significantly lower in the LBP compared to the healthy group: VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$), VO_2 % of peak, HR ($beats \cdot min^{-1}$) and V_E ($L \cdot min^{-1}$). No significant differences were observed between the two groups for the RER, V_E/VO_2 ratio, V_E/VCO_2 ratio and O_2 pulse at the VT.

Cardiorespiratory Responses During the Psychophysical Test

The mean values of the cardiorespiratory responses at the VT and psychophysical evaluation in the healthy and LBP groups are compared in Table 4.2. In the healthy subjects, the MAW was significantly lower than the lifting mass at which the

VT occurred during the RILL. As a result, the mean values of the VO_2 ($L \cdot min^{-1}$, $ml \cdot kg^{-1} \cdot min^{-1}$, and % VO_{2peak}) were all significantly lower at the MAW compared to the VT. However, no significant differences were observed between the two intensities for the HR, V_E, RER and O_2 pulse. The V_E/VO_2 and V_E/VCO_2 ratios were significantly higher at the MAW compared to the VT. In the LBP group the MAW was also significantly lower than that at which the VT occurred. However, there was no significant difference between the two intensities for the mean VO_2 values ($L \cdot min^{-1}$, $ml \cdot kg^{-1} \cdot min^{-1}$, and % VO_{2peak}). The HR, V_E, RER, V_E/VO_2 ratio and V_E/VCO_2 ratio were significantly higher at the MAW compared to the VT, while the O_2 pulse was significantly lower at the MAW compared to the VT.

Comparisons of the physiological responses at the VT between the healthy and LBP subjects (see Table 4.2) indicated that the healthy subjects had significantly higher values for VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$) and % VO_{2peak}, HR and V_E. With respect to the psychophysical evaluation, no significant differences were observed for the MAW, VO_2 (L/min, ml/kg/min and $\%VO_{2peak}$). However, the healthy subjects demonstrated significantly lower HR and RER responses than the LBP subjects during the psychophysical test.

Muscle Blood Volume and Oxygenation Trends at the Psychophysical MAW

Figures 4.1 to 4.4 demonstrate the NIRS trends in a representative healthy and LBP subject during the psychophysical evaluation for Mbv and Mox on the Rt and Lt side erector spinae muscles. Both Mbv and Mox trends were comparable between Rt and Lt sides and subject groups, but there was variation in the trends themselves. In 83% of

the psychophysical evaluations, there was a rapid decrease in Mbv on both the Rt and Lt sides at the start of the test. After the initial decrease, some variability in the trends was evident. Specifically, Mbv systematically increased (~45%) but remained below baseline level, showed a further decrease (~33%), or reached a plateau (~22%) during the remainder of the test. At the termination of the psychophysical evaluation one of the following occurred on both the Rt and Lt sides: a rapid increase in Mbv to resting baseline (~79%), a gradual return to baseline over the 4-min recovery (12%), or some variability with no return to baseline during the 4-min recovery (9%).

The Mox demonstrated an opposite trend when compared to Mbv. At the beginning of the psychophysical evaluation, there was a rapid increase in both right and left side Mox in ~73% of the tests. Following the initial increase, differences within the trends were again evident. Specifically, Mox systematically increased (~52%) above baseline level, decreased (~21%) below baseline level or reached a plateau (~27%) above baseline level. At the termination of the psychophysical evaluation, there was a rapid decrease in Mox towards the baseline (~63%) and the remaining tests demonstrated a more gradual return to baseline values. The Mox recovery trends were variable, with some trends above, below and at baseline during the 4-min period.

Comparison of NIRS Variables

Examination of the ANCOVA results indicated that there was no significant three-way interaction for any of the NIRS variables. This implied that in both groups of subjects, there was no significant difference between the two sides at the two exercise intensities (VT and MAW). Examination of the two-way interactions (sides pooled, see

Table 4.3) indicated that the Mbv-range and Mbv-delta values were significantly higher at the MAW compared to the VT in both groups of subjects. However, no significant differences were observed between the two intensities for the Mox-range and Mox-delta in either group. The ½ rec times were not applicable to the VT measure, as the RILL test was not completed at that point. Comparisons between subject groups indicated no significant differences for any of the NIRS variables except the Mox-delta at VT, which was significantly lower in the LBP subjects.

Correlations for the Cardiorespiratory and NIRS Responses during RILL and Psychophysical MAW

The correlations between selected cardiorespiratory variables during the RILL and psychophysical tests are summarized in Table 4.4. Significant correlations were observed for the absolute and relative VO_2 values at peak RILL, VT and the psychophysical MAW in both groups of subjects, with the exception of the relative VO_2 during the psychophysical test, which was not significantly related to the VO_{2peak} or the VO_2 at the VT in the healthy subjects. In both groups of subjects, the strongest correlations were observed between the VT and VO_{2peak}. With respect to HR, significant correlations were observed only between the VT and HR_{peak} during RILL in both groups of subjects, but these correlations were weaker than those observed for the VO_2 values in the two groups. Additionally, significant correlations were noted between VO_2 at VT and Mox-range (0.65) and-delta (0.58) at VT in the healthy subjects only (see Figures 4.5 and 4.6).

For the psychophysical evaluation, significant correlations were found between VO_2 ($L \cdot min^{-1}$) and Mbv-range (0.69), and VO_2 ($L \cdot min^{-1}$) and Mbv-delta (0.79) in the LBP subjects (see Figures 4.7 and 4.8), but not in the healthy subjects.

DISCUSSION

The purposes of this study were to investigate: (1) VT during RILL in healthy and LBP subjects, (2) the relationship of pertinent physiological variables at VT and the psychophysical MAW in the healthy and LBP subjects, and (3) the Mbv and Mox responses during the MAW protocol in the subjects. The hypotheses were that: (1) VT would occur at a lower exercise intensity in subjects with LBP when compared to healthy subjects, and (2) localized Mox would also be lower in the subjects with LBP. The present findings indicated that the LBP subjects did not work below VT during the psychophysical evaluation, while the healthy subjects did. There were significant correlations between the psychophysical VO_2 and Mbv in the LBP subjects, but not the healthy subjects. The evidence suggests that the LBP subjects may have a lower fitness level as compared to the healthy subjects.

Ventilatory Threshold during the RILL in Healthy and LBP subjects

To the best of our knowledge, VT during incremental lifting and lowering in healthy or LBP subjects has not been reported. During the RILL test, VT was determined using ventilatory equivalents, which is considered a marker of LT [50]. The exercise intensity at which VT occurred (expressed as a percentage of [%] VO_{2peak}) was slightly greater than the range of values reported for other exercise modes such as cycling,

treadmill running and arm cranking [12]. The VO_2 at VT, expressed in ml · kg^{-1} · min^{-1} or as a % VO_{2peak}, was significantly lower in the LBP subjects compared to the healthy subjects. However, it should be noted that the lower VO_2 at VT in the LBP subjects was accompanied by significantly lower HR and V_E values when compared to the healthy subjects, and therefore, there were no significant differences between the two groups for the O_2 pulse and V_E/VO_2 ratio. These findings suggest that the overall cardiorespiratory stress at VT during the RILL was not significantly different between the healthy and LBP subjects.

The VO_2 during exercise is mathematically calculated as the product of blood flow and oxygen extraction (Fick equation). During the RILL test cardiac output and blood flow measurements were not undertaken. However, the results indicated that in both the healthy and LBP subjects, there were no significant correlations between the HR and VO_2 at the VT in either group, implying that oxygen transport was most likely not a determinant of the VO_2 at the VT. However, the healthy subjects demonstrated significant correlations between the VO_2 at VT and Mox-range and Mox-delta at VT indicating a relationship between VT and erector spinae anaerobic metabolism. Previous research has found significant relationships between LT and Mox [3] and VT and Mox [4] during cycling in healthy subjects, which is hypothesized to be associated with the Bohr effect and the influence of lactate accumulation within the working muscle [3, 4]. This relationship was absent in the LBP subjects, indicating a mismatch between the onset of anaerobic metabolism as indicated by VT and anaerobic metabolism within the erector spinae muscle. The lower VT and lack of relationship between VO_2 at VT and Mox in the LBP subjects was associated with a lower erector spinae Mox-delta. A reduced Mox-

delta may indicate a compromised oxidative potential of the erector spinae muscle in the LBP subjects. If the oxidative potential of a muscle is reduced, fatigue may occur earlier predisposing the back to injury as result of reduced postural stability [46].

Cardiorespiratory Responses During the Psychophysical Evaluation

When comparing the results of the present study with other psychophysical studies, the following differences must be borne in mind: level of physical training and occupation of subjects, height and frequency of lift, and the presence of a "lowering phase" in addition to a lifting phase. A summary of several psychophysical lifting studies is provided in Table 4.5. The MAW observed in the present study for both the groups was lower than previously reported values. However, despite the lower MAW, the absolute VO_2 was considerably higher than those previously reported, with the exception of Legg and Pateman [26]. The variation between studies could be due to the following: (1) the presence of a "lowering phase" and (2) differences in MMH experience. The present study used a lifting and lowering phase in the test protocol, whereas all the previous studies cited, except the study by Legg [25], incorporated only a lifting phase. The lowering phase in the current study may have altered the subject's perception of exertion, as lowering the MAW increases the total amount of work (i.e., negative work) involved with a given movement [13]. Additionally, the lack of MMH experience and physical training of the subjects in the present study has been demonstrated to influence the MAW selected by subjects [34]. Generally, previous research has focused on industrial workers or soldiers [26, 33, 34, 42], and in some cases provided physical training to the subjects prior to testing [33]. The healthy and LBP subjects in the present study included those with various

professional and vocational backgrounds (e.g., teachers, accountants, students, plumbers, soldiers and office managers). Many of these individuals lacked MMH experience. These two factors may have significantly influenced the MAW selected by the current subjects increasing the variability between the present study and those listed in Table 4.5.

Relationship between the VT and the Psychophysical Load

The current findings indicated a significant relationship between the absolute and relative VO_2 values at the VT and the psychophysical MAW. The VT, an indirect estimate of the LT [50], is an important measure of submaximal aerobic fitness. Research has demonstrated that at work intensities above the VT, the capacity for prolonged physical work is reduced as a result of the hydrogen ions associated with lactate accumulation [40]. The implications for these correlations underscore the importance of VT to prolonged MMH [40]. The significance of selecting a workload below VT was demonstrated during other forms of exercise [9, 10], and was inferred in lifting research [40]. If a MMH task required a metabolic output that exceeded the VT, the ability to perform the task for prolonged periods would be compromised [40]. Research using arterial blood lactate concentration and HR response specified work intensities between 25 and 40% of lifting VO_{2peak} were suitable for 8-hours of work, with 50% of VO_{2peak} being the upper limit [40]. The results of the present study suggest values between 70% and 60% of the VO_{2peak} during RILL as the upper limit in the healthy and LBP subjects, respectively. It is interesting to note that the healthy subjects sustained a metabolic rate that was below their VT, whereas the LBP subjects sustained an intensity above their VT during the last 5-min of the psychophysical test. The reason for this unclear, but may be due to the fact

that the LBP subjects were accustomed to MMH tasks whereas the healthy subjects were not.

A reduced fitness level as a consequence of a lower level of physical activity has been purported in LBP subjects [36, 38]. Ventilatory threshold can be used as a physiological indicator of fitness level as it is thought to be more closely associated with endurance performance (e.g., prolonged MMH) than VO_{2max} [16]. The present results indicate that the healthy subjects reached a greater percent of their peak values prior to attaining VT, suggesting a greater level of fitness [27]. Furthermore, the healthy subjects' psychophysical MAW elicited a VO_2 response that was lower than VT, while the LBP subjects psychophysical MAW evoked a VO_2 above VT. The LBP subjects psychophysical MAW was less than the load at VT, but their cardiorespiratory response by the end of the test (20-min) was greater than that at VT, which may be indicative of a reduced fitness level. Reduced endurance performance in the LBP subjects, and/or the inability to work near VT for an extended period, is likely explained by physiological changes (e.g., reduced blood volume) associated with reduced fitness [11, 28].

Inter-individual differences found in the present study highlight the importance of identifying each individual's VT in order to correctly determine their physical limit for MMH. Identification of VT may decrease the likelihood of fatigue and injury, which have been associated with reduced motor coordination and truncal stability during repetitive-type MMH tasks [46]. The results of the present study extend previous lifting research by examining the relationship between VT and prolonged MMH and the relationship to LBP.

NIRS Trends during the Psychophysical Evaluation

An extensive literature review failed to find previously reported data on Mbv and Mox (NIRS) trends of healthy and/or LBP subjects during a psychophysical evaluation. The Mbv and Mox trends in the present study indicated no significant differences in the mean values of the NIRS variables between the two groups, and therefore the findings will be discussed together. The Mbv response was consistent in that 83% of the subjects demonstrated an initial decrease, but the subsequent trend varied (45% increase, 33% decrease, 22% plateau). The initial decrease in Mbv was likely due to redistribution at the onset of exercise [7], but the variability that followed was likely a consequence of other factors. The results were similar in Mox as 73% showed an initial increase (27% initially decreased), which was followed by a decrease (52%), increase (21%) or a plateau (27%). The variability displayed in the psychophysical evaluation of the present study was in contrast to the consistent trends of the peak RILL test [22].

The basis for the variability in the psychophysical Mbv and Mox trends is not fully understood, but may be related to methodology. During the psychophysical instructions, subjects were directed to freely adjust the amount of weight in the basket in order to discern a comfortable weight that would not be associated with undue fatigue and/or discomfort [45]. Thus, each subject's ability to find their correct basket weight was based, in whole or in part, on their perceived level of comfort, the number of times the load was adjusted and the speed at which they determined the correct basket weight (i.e., MAW). The total number of adjustments needed to establish the final MAW would determine the level of physical stress on the erector spinae muscle. This would then influence the metabolic demand on the erector spinae muscle, which in turn would

influence regional Mbv and Mox trends [7]. In contrast, the RILL test protocol was predetermined and incremental (2.25 kg/min) to volitional fatigue, reducing the likelihood of variability in the erector spinae Mbv and Mox trends [22]. The lower variability in erector spinae Mbv and Mox trends during RILL was probably the result of both the incremental increase in metabolic stress and systematic increase in erector spinae intramuscular pressure (IMP). Previous research has demonstrated that a progressive increase in the strength of erector spinae isometric contraction is associated with a progressive increase in IMP, thus resulting in changes in blood flow pattern [20].

Maronitis et al. [32] documented the cardiorespiratory and the NIRS responses during a constant submaximal-lifting load (13.6 kg). The subjects performed three 20-min periods at a frequency of 12 lifts/min. They reported an increase in Mbv and Mox trends during the initial 20-min of lifting followed by an asymptotic pattern [32]. The chief difference in Mbv and Mox responses between the present study and that by Maronitis et al. [32] was the methodology. The studies differed on the start and finish positions of the lift, basket weight and lifting frequency. It was likely that the weight of the basket and the squat position for lifting and lowering influenced erector spinae IMP, as demonstrated in speed skating studies [17, 41]. The deeper squat position, lighter basket weight and ad labium adjustments employed in the present study would have influenced IMP and the duration of the erector spinae isometric contraction differently than the method used by Maronitis et al. [32]

Comparison of NIRS Variables at the VT and MAW

Table 4.3 summarizes the NIRS results for the psychophysical MAW and VT during the peak RILL test. Greater range and delta values were evident at the

psychophysical MAW as compared to VT during the peak RILL test. It is important to note when interpreting the results presented in Table 4.3 that the range and delta values provide an index of overall change, but do not indicate the direction of change. The Mbv changes during the psychophysical evaluation were substantially greater than at VT, and in the same direction (i.e., decreasing). As alluded to, the greater change in Mbv during the psychophysical evaluation was potentially due to differences in IMP, or more specifically, the duration of the build-up in IMP.

Increases in IMP have been demonstrated in body weight-only exercises (e.g., speed skating) in which a squatting position is used [41]. This is similar to the body position used in the peak RILL test and the psychophysical evaluation. Previous research has indicated that speed skating in a lower position, relative to a more upright position, was associated with a greater reduction in leg Mbv, but had similar VO_2 measures at the same skating speeds [41]. It is possible that the prolonged work of the psychophysical evaluation was associated with a gradual build-up of IMP in the erector spinae, which at some point exceeded the IMP at VT. The fact that the subjects lifted their upper body weight from a squat position to 76-cm cannot be understated, as implied in the speed skating studies where the body weight was the only weight being supported. Although the MAW that was lifted in the basket during the psychophysical evaluation was less than that lifted at VT during the peak RILL test (see Table 4.2), by the end of the test time (20-min), the subject's body weight during the psychophysical exam was lifted an additional ~14-min (or ~140 times). It is also possible that the greater change (i.e., decline) in Mbv during the psychophysical evaluation was related to an increase in core temperature. Elevated core temperature is associated with a redistribution of blood flow to the periphery for the

purpose of cooling [24], resulting in a smaller portion of cardiac output available for the exercising muscles. Thus, as the test progressed (min 15 to 20) an increase in core temperature likely occurred initiating a redirection of blood flow to the periphery to dissipate heat, possibly compromising circulation to the erector spinae muscle.

Conclusion

The VO_2 at the VT was significantly lower in the LBP subjects compared to their healthy counterparts. In both groups of subjects, the MAW was significantly lower than the lifting mass at which the VT occurred. During the psychophysical evaluation, the healthy subjects selected a work intensity that was below the VT, whereas the LBP subjects selected a work rate that was above the VT. In both groups of subjects, the absolute VO_2 at VT was significantly correlated the VO_{2peak} and the VO_2 at the MAW. There were no significant differences between the healthy and LBP subjects for the Mox and Mbv responses at the VT and during the psychophysical evaluation. Additionally, no significant correlations were found between the VO_2 during the MAW and Mox and Mbv in the healthy subjects. However, significant correlations were observed between the VO_2 and Mbv-range and Mbv-delta in the LBP subjects, suggesting that localized blood volume may be significantly compromised in these subjects.

Table 4.1. Physical characteristics of healthy and LBP subject groups. Values are mean (±SD).

	Groups	
	Healthy (N=12) 6 Male 6 Female	**LBP** (N=12) 6 male 6 female
Variable		
Age (yrs)	39.25(6.73)	37.66(2.27)
Height (m)	1.72(0.09)	1.74(0.09)
Body mass (kg)	81.76(15.32)	80.02(14.53)
Skinfold Left (mm)	4.37(1.47)	5.91(2.65)
Skinfold Right (mm)	4.31(1.49)	6.00(2.54)
Body fat (%)	22.23(4.27)[a]	27.83(5.85)[a]
FM (kg)	18.38(5.53)	22.20(5.27)
LBM (kg)	63.40(11.20)	57.81(11.90)
BMI	27.21(3.08)	26.28(3.50)

[a] indicates a significant difference between healthy and LBP subjects

Table 4.2. Comparison of cardiorespiratory responses at the peak mass, ventilatory threshold and psychophysical MAW in healthy and low back pain subjects, and the percent differences between ventilatory threshold and the psychophysical MAW. Values are mean (±SD).

	Groups							
	Healthy (N=12) (6 Male; 6 Female)				LBP (N=12) (6 Male; 6 Female)			
Variables	**RILL Peak**	**Ventilatory Threshold**	**Psych (MAW)**	**% Diff VT-MAW**	**RILL Peak**	**Ventilatory Threshold**	**Psych (MAW)**	**% Diff VT-MAW**
Mass (kg)	27.3(9.2)	11.6(6.3)	7.0(1.7)	65.38[a]	21.3(6.4)	8.0(1.5)	6.1(3.2)	31.80[a]
VO_2 ($L \cdot min^{-1}$)	2.63(0.47)	1.90(0.47)	1.58(0.35)	20.25[a]	2.50(0.49)	1.68(0.39)	1.76(0.34)	4.76
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	33.96(5.97)	24.29(5.36)[b]	19.83(2.46)	22.54[a]	31.41(6.50)	19.35(3.04)	21.5(3.28)	11.11
VO_2, % of Peak	100	71.17(7.18)[b]	60.5(10.70)	17.68[a]	100	62.4(6.12)	69.26(11.63)	11.01
HR ($beats \cdot min^{-1}$)	168(17.28)	136(20.65)[b]	129(24.58)[c]	5.43	168(14.68)	118(8.40)	149(13.27)	26.27[a]
V_E ($L \cdot min^{-1}$)	79.71(17.25)	42.93(12.05)[b]	42.7(12.20)	0.47	81.65(28.40)	33.63(7.61)	49.99(12.41)	48.64[a]
RER	1.05(0.08)	0.82(0.07)	0.85(0.03)[c]	3.66	1.08(0.07)	0.78(0.06)	0.89(0.06)	14.10[a]
V_E/VO_2 ratio	35.34(3.91)	23.55(1.69)	28.18(3.33)	19.66[a]	34.81(6.23)	22.17(2.00)	29.19(3.06)	31.66[a]
V_E/VCO_2 ratio	33.24(3.04)	28.82(2.53)	32.85(3.43)	13.98[a]	31.16(3.82)	28.65(2.44)	32.53(3.15)	13.54[a]
O_2 pulse ($ml \cdot beat^{-1}$)	16.41(3.96)	14.12(3.65)	12.88(3.73)	9.63	15.17(2.47)	13.22(2.82)	11.81(2.37)	11.94[a]

[a] indicates a significant difference within group between VT and psychophysical values.

[b] indicates a significant difference between groups for VT values.

[c] indicates a significant difference between groups for psychophysical values.

Table 4.3. NIRS (optical density) variables with sides pooled during the peak RILL, ventilatory threshold, and psychophysical evaluation, and the percent differences between ventilatory threshold and the psychophysical MAW. Values are mean (±SD).

	Groups							
	Healthy (N=12) (6 Male; 6 Female)				LBP (N=12) (6 Male; 6 Female)			
Variable	**Peak**	**VT**	**Psych**	**% Diff**	**Peak**	**VT**	**Psych**	**% Diff**
½ SF (mm)	4.34(1.46)	4.34(1.46)	4.34(1.46)	n/a	5.95(2.59)	5.95(2.59)	5.95(2.59)	n/a
Mbv-range	0.286(0.092)	0.181(0.091)	0.323(0.104)	78.5[a]	0.266(0.096)	0.148(0.100)	0.316(0.138)	114.2[a]
Mbv-delta	0.217(0.062)	0.110(0.056)	0.243(0.081)	120.9[a]	0.193(0.062)	0.098(0.064)	0.231(0.096)	121.4[a]
Mox-range	0.130(0.117)	0.073(0.074)	0.170(0.136)	212.3	0.102(0.050)	0.040(0.026)	0.103(0.040)	272.5
Mox-delta	0.097(0.099)	0.045(0.032)[b]	0.095(0.071)	111.1	0.069(0.029)	0.021(0.023)	0.077(0.040)	285.7
½ rec Mbv	69.58(29.03)	NA	54.38(24.68)	NA	76.25(37.24)	NA	61.67(17.46)	NA
½ rec Mox	96.25(28.93)	NA	55.42(22.10)	NA	80.83(24.66)	NA	64.79(21.01)	NA

[a] indicates a significant difference within group between VT and psychophysical values.

[b] indicates a significant difference between groups for VT values.

Table 4.4. Correlations of selected variables during the RILL and psychophysical lifting protocols in healthy and low back pain subjects. Values are mean (±SD).

Variable	Groups					
	Healthy (N=12) (6 Male; 6 Female)			LBP (N=12) (6 Male; 6 Female)		
Absolute	**VO_{2peak}**	**VO_2 at VT**	**VO_2 at Psych**	**VO_{2peak}**	**VO_2 at VT**	**VO_2 at Psych**
VO_{2peak} ($L \cdot min^{-1}$)	1.00	0.91[a]	0.61[a]	1.00	0.92[a]	0.67[a]
VO_2 at VT		1.00	0.76[a]		1.00	0.89[a]
VO_2 at Psych			1.00			1.00
Relative						
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	1.00	0.90[a]	0.18	1.00	0.90[a]	0.68[a]
VO_2 at VT		1.00	0.40		1.00	0.79[a]
VO_2 at Psych			1.00			1.00
Heart Rate						
HR_{peak}	1.00	0.75[a]	-0.00	1.00	0.62[a]	0.20
HR at VT		1.00	0.01		1.00	0.21
HR at Psych			1.00			1.00

[a] indicates a significant Pearson correlation.

Table 4.5. Comparison of the physiological responses of various psychophysical MAW research.

	Studies					
Variables	**Current Study (2004)**	**Mital (1983)**	**Legg & Pateman (1984)**	**Legg (1981)**	**Mital (1984)**	**Samanta & Chatterjee (1981)**
Sex	Male/Female	Male/Female	Male	Male	Male/Female	Male
Subject number	24	10	11	10	Not listed	21
Health status	LBP/Healthy	Healthy	Healthy	Healthy	Healthy	Healthy
Occupation	Various	Industrial workers	Infantry soldiers	Soldiers	Industrial workers	Warehouse workers
Physical Training	None	No	Yes	Yes	No	No
Height of lift phase	76-cm	Average †	Waist	Waist	Knuckle	66-cm
Lowering phase	76-cm	No	No	Yes	No	No
Duration	20-min	25-min	Until exhaustion	20-min	8-hours	10-min
Frequency (lifts/min)	10	Ave. 1, 4, 8, 12	10	2.5	12	9
VO_2 ($L \cdot min^{-1}$)	1.67	0.89	1.79	Not listed	0.9	0.82
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	20.67	Not listed	13.9	Not listed	Not listed	15.74
VT	1.79	Not listed	Not listed	Not listed	Not listed	Not listed
HR	139	112.3	143	Not listed	117.4	106.1
RER	0.87	Not listed	0.91	Not listed	Not listed	Not listed
MAW (kg)	6.53	17.49	22.4	17.6	9.49	9.0

† = Floor to knuckle, knuckle to shoulder, shoulder to reach.

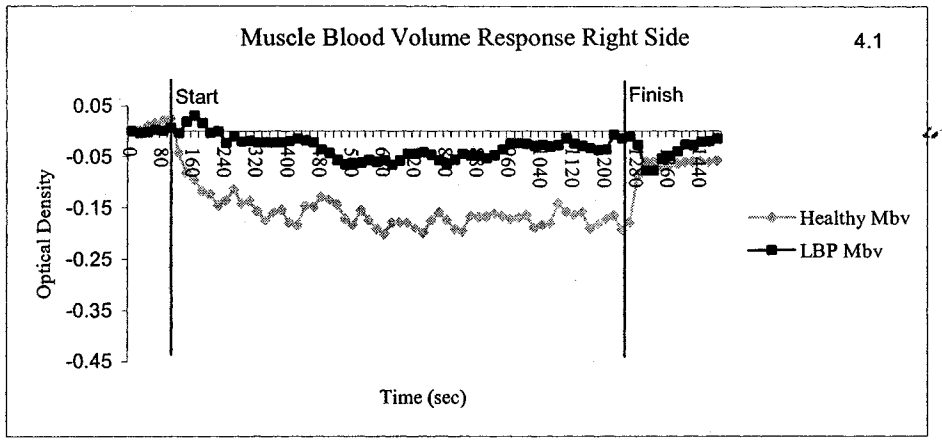


Figure 4.1. An example of muscle blood volume trends on the right side for a typical healthy and LBP subject during the psychophysical evaluation.

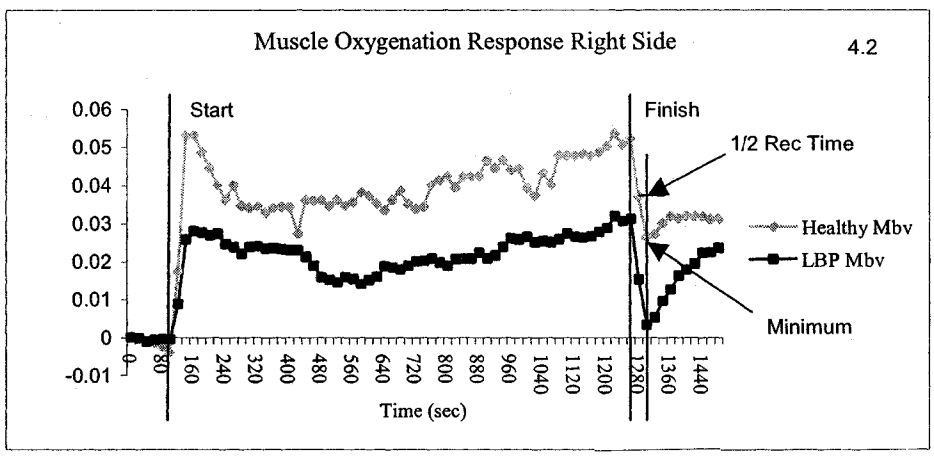


Figure 4.2. An example of muscle oxygenation trends on the right side for a typical healthy and LBP subject during the psychophysical evaluation. The LBP subject demonstrates the maximum and minimum values and ½ rec time markers.

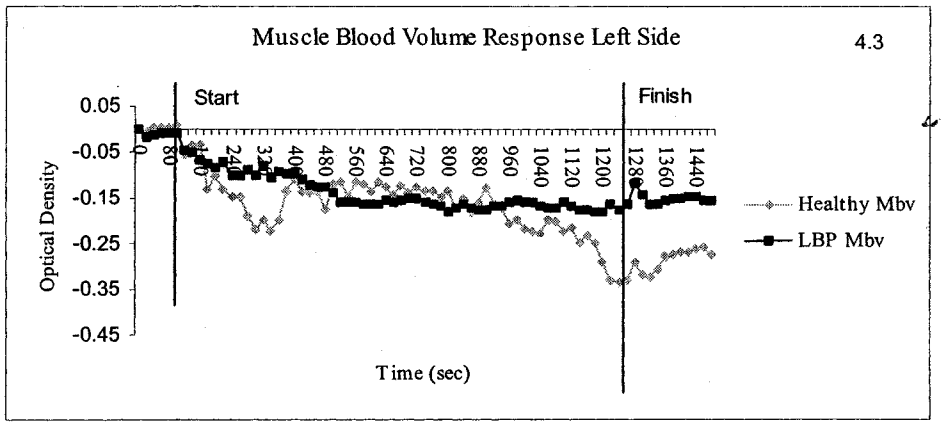


Figure 4.3. An example of muscle blood volume trends on the left side for a typical healthy and LBP subject during the psychophysical evaluation.

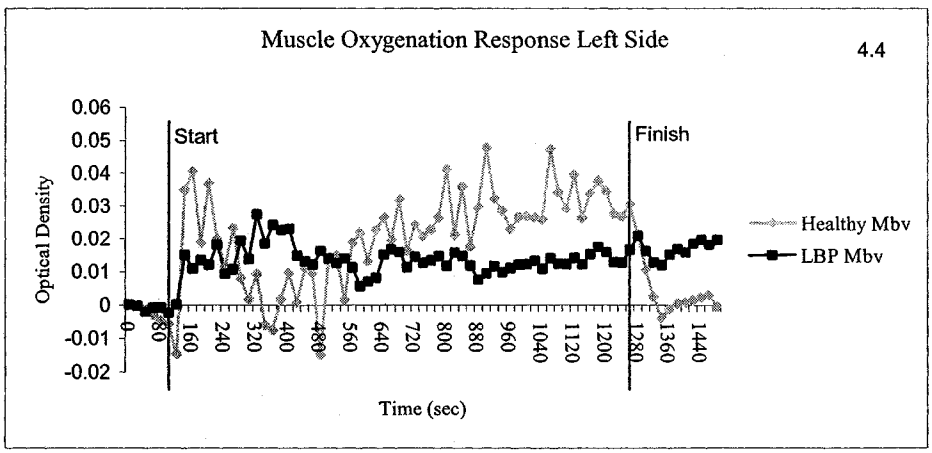


Figure 4.4. An example of muscle oxygenation trends on the left side for a typical healthy and LBP subject during the psychophysical evaluation.

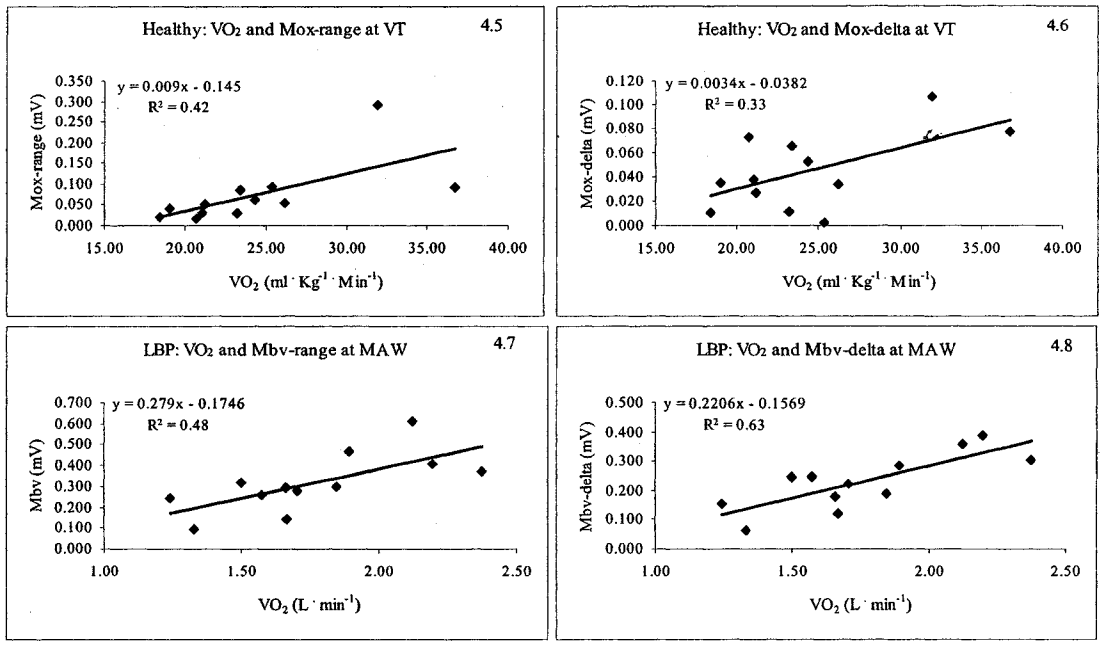


Figure 4.5 - 4.8. Scatter plots illustrating the relationships between VO_2 at VT and Mox-range at VT (healthy), VO_2 at VT and Mox-delta at VT (healthy), absolute VO_2 at the MAW and Mbv-range at the MAW (LBP), and absolute VO_2 at the MAW and Mbv-delta at the MAW (LBP) during the peak RILL test.

REFERENCES

1. Ayoub, M. M. and P. G. Dempsey. The psychophysical approach to manual materials handling task design. *Ergonomics*. 42:17-31., 1999.
2. Bassett, D. R., Jr. and E. T. Howley. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc*. 32:70-84, 2000.
3. Belardinelli, R., T. Barstow, J. Porsasz, and K. Wasserman. Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. *Eur. J. Appl. Physiol.* 70:487-492, 1995.
4. Bhambhani, Y., S. Buckley, and T. Susaki. Detection of ventilatory threshold using near infrared spectrometry in men and women. *Med. Sci. Sports Exer.* 29:402-409, 1997.
5. Bhambhani, Y., R. Maikala, J. Jeon, and G. J. Bell. Reliability of tissue deoxygenation during cuff ischemia in healthy males. *Can J Appl Physiol.* 3:467, 1998.
6. Canadian Society for Exercise Physiology. *The Canadian Physical Activity, Fitness & Lifestyle Appraisal Manual*. Ottawa: The Canadian Society for Exercise Physiology, 1996.
7. Chance, B., M. Dait, C. Zhang, T. Hamaoka, and F. Hagerman. Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. *Am J Physiol.* 262:C766-C775, 1992.
8. Cole, M. H. and P. N. Grimshaw. Low back pain and lifting: a review of epidemiology and aetiology. *Work*. 21:173-184, 2003.

9. Costill, D. L., H. Thomason, and E. Roberts. Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports*. 5:248-252, 1973.

10. Coyle, E. F. Physiological determinants of endurance exercise performance. *J Sci Med Sport*. 2:181-189, 1999.

11. Coyle, E. F., M. K. Hemmert, and A. R. Coggan. Effects of detraining on cardiovascular responses to exercise: role of blood volume. *J Appl Physiol*. 60:95-99, 1986.

12. Davis, J. A., P. Vodak, J. H. Wilmore, J. Vodak, and P. Kurtz. Anaerobic threshold and maximal aerobic power for three modes of exercise. *J Appl Physiol*. 41:544-550, 1976.

13. de Looze, M. P., H. M. Toussaint, D. A. Commissaris, M. P. Jans, and A. J. Sargeant. Relationships between energy expenditure and positive and negative mechanical work in repetitive lifting and lowering. *J Appl Physiol*. 77:420-426., 1994.

14. Dickens, C., M. Jayson, and F. Creed. Psychological correlates of pain behavior in patients with chronic low back pain. *Psychosomatics*. 43:42-48, 2002.

15. Durnin, J. V. G. A. and J. Womersley. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutri*. 32:77-97, 1974.

16. Farrell, P. A., J. H. Wilmore, E. F. Coyle, J. E. Billing, and D. L. Costill. Plasma lactate accumulation and distance running performance. 1979. *Med Sci Sports Exerc*. 25:1091-1097; discussion 1089-1090, 1993.

17. Foster, C., K.W. Rundell, A.C. Snyder, J. Stray-Gundersen, G. Kemkers, N. Thometz J. Broker, E. Knapp. Evidence for restricted muscle blood flow during speed skating. *Med. Sci. Sports Exer.* 31:1433-1440, 1999.

18. Fritzell, P., O. Hagg, P. Wessberg, and A. Nordwall. Chronic low back pain and fusion: a comparison of three surgical techniques: a prospective multicenter randomized study from the Swedish lumbar spine study group. *Spine.* 27:1131-1141, 2002.

19. Garg, A. and J. S. Moore. Epidemiology of low-back pain in industry. *Occup Med.* 7:593-608., 1992.

20. Jensen, B. R., K. Jorgensen, A. R. Hargens, P. K. Nielsen, and T. Nicolaisen. Physiological response to submaximal isometric contractions of the paravertebral muscles. *Spine.* 24:2332-2338, 1999.

21. Kauppila, L. I. Prevalence of stenotic changes in arteries supplying the lumbar spine. A postmortem angiographic study on 140 subjects. *Ann Rheum Dis.* 56:591-595, 1997.

22. Kell, R. T. and Y. Bhambhani. Cardiorespiratory & Hemodynamic Responses during Repetitive Incremental Lifting & Lowering in Healthy Males & Females. *Eur J Appl Physiol.* 90:1-9, 2003.

23. Kell, R. T., M. Farag, and Y. Bhambhani. Reliability of erector spinae oxygenation and blood volume responses using near-infrared spectroscopy in healthy males. *Eur J Appl Physiol.* 91:499-507, 2004.

24. Kenney, W. L. and J. M. Johnson. Control of skin blood flow during exercise. *Med Sci Sports Exerc.* 24:303-312, 1992.

25. Legg, A. J. Maximum acceptable repetitive lifting workloads for an 8-hour work-day using psychological and subjective rating methods. *Ergonomics*. 24:907-916, 1981.

26. Legg, A. J. and C. M. Pateman. A physiological study of the repetitive lifting capabilities of healthy young males. *Ergonomics*. 27:259-272, 1984.

27. Londeree, B. R. Effect of training on lactate/ventilatory thresholds: a meta-analysis. *Med Sci Sports Exerc*. 29:837-843, 1997.

28. Madsen, K., P. K. Pedersen, M. S. Djurhuus, and N. A. Klitgaard. Effects of detraining on endurance capacity and metabolic changes during prolonged exhaustive exercise. *J Appl Physiol*. 75:1444-1451, 1993.

29. Maikala, R. and Y. Bhambhani. Low-back muscle oxygenation trends during simple postural variations-intersession reliability using near infra-red spectroscopy. In *IEA2000/HFES Congress*, pp. 5-9 to 9-12, 2000.

30. Mancini, D., L. Bolinger, L. Li, K. Kendrick, B. Chance, and J. Wilson. Validation of near-infrared spectroscopy in humans. *J Appl Physiol*. 77:2740-2745, 1994.

31. Mannion, A. F., L. Kaser, E. Weber, A. Rhyner, J. Dvorak, and M. Muntener. Influence of age and duration of symptoms on fibre type distribution and size of the back muscles in chronic low back pain patients. *Eur Spine J*. 9:273-281, 2000.

32. Maronitis, A. B., K. M. Kovacs, R. E. Splittstoesser, and W. S. Marras. The effectiveness of whole body localized measures of fatigue. In *HFES*: Proceedings of the IEA, pp. 5-91-95-94, 2000.

33. Mital, A. Comprehensive maximum acceptable weight of lift database for regular 8-hour work shifts. *Ergonomics*. 27:1127-1138, 1984.

34. Mital, A. The psychophysical approach in manual lifting--a verification study. *Hum Factors*. 25:485-491., 1983.

35. National Institute for Occupational Safety and Health. *Work Practices Guide for Manual Lifting*. Washington: U.S. Government Printing Office. DHHS Pub. No. 81-122, 1981.

36. Nielens, H. and L. Plaghki. Cardiorespiratory fitness, physical activity level, and chronic pain: are men more affected than women? *Clin J Pain*. 17:129-137, 2001.

37. Nindl, B. C., M. A. Sharp, R. P. Mello, V. J. Rice, M. M. Murphy, and J. F. Patton. Gender comparison of peak oxygen uptake: repetitive box lifting versus treadmill running. *Eur J Appl Physiol Occup Physiol*. 77:112-117, 1998.

38. Payne, N., N. Gledhill, P. T. Katzmarzyk, and V. Jamnik. Health-related fitness, physical activity and history of back pain. *Can J Appl Physiol*. 24:236-249, 2000.

39. Petrofsky, J. S. and A. R. Lind. Comparison of metabolic and ventilatory responses of men to various lifting tasks and bicycle ergometry. *J Appl Physiol*. 45:60-63, 1978.

40. Petrofsky, J. S. and A. R. Lind. Metabolic, cardiovascular, and respiratory factors in the development of fatigue in lifting tasks. *J Appl Physiol*. 45:64-68., 1978.

41. Rundell, K., S. Nioka, and B. Chance. Hemoglobin/myoglobin desaturation during speed skating. *Med. Sci. Sports Exer*. 29:248-258, 1997.

42. Samanta, A. and B. B. Chatterjee. A physiological study of manual lifting of loads in Indians. *Ergonomics*. 24:557-564., 1981.

43. Sharp, M. A., E. Harman, J. A. Vogol, J. J. Knapik, and S. J. Legg. Maximal aerobic capacity for repetitive lifting: comparison with three standard exercise tests and modes. *Eur J Appl Physiol Occup Physiol.* 57:753-760, 1988.

44. Snook, S. H. Future directions of psychophysical studies. *Scand J Work Environ Health.* 25:13-18., 1999.

45. Snook, S. H. and V. M. Ciriello. The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics.* 34:1197-1213, 1991.

46. Sparto, P. J., M. Parnianpour, T. E. Reinsel, and S. Simon. The effect of fatigue on multijoint kinematics and load sharing during a repetitive lifting test. *Spine.* 22:2647-2654., 1997.

47. Spenkelink, C. D., M. M. Hutten, H. J. Hermens, and B. O. Greitemann. Assessment of activities of daily living with an ambulatory monitoring system: a comparative study in patients with chronic low back pain and nonsymptomatic controls. *Clin Rehabil.* 16:16-26, 2002.

48. van Beekvelt, M. C., M. S. Borghuis, B. G. van Engelen, R. A. Wevers, and W. N. Colier. Adipose tissue thickness affects in vivo quantitative near-IR spectroscopy in human skeletal muscle. *Clin Sci.* 101:21-28., 2001.

49. van der Velde, G. and D. Mierau. The effect of exercise on percentile rank aerobic capacity, pain, and self-rated disability in patients with chronic low-back pain: a retrospective chart review. *Arch Phys Med Rehabil.* 81:1457-1463, 2000.

50. von Duvillard, S. P., L. M. LeMura, D. W. Bacharach, and P. Di Vico. Determination of lactate threshold by respiratory gas exchange measures and

blood lactate levels during incremental load work. *J Manipulative Physiol Ther.* 16:312-318, 1993.

CHAPTER FIVE

GENERAL DISCUSSION

INTRODUCTION

Many occupations require the use of either static (isometric) and/or dynamic muscle contractions. Depending on the occupation one type of muscle contraction may be more prevalent. For example, in occupations such as dentistry, sales and crane operation, sustained static contractions of the lumbar region have been shown to be more dominant [1, 23, 25]. Sustained static postures have been associated with musculoskeletal disorders, and a sequence of events beginning with muscle ischemia and fatigue, and resulting in pain and injury is suspected [23, 27]. Research has suggested that in a static position a large percentage (~50%) of muscle mass is required to maintain the posture, and the level of static contraction needed for stabilization may be more physically taxing than dynamic contractions [23].

In contrast, occupations such as plant work and construction have been associated with low back pain (LBP) due to lifting of loads [7, 31]. Low back pain may also occur as a result of repetitive dynamic contractions, such as during lifting and lowering [2]. Dynamic contractions of the erector spinae muscle may lead to strains and sprains of the soft tissue due to cyclic loading and unloading of the erector spinae muscle and changes in spinal compression [6, 22].

Research has demonstrated that the aerobic capacity of the erector spinae muscles in individuals with LBP was reduced as a result of alterations in erector spinae vasculature [10] and oxidative capacity [16]. Fast fatigable motor units have been shown to be more prevalent in LBP subjects as compared to healthy controls [17]. Where the differences in vasculature and musculature between healthy and LBP subjects lead to low back pain or resulted from low back pain has not been determined. These observations

suggest that peripheral oxygen extraction would likely be lower in LBP subjects, thus reducing the oxidative ability and the endurance of the erector spinae muscles in this subject group.

However, a reduced fitness level, as it relates to diminished cardiorespiratory fitness, has also been associated with LBP [20, 28]. Individuals with LBP have been shown to possess a lower level of cardiorespiratory fitness [20] and a reduced physical activity [20]. In order to examine the association between a reduced fitness level and LBP, three tests were used in these studies: the Biering-Sorensen Muscular Endurance (BSME) test, the repetitive incremental lifting and lowering (RILL) test, and the psychophysical maximal acceptable weight test on both healthy and LBP subjects. The LBP subjects were divided into two groups, LBP-active (A) and LBP-sedentary (S), in an attempt to determine if there were any group differences, aside from the presence of LBP, which may be due to a lower fitness level. Cardiorespiratory and erector spinae muscle blood volume (Mbv) and muscle oxygenation (Mox) responses during work were measured as indicators of oxygen delivery and muscle uptake responses, respectively. The following sections will discuss the individual studies presented in this thesis followed by a short summary.

Biering-Sorensen Muscular Endurance (BSME) Test

The BSME (Chapter 2) simulated a moderate intensity static contraction of the erector spinae, with no difference between healthy, LBP, LBP-A and LBP-S subjects noted in endurance time. Most research suggests low back static muscular endurance time differs between healthy and LBP subjects [11, 15, 19, 21], with the healthy subject showing a longer static endurance time. However, other research has found no

significant difference in endurance time between healthy and LBP subjects [19]. One interpretation of these findings is that the BSME test to volitional fatigue may not be sufficiently sensitive to consistently differentiate between healthy and LBP subjects. This theory was supported by the current findings.

An alternative method to evaluate fatigue may be through the monitoring of Mbv and Mox changes via near infrared spectroscopy. During the BSME test, differences between healthy, LBP and LBP-S subjects in the change in amplitude of the Mbv and Mox variables were noted. The range and delta change values are of particular interest as they provide an index of the overall blood supply and oxygen extraction during the period of muscle contraction. The healthy subjects demonstrated a greater change in Mbv and Mox when compared to the LBP and LBP-S subjects when the two sides were compared. Also, a longer ½ recovery (rec) time by the LBP and LBP-S subjects suggests that blood supply to the erector spinae muscle upon relaxation was significantly less than that of the healthy subjects. The reduced Mbv, Mox and longer ½ rec time values suggest that healthy subjects had a greater ability to meet the oxygen demand of the exercising muscle when compared to LBP and LBP-S subjects [3, 18]. The Mbv and Mox results indicate that the LBP subjects demonstrate a reduced muscle blood volume and oxygen extraction capabilities during moderate intensity static contractions of the erector spinae muscle as compared to the healthy subjects.

Significant correlations were revealed for the LBP and LBP-A subjects between the BSME time and Mox-range and Mox-delta, which suggests a relationship between erector spinae muscle endurance and changes in erector spinae Mbv and Mox in the LBP subjects. The lack of a significant relationship between these same variables in the

healthy and LBP-S subjects may have been related to other factors that influence BSME time [8, 9], while the significant relationship in the LBP subjects may be a result of an overall reduced fitness level as noted by a reduced blood flow and oxygen supply during the moderate intensity contractions used during the BSME. However, the results do suggest an unpredictable nature of both groups' BSME time.

Repetitive Incremental Lifting and Lowering (RILL) Test

The cardiorespiratory responses of the healthy and LBP subjects to incremental dynamic (Chapter 3) contractions were significantly different. During the incremental dynamic contractions of the RILL, significantly greater peak oxygen consumption (VO_{2peak}) and breathing frequency (Bf) were found in the healthy subjects when compared to the LBP subjects. As well, the healthy subjects demonstrated significantly greater VO_{2peak}, Bf and ventilation (V_E) than the LBP-S subjects. The LBP-A subjects showed significantly greater values for VO_{2peak} and V_E in comparison to the LBP-S subjects. At present there appears to be no other published research reporting peak cardiorespiratory response of LBP subjects during incremental lifting and lowering. However, VO_{2peak} of LBP subjects was shown to be ~23.0 ml $\cdot$ kg^{-1} $\cdot$ min^{-1} during other modes of exercise (treadmill and step tests) [28-30], but is less than the mean peak oxygen consumption found in the LBP subjects of the present study. This was most likely the result of differences in methodology, variation in the method of pain measurement between the studies [30], and/or subject selection. In subject selection, the duration of pain was typically similar ≥3 months, but the mechanism of pain often varied from radicular pain [30] to musculoskeletal [21] in nature.

A stepwise regression analysis indicated that peak values of O_2 pulse and heart rate (HR) were significant predictors of absolute VO_{2peak} in the healthy subjects. Collectively, these two variables explained 98% of the common variance. In the LBP subject's V_E, O_2 pulse and HR best predicted VO_{2peak}, explaining 98% of the common variance. Similarly, relative VO_{2peak} in the healthy subjects was explained by HR_{peak} and peak O_2 pulse, explaining 75% of the common variance. However, for relative VO_{2peak} in the LBP subjects Mox-delta became a significant predictor explaining 15% of the common variance. Thus, in the LBP subjects HR_{peak}, Mox-delta and peak O_2 pulse explained a total of 74% of the common variance. These findings suggest that intramuscular factors that influence the capacity of the erector spinae muscles to extract oxygen play a role in determining the relative VO_{2peak} in LBP subjects.

The healthy subjects showed greater ability to supply and extract oxygen than did the LBP and LBP-S subjects, which suggested a greater oxidative potential in the erector spinae muscle of the healthy subjects [3]. The ½ rec time was longer in the LBP as compared to the healthy subjects. The ½ rec time represents factors that control adenosine triphosphate re-synthesis [3], which are the supply of oxygen via the blood and/or the oxidative capacity of the muscle. Thus, a longer ½ rec time may reflect a reduced ability in one or both of these factors [3, 18]. In contrast, Kovacs et al. [13] employed rapid forward flexion and extension from a standing posture with varying degrees of twisting in both healthy and muscular LBP subjects. The results indicted that the LBP subjects showed significantly greater changes in oxygenation than did the healthy group, which is in contrast to the present study's findings. However, the methodological differences between the studies make comparison difficult. The finding that the LBP

subjects in the present study demonstrated a slower erector spinae ½ rec time was similar to research on scoliosis subjects, which indicated a slower ½ rec time as well [14, 18]. Overall, the present study's Mbv and Mox results indicate that the LBP subjects demonstrate reduced muscle blood supply and/or oxygen extraction capabilities during moderate intensity static and incremental dynamic contractions of the erector spinae muscle as compared to the healthy subjects. However, with near infrared spectroscopy we cannot be certain which factor contributes to the differences between the healthy and LBP subjects, but simply suggest that a difference exists between the two groups [13].

Psychophysical Evaluation

There was no significant difference in the maximum acceptable weight between the healthy and LBP subjects during the psychophysical evaluation. However, the LBP subjects demonstrated significantly greater HR and respiratory exchange ratio (RER) responses at their maximal acceptable weight of lift as compared to the healthy subjects. The cardiorespiratory response (HR, V_E, RER) of the LBP subjects at their maximal acceptable weight of lift was significantly elevated over their own response at ventilatory threshold (VT), while the healthy subjects showed a significantly lower cardiorespiratory response (% of VO_{2peak}) at their maximal acceptable weight of lift as compared to their VT. Additionally, both groups showed a significant relationship between VO_2 at VT and VO_2 at the maximal acceptable weight of lift, underscoring the importance of VT during prolonged submaximal dynamic contractions seen in manual materials handling.

The Mbv changes during the psychophysical evaluation showed a significantly greater decrease in amplitude than at VT. The greater change in Mbv during the

psychophysical evaluation was possibly a result of a greater build-up of intramuscular pressure (IMP) over the duration of the test. Speed skating research indicated that a lower position, relative to a more upright position, was associated with a greater reduction in leg Mbv with similar VO_2 measures [24]. Perhaps the prolonged work of the psychophysical evaluation was associated with a gradual build-up of IMP in the erector spinae, which at some point exceeded the IMP at VT. The load lifted during the psychophysical evaluation was less than that lifted at VT, but by the conclusion of the psychophysical test the subject's body weight was lifted approximately 140 times more than during the RILL test. Additionally, Mbv during the psychophysical evaluation may have been influenced by an increase in core temperature. Elevated core temperature is associated with a redistribution of blood flow to the periphery for the purpose of cooling [12], reducing the proportion of cardiac output available for the working muscles (e.g., erector spinae).

Summary

The results of these studies suggest that the LBP subjects, as compared to healthy, demonstrate a reduced cardiorespiratory function during incremental dynamic contractions (Chapter 3) and submaximal dynamic contractions (Chapter 4), as well as reduced Mbv and Mox responses during submaximal static contraction (Chapter 2) and incremental dynamic contractions of the erector spinae (Chapter 3). Reduced cardiorespiratory function in LBP subjects has been previously reported [20, 28], but reduced Mbv and Mox responses have not. The rationale for the stated differences may be related to a reduced fitness level [20, 28]. Research suggests that individuals with LBP may

demonstrate a reduced physical activity level [21, 26], which may compromise central circulations ability to transport oxygen as well as reduce peripheral oxygen extraction [4]. The lower level of physical activity has been suggested to be associated with fear and avoidance of pain during activity [5].

REFERENCES

1. Burdorf, A. and H. Zondervan. An epidemiological study of low-back pain in crane operators. *Ergonomics*. 33:981-987, 1990.
2. Chaffin, D. B. and K. S. Park. A longitudinal study of low-back pain as associated with occupational weight lifting factors. *Am Ind Hyg Assoc J.* 34:513-525, 1973.
3. Chance, B., M. Dait, C. Zhang, T. Hamaoka, and F. Hagerman. Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. *Am J Physiol.* 262:C766-C775, 1992.
4. Coyle, E. F., M. K. Hemmert, and A. R. Coggan. Effects of detraining on cardiovascular responses to exercise: role of blood volume. *J Appl Physiol.* 60:95-99, 1986.
5. Crombez, G., L. Vervaet, R. Lysens, F. Baeyens, and P. Eelen. Avoidance and confrontation of painful, back-straining movements in chronic back pain patients. *Behav Modif.* 22:62-77, 1998.
6. Garg, A. and J. S. Moore. Epidemiology of low-back pain in industry. *Occup Med.* 7:593-608., 1992.
7. Goldsheyder, D., M. Nordin, S. S. Weiner, and R. Hiebert. Musculoskeletal symptom survey among mason tenders. *Am J Ind Med.* 42:384-396, 2002.
8. Jørgensen, K. and T. Nicolaisen. Two methods for determining trunk extensor endurance: A comparative study. *Eur J Appl Physiol.* 55:639-644, 1986.
9. Kankaanpaa, M., D. Laaksonen, S. Taimela, S. M. Kokko, O. Airaksinen, and O. Hanninen. Age, sex, and body mass index as determinants of back and hip

extensor fatigue in the isometric Sorensen back endurance test. *Arch Phys Med Rehabil.* 79:1069-1075., 1998.

10. Kauppila, L. I. Prevalence of stenotic changes in arteries supplying the lumbar spine. A postmortem angiographic study on 140 subjects. *Ann Rheum Dis.* 56:591-595, 1997.

11. Keller, A., J. Hellesnes, and I. B. a. a. Jens. Reliability of the Isokinetic Trunk Extensor Test, Biering-Sorensen Test, and Astrand Bicycle Test: Assessment of Intraclass Correlation Coefficient and Critical Difference in Patients With Chronic Low Back Pain and Healthy Individuals. *Spine.* 26:771-777., 2001.

12. Kenney, W. L. and J. M. Johnson. Control of skin blood flow during exercise. *Med Sci Sports Exerc.* 24:303-312, 1992.

13. Kovacs, K. M., W. S. Marras, A. S. Litsk, P. Gupta, and S. A. Ferguson. Localized oxygen use of healthy and low back pain individuals during controlled trunk movements. *J Spinal Disord.* 14:150-158, 2001.

14. Kunimune, Y., Y. Harada, Y. Kabuto, K. Takeuchi, M. Senda, and H. Inoue. Recovery from exercise-induced desaturation in the paraspinal muscles in idiopathic scoliosis. *Spine.* 24:2019-2024, 1999.

15. Latimer, J., C. G. Maher, K. Refshauge, and I. Colaco. The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. *Spine.* 24:2085-2089; discussion 2090., 1999.

16. Mannion, A. F., L. Kaser, E. Weber, A. Rhyner, J. Dvorak, and M. Muntener. Influence of age and duration of symptoms on fibre type distribution and size of the back muscles in chronic low back pain patients. *Eur Spine J.* 9:273-281, 2000.

17. Mannion, A. F., B. R. Weber, J. Dvorak, D. Grob, and M. Muntener. Fibre type characteristics of the lumbar paraspinal muscles in normal healthy subjects and in patients with low back pain. *J Orthop Res.* 15:881-887, 1997.

18. Miyake, M., Y. Harada, M. Senda, K. Oda, and H. Inoue. Oxygen dynamics at paraspinal muscles during exertion using near-infrared spectroscopy in patients with degenerative lumbar scoliosis. *J Orthop Sci.* 81:187-191, 2003.

19. Nicolaisen, T. and K. Jorgensen. Trunk strength, back muscle endurance and low-back trouble. *Scand J Rehab Med.* 17:121-127, 1985.

20. Nielens, H. and L. Plaghki. Cardiorespiratory fitness, physical activity level, and chronic pain: are men more affected than women? *Clin J Pain.* 17:129-137, 2001.

21. Payne, N., N. Gledhill, P. T. Katzmarzyk, and V. Jamnik. Health-related fitness, physical activity and history of back pain. *Can J Appl Physiol.* 24:236-249, 2000.

22. Pope, M. H. Risk indicators in low back pain. *Ann Med.* 21:387-392., 1989.

23. Ratzon, N. Z., T. Yaros, A. Mizlik, and T. Kanner. Musculoskeletal symptoms among dentists in relation to work posture. *Work.* 15:153-158, 2000.

24. Rundell, K., S. Nioka, and B. Chance. Hemoglobin/myoglobin desaturation during speed skating. *Med Sci Sports Exer.* 29:248-258, 1997.

25. Skov, T., V. Borg, and E. Orhede. Psychosocial and physical risk factors for musculoskeletal disorders of the neck, shoulders, and lower back in salespeople. *Occup Environ Med.* 53:351-356, 1996.

26. Spenkelink, C. D., M. M. Hutten, H. J. Hermens, and B. O. Greitemann. Assessment of activities of daily living with an ambulatory monitoring system: a comparative study in patients with chronic low back pain and nonsymptomatic controls. *Clin Rehabil.* 16:16-26, 2002.

27. Valachi, B. and K. Valachi. Mechanisms leading to musculoskeletal disorders in dentistry. *J Am Dent Assoc.* 134:1344-1350, 2003.

28. van der Velde, G. and D. Mierau. The effect of exercise on percentile rank aerobic capacity, pain, and self-rated disability in patients with chronic low-back pain: a retrospective chart review. *Arch Phys Med Rehabil.* 81:1457-1463, 2000.

29. Wittink, H., T. Hoskins Michel, A. Wagner, A. Sukiennik, and W. Rogers. Deconditioning in patients with chronic low back pain: fact or fiction? *Spine.* 25:2221-2228, 2000.

30. Wittink, H., T. H. Michel, A. Sukiennik, C. Gascon, and W. Rogers. The association of pain with aerobic fitness in patients with chronic low back pain. *Arch Phys Med Rehabil.* 83:1467-1471, 2002.

31. Xiao, G. B., P. G. Dempsey, L. Lei, Z. H. Ma, and Y. X. Liang. Study on musculoskeletal disorders in a machinery manufacturing plant. *J Occup Environ Med.* 46:341-346, 2004.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The results of the studies contained in this thesis indicate that the following conclusions may be warranted:

1) Subjects with chronic (>3 months) non-specific low back pain (LBP) were able to complete three tests requiring submaximal static (BSME), incremental dynamic (RILL), and submaximal dynamic (Psychophysical MAW) contractions from start to finish without terminating due to pain.

2) No significant difference in low back static endurance (i.e., BSME) was found between the healthy and LBP subjects, which suggested that low back static endurance may not be able to adequately differentiate between healthy and LBP subjects.

3) The LBP subjects demonstrated significantly smaller changes in amplitude on some of the muscle blood volume and muscle oxygenation variables during the BSME test suggesting a reduced ability of the erector spinae muscles to supply and extract oxygen during submaximal static contraction.

4) The RILL test was able to differentiate between healthy, LBP, LBP-A and LBP-S subjects on numerous cardiorespiratory, and Mbv and Mox variables. The LBP subjects demonstrated a significantly reduced cardiorespiratory response to the RILL test, indicating diminished ability to supply and utilize oxygen during exercise.

5) During the RILL test the LBP subjects showed a reduced capability to supply and extract oxygen in the erector spinae muscle as indicated by a significantly reduced change in amplitude in some of the Mbv and Mox variables as compared to the healthy subjects.

6) There was a significant relationship between ventilatory threshold and the maximal acceptable weight of lift in both healthy and LBP subjects, demonstrating the importance of ventilatory threshold to prolonged submaximal tasks. This finding suggests that ventilatory threshold is equally as important as VO_{2peak}, or may be more important, when examining the required fitness level of individuals employed in manual materials handling.

7) The lack of a significant relationship between VO_2 at ventilatory threshold and change in muscle oxygenation in the LBP subjects was associated with a lower erector spinae muscle oxygenation and earlier fatigue of the erector spinae muscle, which may place the LBP subjects at an increased risk of further LBP problems.

8) There was evidence of a reduced fitness level in the LBP subjects. The reduced cardiorespiratory function, peripheral muscle blood volume and muscle oxygenation responses of the LBP subjects as compared to the healthy subjects supported this hypothesis. Whether the reduced fitness level occurred prior to the LBP, or the LBP occurred prior to the reduction in fitness level cannot be

determined from this study, but a reduced fitness level appears to be present both centrally and peripherally.

The significance of this thesis is the innovation of a dynamic test (RILL) that was able to differentiate between healthy and LBP subjects on cardiorespiratory, and Mbv and Mox measures. This is in contrast to the BSME test, which is typically used to differentiate between healthy and LBP subjects based on endurance time, which was not supported in the present study. Additionally, the present thesis verified that NIRS technology was beneficial in objectively differentiating between healthy and LBP subjects during both static and dynamic muscle contractions. This thesis confirmed what had been assumed, but not directly studied, that during prolonged work periods healthy subjects would self-select (psychophysical evaluation) a work intensity below anaerobic threshold (ventilatory threshold), while the LBP subjects self-selected a work intensity that was greater than ventilatory threshold. The rationale for the discrepancy between the groups was likely the fact that the LBP and LBP-S subjects had a reduced fitness level, which may have resulted from a lower level of physical activity.

RECOMMENDATIONS

1) In order to more clearly identify significant differences between groups a larger sample size would be desirable. A larger sample size would increase the power of the design, which would assist in determining if significant differences between healthy and LBP subjects are present. Moreover, a larger sample size would

enable the examination of potential sex differences within and between the healthy and LBP subjects which was not accomplished in this thesis.

2) The measurement of central circulation (cardiac output) would help achieve a better understanding of the effect of manual materials handling type activities on central circulation, as well as help determine if a lower fitness level was present in LBP subjects as compared to healthy subjects. In the current study, O_2 pulse and heart rate were used to provide an estimate of central circulation. However, the measurement of stroke volume via carbon dioxide re-breathing would provide a more direct measure of central circulation.

3) The determination of recreational activity level for the present study was based on one question asked in the subject data collection sheet (Appendix F). Based on the response to the question, the subject was placed in either the LBP-active or the LBP-sedentary subject group. However, the incorporation of an accelerometer, which measures the amount of movements over a period of time, would more objectively measure daily recreational physical activity level, in comparison to the subjective response of the subject in the questionnaire. Additionally, the use of an accelerometer would allow the measurement of the amount of physical activity involved in the subjects' work (occupation). However, if the subject's occupation involved more static type contractions, then the total daily time maintaining static contractions would need to be accounted for (e.g., paper & pencil record). This would permit the researcher to more objectively place the subjects into one of the

LBP groups (LBP-active or LBP-sedentary) based on recreational physical activity, occupational physical activity and/or total physical activity. A less expensive alternative to an accelerometer would be a daily physical activity analysis questionnaire, where by the subject would note all daily activities and the duration of the activity, much the same as a daily dietary analysis book. Overall these methods would improve the objectivity and accuracy of determining the subject's physical activity level, reducing the risk of placing a subject into an incorrect group.

4) The application of a questionnaire to measure fear and avoidance of physical activity (e.g., kinesiophobia questionnaire) in the LBP-active and-sedentary subjects. This would help determine if a difference exists between fear of physical activity and the level of physical activity between LBP-A and LBP-S subject groups. If fear and avoidance is present in the LBP subjects an intervention program could be implemented to reduce the fear and avoidance behaviour. For example, it would assist in determining if LBP-S subjects who are afraid of physical activity actually have a lower daily level of physical activity (e.g., measured by an accelerometer) and as a result a proportionally lower cardiorespiratory fitness level (e.g., peak VO_2).

5) Last, the implementation of an exercise program in the LBP-sedentary subject group. The inclusion of an exercise program would help understand if the behaviour of fear and avoidance of physical activity, if it is present, can be

changed. Additionally, the use of an exercise program in the LBP-sedentary subjects would allow the evaluation of changes in fitness level from pre-training to post-training scores. Additionally, it would allow the comparison of the post-training LBP-sedentary fitness level to those of the initial fitness levels of the LBP-active and healthy subjects. This would assist in determining if differences in fitness level between the LBP groups can be diminished via exercise training.

APPENDIX A: *Review of Literature*

REVIEW OF LITERATURE

The review of literature will be discussed in the following sections: (1) Factors Associated with Low Back Pain, (2) Near Infrared Spectroscopy, (3) BSME test, (4) RILL test, (5) psychophysical test, and (6) Canadian Physical Activity and Lifestyle Appraisal (CPAFLA) Manual and Modified Schober test.

Factors Associated With Low Back Pain

There are many suspected risk factors associated with LBP, psychosocial stress, work environment, neurologic, psychological, level of social security, cultural factors, physical loading, smoking, infection, and genetics have all been implicated [176]. This proposal is investigating non-specific low back pain (ns-LBP) from a physiological/physical stress perspective and thus will focus primarily on overexertion type factors associated with ns-LBP. Many different forms of physical stress and overexertion are associated with ns-LBP [140], such as the handling of manual materials (MMH) in a laborer type job [178]. Repetitive trauma and overexertion during MMH resulting in back muscle fatigue has been of interest to researchers for many years because of the relationship to ns-LBP [140, 149]. The diagnosis of patients with ns-LBP is very difficult [141]. However, when diagnosed with a low back injury which results in ns-LBP, the order of events that lead to the injury are also complicated.

Largely two types of studies have provided insight into ns-LBP, prospective/retrospective and cross-sectional. Prospective studies indicate that the best predictor of recurrent ns-LBP is a previous bout of low back pain or the recency of the

previous bout of low back pain [24, 25]. While variables such as age, epigastric pain, daily smoking, low isometric endurance of the back muscles, thoracic acceleration during a trunk velocity test, median frequency electromyography at L3, quadriceps strength and endurance, self-assessment of fitness level, having a confidante, and the number of medications taken have all been shown to be strong risk indicators for the first time occurrence of ns-LBP [24, 169]. Additionally, both prospective [22, 24] and cross-sectional [133] research has found sex (gender) to influence the factors associated with the first time occurrence of low back pain. Biering-Sørensen [22] found that the factors that best predicted the first time occurrence of ns-LBP for males were age, modified Schober test score and low back isometric endurance, while for females they were age, maximal volitional contraction strength during a back extension and low back isometric endurance. In attempts to differentiate between those with a history of ns-LBP and those with no history of ns-LBP Payne et al. [133] found through physical evaluation that males with no history of ns-LBP had significantly better scores on trunk flexion, partial curl-ups, back extensor endurance, physical activity participation, and waist girth, while females with no history of ns-LBP scored significantly better on trunk flexion, back extensor endurance, physical activity participation, and waist girth than subjects with a history of ns-LBP.

Studies have demonstrated that individuals with ns-LBP most often exhibit reduced isometric trunk extensor strength and/or endurance as compared to healthy (no LBP) controls [2, 67, 119, 130]. These results suggest that trunk muscle strength and endurance is strongly associated with back pain and injury. Latimer et al. [95] employing three subject groups (23 currently with ns-LBP; 20 who had had an episode of ns-LBP in the previous 3-months but are now pain free; and 20 who were asymptomatic for ns-LBP) indicated

that the BSME is able to discriminate between individuals with and without LBP based on endurance time. However, the BSME was unable to differentiate between the current ns-LBP subjects and those who had previously had a bout of ns-LBP [95]. McNeill [119] compared isometric trunk extensor strength (standing position) in men and women with and without ns-LBP, and found that ns-LBP individuals had reduced trunk extensor strength compared to healthy individuals. Isokinetic measures of lower back strength also demonstrate a reduction in strength in ns-LBP individuals [91, 96, 172]. In contrast, research also indicates that people with ns-LBP may exhibit similar absolute strength (maximal volitional contraction-MVC) to healthy individuals, but will most likely demonstrate reduced low back isometric muscular endurance [67, 75]. Additionally, isometric strength has shown no predictive value for the later development of ns-LBP [11, 21, 22, 130].

In order to better understand ns-LBP various research tools and techniques have been used aside from basic endurance time [27]. Muscle fiber analysis (metabolic characteristics, muscle cross-sectional area, fiber cross-sectional area) and electromyography (EMG) are common techniques that have been used for this purpose. These methods have been used in an attempt to distinguish between healthy and ns-LBP individuals in a more objective manner [63, 78, 109-111, 149]. Mannion et al. [109] studied the erector spinae muscle of males and females with ns-LBP and suggested that the duration of symptoms of ns-LBP was positively associated ($r = .40$; $P = 0.0018$) with an increased proportion of Type IIX (glycolytic profile) and reduced Type I fibers, indicating that ns-LBP sufferers may be distinguished by muscle fiber type. EMG has demonstrated similar muscle activity levels and initial median frequency (MFslope) during muscle loading in

both LBP and control, while spectral decreases in MF slope indicated that lumbar paraspinal muscle fatigability was similar in both groups [78]. The differences in fiber typing and EMG analyses may be due to a reduced fitness level or a genetic predisposition, however, these studies could not determine which would be the case. Additionally, research suggests that the erector spinae muscle of men were more fatigable than those of women, which may reflect variation in muscle fiber type between the sexes [105]. Greater low back muscle fatigability was connected with the existence of, and the risk of serious LBP. Thus, in theory the use of muscle fiber typing and EMG may be viable methods for examining LBP and possibly predicting the likelihood of LBP. Surface electrode EMG is non-invasive and may be a practical option in the identification of ns-LBP, but muscle biopsies of the low back are an invasive procedure that is better suited for understanding the characteristics of ns-LBP, not the identification of ns-LBP.

Additionally, other low back research in the mid 1990's suggested that chronic ns-LBP might be associated with the obliterated, stenotic, or occluded arteries to the lumbosacral region [80, 81, 84]. Kauppila's [82] post-mortem research indicated that stenotic change in the arteries of the low back are associated with a higher rate of chronic LBP. These arteries originate primarily from the abdominal aorta and supply blood to the ligaments, muscles, spinal cord, and dura of the back. If these arteries become stenotic due to a narrowed passage, occluded due to cardiovascular disease, or are missing then the structures (e.g., skeletal muscle) supplied by these arteries become hypoxic and enter an ischemic state resulting in atrophy of the tissue [82]. Occluded arteries generally develop a substantial network of smaller anastomoses, but the anastomers most often develop slowly and never fully balance for the missing vascular supply [115]. Thus,

suggesting that a lack of blood flow to the low back may be associated with the pain (ischemia and nocioceptive pain receptors) [80], atrophy of the surrounding structures (muscle) [41, 80] and earlier fatigue due to a lack of oxygen supply to the working muscles [183].

Near Infrared Spectroscopy (NIRS)

Principle of NIRS

A relatively new and non-invasive approach in the examination of ns-LBP may be the use of NIRS. Continuous wave NIRS is a non-invasive, optical technique that has been used to measure skeletal muscle blood volume and oxygenation (i.e., hemodynamic) trends in a variety of experimental conditions. The principle of NIRS is based on the differential absorption properties of chromophores, principally hemoglobin (Hb, in blood), myoglobin (Mb, in muscle) and cytochrome oxidase (cyt aa_3), which are in the near infrared range of the absorption spectrum (i.e., between 700 nm and 1000 nm wavelength) [35, 104]. The transmission of near infrared light through tissue has an average path length of 60% of the distance between the light and sensors (optodes). Oxygenated and deoxygenated forms of Hb (oxy-Hb and deoxy-Hb, respectively) and Mb (oxy-Mb and deoxy-Mb, respectively) can be differentiated at specific wavelengths [16]. The variability of the absorbance spectra of the heme or copper centers of chromophores can be seen and measured by Beer's Law [156]. At 760 nm, the chromophores occur in the deoxygenated form, while at 850 nm they occur in the oxygenated state. Therefore, as Hb becomes oxygenated the absorption of light at 760nm decreases while the absorption at 850nm increases. Consequently, by monitoring the difference in tissue absorbency

between these two wavelengths (850 nm – 760 nm), the relative change in oxygenation can be determined (MicroRunman, NIM Inc., PA, USA). The sum signal at these two wavelengths (850 nm + 760 nm) indicates the relative change in total Hb, which is an index of localized changes in tissue blood volume [35]. At present the ability to calculate cyt aa_3 is tentative because of the overlap in the near infrared spectra and the low intensity of the oxidized copper band in cyt aa_3 [52, 137].

The equation used to calculate the change in chromophore concentration is based on Modified Beer's law [44, 156] as follows: (equation 1)

$$OD = c \times a \times d \times B + G$$

Where:

OD = light absorption expressed as optical density,

c = concentration of chromophores *(μM)*,

a = absorption coefficient of chromophores for a specific wavelength,

d = physical distance (cm) between the light source and the optode sensor,

B = the difference in pathlength factor of light through tissue, and

G = a tissue correction factor accounting for optode position.

In human tissue research, the optical path length must be corrected in Beer's law to account for the dilemma of multiple scattering. Thus the distance traveled by the light is greater than the physical distance between the light and the sensor (d) by a factor of B, which is equivalent to the product of d and B [49]. The variable G is complex to measure as

it varies with the type of optode geometry (light sensor spacing) and tissue (brain, muscle) under analysis. As with any mathematical computation, once certain variables have been determined the final product can be known. Thus, once "a d B and G" have been determined the light absorbance can be attributed to the change in chromophore concentration ($c = \mu M$; Δc) [103].

Britton Chance and colleagues [34, 36] developed one type of NIRS unit that measures chromophore concentration in biological tissue. It is a continuous wave NIRS system, which employs Beer's Law. This unit (MicroRunman, NIM Inc., PA, USA) consists of:

1. superficial probes fitted with a light emitting tungsten lamp and two silicone diodes that absorb the light in the near infrared spectrum (760 nm and 850 nm),
2. a MRM-96 processing unit which is amplifies and displays the absorbance signal sending to be viewed on a monitor, and
3. NIRCOM software for calibration and processing of the absorbency signal (OD).

One limitation of continuous wave NIRS is that the absolute oxygen uptake cannot be quantified because the pathlength of the signal cannot be definitively determined. Photons travel in a random manner in biological tissue (e.g., human skeletal muscle), and because of this, the optical pathlength cannot be accurately calculated [61]. As a result, changes in optical density relative to a specific point during the test are used for analysis. As well, this technique is unable to differentiate between the degree of deoxygenation due to Hb and Mb because the absorption spectra of these two

chromophores overlap in the near infrared range [104]. However, Chance et al. [35] extrapolated from animal studies that ~25% of the NIRS signal is obtained from Mb, while ~75% is acquired from Hb. However, Wilson et al. [182] suggest that the fraction of the signal accounted for by Mb may even be lower.

Validity and Reliability of NIRS

The validity and reliability of NIRS estimation of oxygen saturation in muscle tissue has been well established [44, 61, 88, 102, 151, 182]. NIRS validity has been verified alongside femoral venous blood oxygen tension during exercise [104], as well as nuclear magnetic resonance imaging [174]. Mancini et al. [104] showed correlations between the 760-800 nm absorption and changes in venous saturation ranging from 0.82 to 0.97 ($P < 0.05$). However, NIRS is not without criticism. An article by MacDonald et al. [101] suggested that when NIRS (vastus lateralis) is compared to femoral venous O_2 saturation during cycling in normoxia, hypoxia, and hyperoxia the trends between the two are not similar. Another study indicated similar findings during isometric contractions of the forearm at 10% and 30% of maximal volitional contraction (MVC) under normoxia and hypoxia [65]. In both of these studies the authors found that the Mox measured by NIRS initially decreased and then systematically increased over the course of the exercise. However, the venous O_2 saturation demonstrated a continued decrease or a plateau at the minimum point until the completion of the exercise. An explanation for these differences in oxygenation may be the fact that femoral O_2 saturation is a composite of all blood exiting the quadriceps muscle group [144], while NIRS represents oxygen changes within the specific volume of muscle under investigation (vastus lateralis or forearm). The key

point taken from this is that care must be taken in the interpretation of NIRS and the comparison to other methods of tissue oxygen measurement.

NIRS reliability during sustained cuff ischemia of various muscles has also been demonstrated [19, 104, 182], as well as reliability in trends without cuff ischemia [102]. Maikala et al. [102] demonstrated good reliability (Pearson correlation coefficients range from 0.74 to 0.99) in Mox and Mbv in both the seated and standing position during maximal isometric contraction of the erector spinae muscles. The variation in absorbency by chromophores (e.g., Hb) between a fully reduced condition (cuff ischemia) and maximum oxidation accomplished by increasing O_2 delivery to the tissue or breathing room air is considered the Total Labile Signal (TLS) [103, 138].

Muscle Oxygenation and Blood Volume trends during Exercise

The directional changes monitored by NIRS indicate muscle oxygenation trends from one state to another, not known quantities of oxygen. Trends in muscle oxygenation and blood volume during a variety of exercise modes have been published [5, 14, 17, 18, 35, 54, 86, 88, 145]. An example of a typical Mox trend from the vastus lateralis during incremental cycle ergometer exercise to maximum (VO_{2max}) is, a sudden increase in oxygenation (due to a redistribution of blood in the leg) at the onset of exercise, followed by a systematic deoxygenation throughout the remainder of exercise reaching a nadir at the termination of exercise, with substantial reoxygenation during recovery [35]. The Mbv response during the same exercise demonstrates a sudden decrease followed by a gradual increase above the baseline until recovery, with a gradual decrease in Mbv during recovery [35]. The Mox trend found in the vastus lateralis during incremental cycle ergometry exercise [35] are

similar to those of the erector spinae seen during RILL, as will be discussed later [86]. Belardinelli [14] demonstrated a similar Mox trend during cycling (vastus lateralis) without the initial increase, followed by a progressive decrease in Mox until volitional fatigue, during recovery a marked increase in Mox was again visible (due to hyperemia and decreased VO_2). Additionally, Belardinelli [14] suggested that there was a rapid decrease (breakpoint) in Mox at the lactate threshold, with a rapid deoxygenation as the work rate exceeded the lactate threshold approaching peak oxygen consumption. Similarly, Grassi et al. [57] found that at the same point Mox decreased sharply blood lactate increased significantly ($\leq$ 2 mM), corresponding to ~62.5 $\pm$ 7% of VO_{2peak}. A high positive correlation ($r^2 = 0.95$; $P = 0.0045$) was found between the blood lactate inflection points of muscle deoxygenation [57].

Muscle Oxygenation and Blood Volume trends and the Low Back

With respect to the application NIRS to the lower back, limited published work is available [5, 74, 86, 88, 93, 102, 112, 118, 184]. Maronitis et al. [112] measured erector spinae Mox and Mbv during repetitive dynamic box (30 lb) lifting at 12 lifts/min for 60-min and demonstrated a steady increase in Mox and Mbv over the initial 20-min followed by a plateau over the remainder of the time (40-min). McGill et al. [118] examined the relevance of Mox and Mbv measurement by NIRS during isometric contraction of the erector spinae muscles. The test was carried out in the sitting position, with the pelvis supported, facing a dynamometer, which was attached to a load cell. Results indicated that all levels of 30s isometric contraction (2, 5, 10, 20, and 30% of MVC) resulted in a decrease in muscle oxygenation due to reduced Mbv and increased cellular uptake of oxygen. The

authors commented that NIRS was the only non-invasive tool available to indicate total available oxygen during prolonged low-level isometric contraction [118]. Jensen [74] used brief 30-sec contractions of the paravertebral muscles at 5, 20, 40, 60, and 80% of MVC and a 3-min trunk extension at 20% of MVC to investigate Mox and Mbv in healthy males. The results indicated a significant decrease in oxygenation at 20% MVC which corresponded to an intramuscular pressure of 30-to 40-mmHg.

Yoshitake et al. [184] investigated lower back muscle fatigue during a 60-sec low back submaximal muscular contraction (not to volitional fatigue) using EMG, mechanomyography (MMG), and NIRS. Eight male subjects performed isometric back extensions at an angle of 0° and 15° with reference to the horizontal plane, for a duration of 60-sec. Surface EMG, MMG and NIRS signals were recorded simultaneously from the center of the erector spinae (L3). The results showed that Mox and Mbv decreased dramatically at the onset of the contraction reaching a nadir within the first 20-to 30-secs, followed by a plateau throughout the remainder of the contraction, followed by a large and rapid reoxygenation (Mox) and hyperemia (Mbv) at the cessation of contraction. A study by Maikala et al. [102] using maximal isometric contractions of the erector spinae muscle for 2-min demonstrated similar trends to the Yoshitake et al. [184] study, marked by rapidly decreasing Mox and Mbv at the onset of contraction, followed by a plateau over the middle of the test, with a rapid reoxygenation and hyperemia during recovery.

To date only a couple of studies have compared NIRS results in healthy and LBP subjects (scoliosis, structural and muscular) [93, 94, 124]. Kunimune et al. [94] showed that following 30-sec of forward bending, the ½ recovery time on the convex side in the LBP patients with scoliosis was slower than that of the healthy subjects ($P<.05$). Additionally,

the ½ recovery time of the LBP patients was faster than on the concave side in comparison to the convex side, and that the ½ recovery time of Mox was also greater on the convex side in LBP subjects as compared to healthy adults. The ½ recovery time was considered by the investigators to indicate back muscle stress [94]. Additionally, 3 males and 3 females were measured 6 times each and the coefficient of variation for the NIRS data was below 7%.

Kovacs et al. [93] investigated the right side erector spinae muscle (exact site not stated) concurrently with a lumbar motion monitor on 3 subject groups (1) healthy (no LBP), (2) structural LBP (e.g., Spondylolisthesis), and (3) muscular LBP with no known cause of pain (similar to the proposed study's population). The subjects were asked to flex and extend the trunk as rapidly as possible while maintaining a twisted position (0°, 15°, and 30°) in a positive (right) and negative (left) direction. The results indicated significant ($P<.05$) differences in Mox between the healthy and LBP muscular subject groups (at 0° and15°), and a significant difference in Mbv between the healthy and LBP structural groups (0°) [93]. It was suggested that the differences found in Mox between the healthy and LBP muscular subjects were related to muscle cell damage corresponding to mitochondrial damage and decreased oxidative enzyme activity. Further to this, the authors suggest that NIRS is an effective measure for differentiating between healthy subjects and those with muscular LBP [93].

The Biering-Sorensen Muscular Endurance Test (BSME)

The most commonly used tool for clinical assessment of erector spinae muscle endurance is the BSME [3, 21-23, 76, 95, 116, 170]. Biering-Sorensen muscular endurance time is

considered an indicator of low back isometric muscle fatigue, and studies suggest that the longer the endurance time the greater the fatigue resistance [46, 77]. The position for the BSME test can vary, but a common position is lying prone on a couch (i.e., plinth) positioned so that the end of the couch is level with the iliac crest. The support for the upper torso is then removed and the subject maintains a horizontally neutral position for as long as possible. The advantage of the BSME as a clinical tool for diagnosis of low back muscular endurance is that it is easily administered, inexpensive, a substantial amount of data has been compiled, and it has been demonstrated to be reliable in test-retest situations (healthy and LBP subjects) [95, 126].

Research suggests that poor back muscle fitness, as illustrated by the BSME, is associated with back pain and dysfunction regardless of gender [67, 76, 133]. Investigations indicate that good back isometric endurance can prevent the incidence of first-time ns-LBP [21, 22, 24, 130], as well as discriminate between individuals with and without low back injuries [67, 73, 76, 95, 130]. Holmstrom et al. [67] studied back muscle isometric strength and endurance and found that people with a long history of ns-LBP had significantly ($p<0.01$) less back muscle isometric endurance as compared to those asymptomatic for LBP. However, no significant difference in back muscle maximum isometric strength was noted between the populations. The evaluation of back health or susceptibility to low back pain was accomplished by examining the endurance times of the subjects. A shorter endurance time (increased rate of fatigue) is associated with low back pain, or a predisposition to low back pain [21, 22, 24, 67, 95].

Endurance time of the erector spinae muscles during an isometric contraction can be limited by local tissue factors. Several mechanisms have been proposed to explain

reduced isometric endurance time: (1) local tissue blood flow (and thus oxygen), (2) muscle fiber composition, and (3) motor unit activation patterns. Isometric endurance, which is a measure of resistance to fatigue, may be associated with reduced local blood circulation resulting from an elevated intramuscular pressure [10]. Consequently, the limited oxygen supply slows down the rate of energy production thereby reducing linkage of the muscle contractile elements and inducing fatigue. The muscle fiber type composition within the erector spinae muscles is predominantly slow twitch (ST) [75]. There may be some sex differences with respect to mean fiber size, as males demonstrated similar mean ST and fast twitch (FT) size, while females show significantly larger ST fibers compared to FT [107]. This has been demonstrated functionally as women tend to have longer endurance times on the BSME [133]. Additionally, it is thought that some variation in fiber type composition (%ST to %FT) and size may exist amongst individuals, thus affecting endurance time [108]. The relative area of the muscle occupied by ST fibers (determined by relative size and distribution of fiber types) showed a highly significant relationship with resistance to fatigue as determined by median frequency (MF) EMG during a Sorensen test [108]. The significance of having a greater proportion of ST or larger cross sectional area of ST fibers can be seen in the functional characteristics of the fibers. Slow twitch muscle fibers are in general more oxidative and fatigue resistant than FT muscle fibers due to a higher: mitochondrial density, capillary density, myoglobin content, triglyceride stores, and oxidative enzyme activity [139]. These characteristics are associated with greater fatigue resistance and allow muscles that are predominately ST, like the erector spinae, to be more suited for postural (endurance) type work [75].

Motor unit activation pattern of the erector spinae muscles has been proposed to influence muscle endurance time to fatigue, indicating that differences in neurogenic factors may play a role during submaximal isometric contraction of the erector spinae muscles in fatigue [47]. Several studies have used EMG during the BSME to examine patterns of fatigue in the lumbar musculature. The trend for mean power frequency EMG is to decline over time as the subject approaches exhaustion [125, 184]. The use of EMG to demonstrate fatigue has shown reliability in test-retest situations, over both short-and long-term time intervals [20, 173]. Electromyographic analysis is considered a more objective tool than endurance time, as EMG analysis is not influenced by motivational factors. Research suggests that the greater rate of decline in both mean-and median-MF and asymmetrical fatigability of the erector spinae muscles could differentiate between subjects with and without ns-LBP [117, 148]. In contrast, other studies indicate that as objective as EMG is purported to be, it may be unreliable in identifying individuals that fall outside the "normal range". For example, distinguishing between subjects with and without ns-LBP [114, 117].

Localized blood flow is known to play a prominent role in the onset of fatigue [158, 184]. There are two primary reasons why fatigue is accelerated during a sustained isometric muscle contraction or intermittent muscle contraction. First, during a muscular contraction the metabolic rate of the working muscle is accelerated, thereby necessitating a need for increased blood flow. Second, reduced blood flow limits the vascular systems ability to remove fatigue-associated by-products of metabolism (e.g., H^+), supply oxygen to the active musculature to regenerate needed products (NAD^+, ATP, CP), as well as maintain muscle pH [10, 26, 180]. The higher the intensity of the muscular contraction, the

greater the increase in metabolic rate, and the greater the need for oxygen to support oxidative metabolism (aerobic ATP production) [53, 157, 158, 180]. During a sustained muscle contraction muscle blood flow is reduced due to an increase in intramuscular pressure. A reduction in blood flow and oxygen availability will increase the rate of anaerobic metabolism resulting in an increase in the accumulation of metabolic by-products (e.g., H^+) associated with fatigue. The result of these two circumstances is further exacerbated when the duration of the muscle contraction increases and/or the intensity of the contraction increases, both resulting in the recruitment of more and different forms of muscle fiber (ST → FT a → FT b) [53]. The recruitment of FT muscle fiber allows power to be maintained and the test duration to be temporarily extended, or power to increase as the intensity (workload) of the exercise is increased to the point of volitional fatigue.

Until recently it has been problematic to study muscle blood flow patterns, with one of the earlier means being the ultrasound Doppler method [75]. Some research suggests that arm muscle blood flow increases during isometric work up to 50% of MVC [70]. In contrast, Barnes [10] suggested that forearm muscle blood flow was maximal at 20-25% of MVC, with occlusion at 63.5 % of MVC. A study of paraspinal muscle blood flow by Bondra-Petersen et al. [26] suggested that blood flow was maximal at 20% of MVC and reached zero at 40% of MVC. An investigation of the erector spinae muscle using NIRS indicated that blood volume (NIRS measures trends in blood volume, not flow) might have been decreased at contraction levels as low as 2% of MVC [118]. However, it is generally agreed that muscle blood flow is fully occluded at 60-70% of MVC [70, 75].

The inconsistency in the literature with respect to intramuscular pressure, percent of MVC, and blood flow or blood volume measures maybe due to (1) experimental error,

(2) the muscle group examined, or (3) the method of blood flow measurement (plethysmography, ultrasound Doppler, tracer techniques (e.g., ^{133}Xe) or NIRS). Additionally, the ultrasound Doppler method is difficult to employ in the paraspinal muscle region due to the small diameter of the lumbar vertebra arteries (<2 mm) [75]. The BSME is considered to elicit a muscular contraction of 45 to 55% of MVC [106, 159], which should substantially reduce or occlude erector spinae muscle blood flow.

The application of NIRS has a distinct advantage over earlier methods of blood volume measurement, as NIRS is noninvasive and will not only monitor trends in skeletal Mbv, but also local Mox. NIRS provides a continuous and sensitive measurement of Mbv changes and Mox availability in microcirculation [33, 104]. Research suggests that as Mbv decreases, Mox will decrease in proportion as oxygen is transported via the blood as oxyhemoglobin. However, the decrease in oxygenation is not simply the result of reduced blood flow, but also increased cellular uptake of oxygen by the local working musculature [118].

The use of NIRS to monitor local Mox and Mbv trends in individuals with ns-LBP may be a plausible alternative, and/or complementary analysis to the measurement of the endurance time and EMG activity. The Mox and Mbv trends of the erector spinae muscles of healthy subjects during a maximal isometric contraction in the seated and standing positions have shown good reliability (Pearson's correlations ranging from 0.74 to 0.99) [102].

A recently submitted manuscript from our lab has found an increase in Mbv initially, followed by a levelling off until fatigue. However, Mox demonstrates an initial increase, followed by steady decline for the remainder of the test duration [87] (Figure 1, 2).

The rationale for the opposite trends in Mbv, as compared to Yoshitake et al. [184], are not entirely understood, but are likely in part due methodological differences (e.g., probe placement and endurance time) between the two studies. The Yoshitake et al. [184] study utilized the BSME from a procedural standpoint (body position on the couch), but did not have the subjects complete the BSME test to volitional fatigue. This may have affected the NIRS trends in their study, making them difficult to compare to ours. However, we feel that Mbv may increase due to blood from the deeper muscle of the back moving to the surface, intramuscular pressure trapping blood in that region, and/or a highly developed collateral supply bringing blood into the region (ST muscle fiber, high vascularization). The Mox on the right side is similar (decreasing trend) to that of Yoshitake et al. [184], however, they did not measure Mbv or Mox on the left side, so we cannot compare our left side trends.

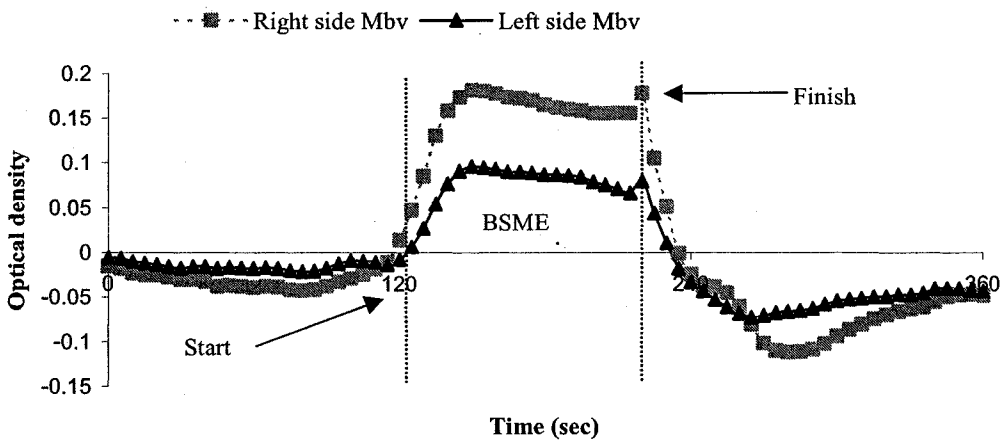


Figure 1. Muscle blood volume response on the right and left side erector spinae muscle during a BSME to volitional fatigue.

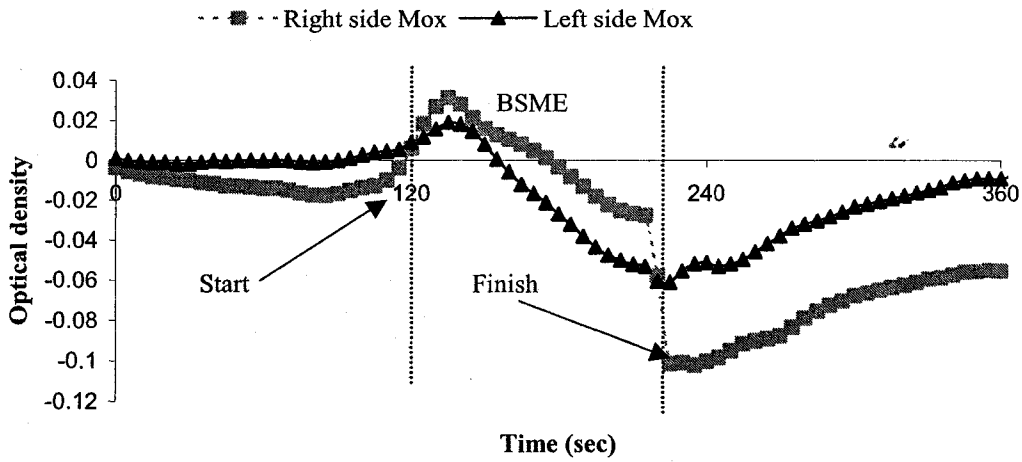


Figure 2. Muscle oxygen response on the right and left side erector spinae muscle during a BSME to volitional fatigue.

It is hypothesized that the initial increase in Mox at the onset of exercise is associated with a redistribution of blood to the active motor units and is supported by the localized increase in Mbv observed in this study. The gradual decrease in Mox below the resting baseline value is most likely related to the delivery and uptake of oxygen by the working muscle. A study of back Mox and Mbv in 19 healthy males using the BSME and two BSME trials within one-week indicated an ICC for endurance time of 0.98 [88], which is consistent with previous reports on healthy males [89, 95], and moderate test-retest reliability for four NIRS variables (Table 1) [88]. Intraclass correlation coefficient $\geq$0.80 are considered to be acceptable [129]. The current findings by Kell et al. [88] suggest that Mbv responses during the BSME are more reliable than the Mox responses. To the best of our knowledge, ICC values for Mox and Mbv of the erector spinae muscle during the BSME have not previously been published.

Table 1. The *F* ratios and intraclass correlations (ICCs) between trials and sides for oxygenation and blood volume measured by near infrared spectroscopy (N= 19).

Variables	*F* ratio * Trial by Side	*F* ratio * Trials	*F* ratio * Sides	ICC **
Mox delta	0.90	0.446	0.148	0.69
Mox range	1.70	0.297	0.097	0.75
Mbv delta	1.21	0.898	0.197	0.84
Mbv range	0.66	0.947	0.155	0.82

* *F* ratios were non-significant at .05 level following a Bonferroni correction factor.

** Average ICC calculated between trials on the right and left sides.

One issue in the study of ns-LBP as with many types of research (e.g., heart failure) is one of reduced fitness. A potential confounding factor in the assessment of ns-LBP is whether reduced low back muscular strength and endurance is a product of LBP. With only two groups, one with ns-LBP and the other healthy, the difference between the groups in test results may be due to reduced fitness. A lower fitness level can result from reduced activity levels following the development of ns-LBP. In an attempt to clarify the effect of a reduced level of fitness, three distinct subject groups will be formed (healthy, sedentary ns-LBP, and active ns-LBP). Using the BSME endurance times from the active ns-LBP subjects as a covariate, we will provide a statistical adjustment in the results for differences that may exist between the subjects due to a reduced fitness level [90]. Basic comparisons on Mox and Mbv trends, delta change, max and min values can be made between the three groups.

Additionally, by comparing the three subject groups on BSME and RILL endurance times we can examine the relationship between the isometric and isotonic back

muscle endurance. The BSME time is considered an indicator of low back muscle fatigue resistance, as studies suggest that the longer the endurance time the greater the fatigue resistance [46, 77]. It would be interesting to note if there is a significant positive correlation between endurance times on the BSME and RILL, indicating that subjects with good or poor isometric endurance show similar isotonic endurance, and to determine if the trends are similar for all subject groups. Hypothesis: the healthy subjects will have a significantly greater BSME endurance time than both the active and sedentary ns-LBP subjects. Moreover the healthy subjects will demonstrate slower more gradual Mox and Mbv trends, achieving a greater decrease in Mox and a larger increase in Mbv than the ns-LBP groups. The healthy subjects will show quicker ½ recovery times following exercise for Mox and Mbv than the sedentary ns-LBP subjects. The rationale for this hypothesis is based on research suggesting that healthy subjects are more likely to have unimpaired circulation to the low back, while ns-LBP subjects may have a reduced or occluded low back blood supply [80, 82, 84]. Kauppila et al. [82] found that subjects (postmortem) with one or more occluded or narrowed arteries were 8.5 times more apt to have suffered from chronic ns-LBP at some time during their life. If structures (e.g., skeletal muscle) supplied by these arteries become hypoxic and enter an ischemic state the result may be atrophy of the tissue [82]. Thus, if ns-LBP subjects have occluded or missing arteries they may likely demonstrate shorter endurance times due to muscle weakness associated with atrophy, and a quicker decrease in Mox and a smaller increase in Mbv due to lack of blood supply and reduced oxygen availability.

The Repetitive Incremental Lifting And Lowering Test (Rill)

The repetitive lifting and lowering of loads requires both isotonic (eccentric and concentric) and isometric muscular contraction in the lower back. Isotonic muscular contractions are characterized by an oscillating relaxation-contraction of skeletal muscles [55]. During relaxation, blood perfuses local tissue vascular beds supplying needed nutrients and oxygen to the working muscles, while removing metabolic by-products (e.g., H^+). However, during contraction blood supply is reduced or occluded because the intramuscular pressure exceeds the intravascular pressure [10, 158]. Studies of intermittent handgrip exercise demonstrate that blood flow decreases during contraction, but during relaxation blood flow is elevated to greater than resting level [158]. Increased muscle blood flow during relaxation is related to an increase in heart rate and blood pressure during the work portion, which can now overcome the vascular resistance during the relaxation portion [1, 158].

During activities that involve heavy lifting, whether they are static or dynamic in nature, the use of intraabdominal (IAP) and intrathoracic pressure (ITP) to stabilize the upper body (back and abdominal) has been shown [43, 63, 99]. Lentini et al. [99] indicated that during high intensity dynamic leg press large changes in ITP, contractility and cardiac volumes were present. Other studies have revealed comparable results when examining IAP during lifting activities in healthy and LBP subjects [43, 63]. Interestingly, Hemborg and Moritz [63] found that there was no significant difference in IAP during lifting between healthy and ns-LBP patients even though ns-LBP subjects had significantly reduced abdominal strength, concluding that abdominal strength was not related to IAP.

However, in as much as the RILL test has many resistance-exercise like qualities (strong isometric and dynamic muscular contractions), it is still an aerobic activity. As an incremental RILL test starts with a relatively low mass and progresses to volitional fatigue, it is considered a peak aerobic test [40, 59, 86, 154] (Table 2). Figures 3 and 4 are from pilot work from our lab, which demonstrate the ventilatory and oxygen consumption responses to at RILL test. These trends demonstrate a linear response comparable to a cycle ergometer or treadmill exercise test. As incremental lifting continues the musculoskeletal system places an increased demand on the cardiorespiratory system, noted by a further increase in heart rate, and oxygen uptake until volitional fatigue [40, 146, 154]. Research by Sharp et al. [154], Commissaris and Toussaint [40], and Nindl et al. [131] used discontinuous protocols in healthy subjects to reduce the likelihood of peripheral muscle fatigue in an attempt to elicit a maximal aerobic response. The discontinuous protocols may have been successful in one respect, as each study reached a greater VO_2 than the present research conducted in our laboratory [86]. However, as indicated by Sharp et al. [154], the repetitive lifting was still not a maximal aerobic test, as both the treadmill and cycle ergometer elicited a greater VO_2 response (treadmill 4.12 ± 0.53 L · min^{-1}, cycle 3.63 ± 0.56 L · min^{-1}). Other distinctions between the studies were the height of lift, whether the movement included a lowering phase, and the frequency of the movements. All of these factors can influence the cardiorespiratory response to the exercise task [45, 121].

Table 2. Comparison of peak cardiorespiratory responses during continuous and discontinuous lifting-lowering protocols in healthy subjects.

Variable	Kell et al. (unpublished manuscript)		Commissaris, D. (EJAP 74: 264-73. 1996)	Nindl, B.C. (EJAP 77: 112-17. 1998)		Sharp, M.A. (EJAP 57: 753-60. 1988)
Sex	Male	Female	Male	Male	Female	Male
Subject number	14	18	5	20	20	18
VO_{2peak} ($L \cdot min^{-1}$)	2.91(0.60)	2.21(0.30)	3.24(0.28)	3.43(0.41)	2.32(0.27)	3.20(0.42)
VO_{2peak} ($ml \cdot kg \cdot min^{-1}$)	37.2(8.4)	35.8(5.5)	45.9(4.0)	42.8(4.1)	39.0(3.9)	42.2(5.5)
V_{Epeak} ($L \cdot min^{-1}$)	92.5(22.2)	62.7(12.7)	86.6(11.7)	114.5(16.8)	80.1(17.5)	109.9(18.3)
HR_{peak} ($beats \cdot min^{-1}$)	177.3(26.8)	174.2(9.3)	170.4(5.5)	185.7(5.8)	189.3(8.4)	181.0(8.4)
RER_{peak}	1.01(0.10)	0.94(0.10)	0.95(0.07)	0.96(0.06)	0.94(0.06)	1.02(0.08)
O_2 pulse ($ml \cdot beat^{-1}$)	16.37(2.63)	13.13(1.79)	18.83(5.1)	18.47(6.9)	12.25(3.2)	17.67(5.0)
Protocol	Continuous	Continuous	Discontinuous	Discontinuous	Discontinuous	Discontinuous
Movement phase(s)	Lift/lower	Lift/lower	Lift/lower	Lifting	Lifting	Lifting
Freq ($mov \cdot min^{-1}$)	10	10	13.6 to 24	15	15	15
Lifting height (m)	0.76	0.76	From 0.20m to Knuckle ht	1.32	1.32	1.32

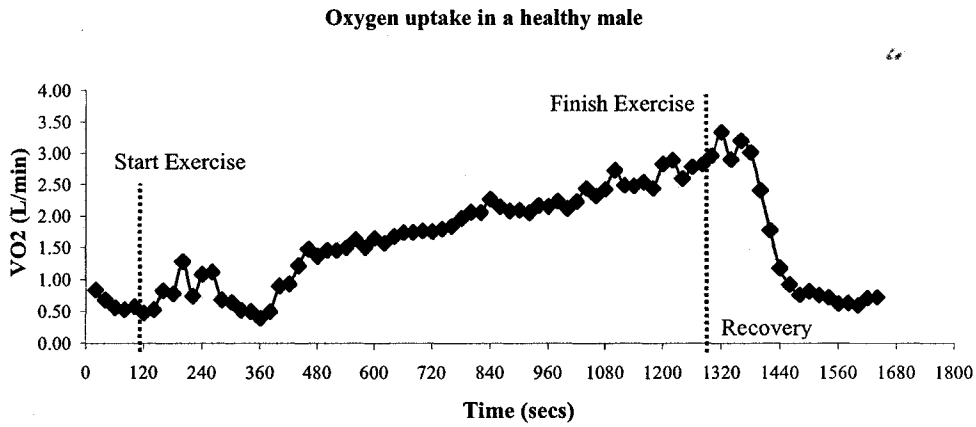


Figure 3. Ventilatory response to the RILL test covering rest (2-min), exercise, and recovery (4-min) in a healthy male.

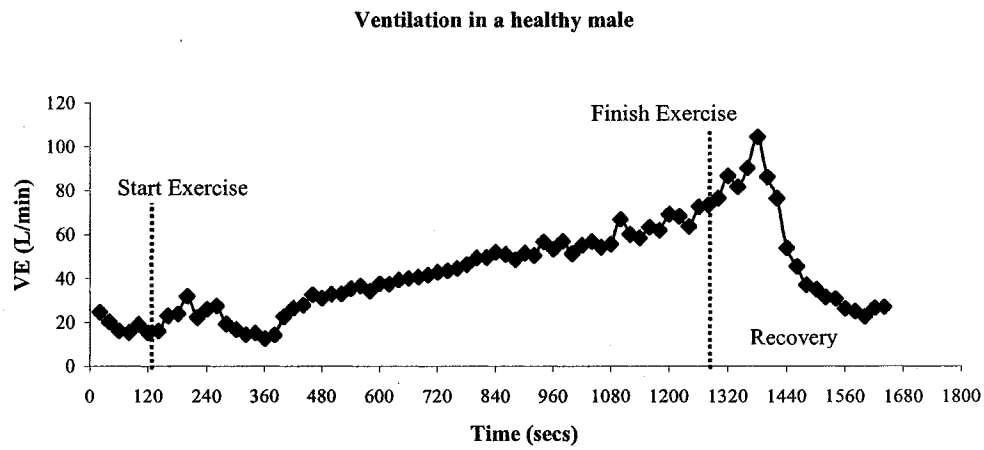


Figure 4. Oxygen uptake response to the RILL test covering rest (2-min), exercise, and recovery (4-min) in a healthy male.

The use of a repetitive incremental lifting and lowering protocol was derived from the desire to measure: (1) the cardiorespiratory response to a continuous incremental protocol, as in most maximum oxygen consumption tests; (2) to examine if the termination of the test would be due to central or peripheral fatigue and; (3) the Mox and Mbv responses of the erector spinae muscles during exercise and recovery. As previously demonstrated the application of indirect open circuit spirometry to measure the cardiorespiratory responses to repetitive lifting has been done [40, 97, 146, 154]. Repetitive incremental lifting (no lowering) studies have investigated the possibility of a lifting VO_{2peak} [154] and the biomechanical aspects of lifting techniques [48, 113, 167]. Current research has been carried out on both lifting and lowering in combination [40, 45, 59, 142, 146]. For example, De Looze et al. [45] examined the energy expenditure of both positive (lifting) and negative (lowering) work and found that the cost of negative work was ~0.3 – 0.5 times the cost of positive work. However, there are presently two published research studies on repetitive (continuous) incremental lifting and lowering to volitional fatigue [59, 86]. Hagen et al. [59] (N = 10, male) used a repetitive lifting and lowering protocol for both the stoop and squat techniques with a starting basket weight of 11-to 14-kg and increasing the weight by 2.5-kg every 2-min until VO_{2peak}. The peak cardiorespiratory values in Hagen et al. [59] study for the squat technique (most similar to our technique) are: VO_2 ml · kg^{-1} · min^{-1} = 38.7 ± 5.8; V_E = 95.8 ± 16.6 L/min^{-1}; HR = 184 ± 10. If subjects did not reach volitional fatigue by 24-kg the frequency of lifting was increased by 4 lifts/min every 2-min until volitional fatigue. These values are similar to our recently submitted manuscript [86]. However, there are variations in the protocol between the two studies: lifting frequency 20 lifts/min – Hagen; 10 lifts/min - our lab; a maximum weight

limit-Hagen; no maximum weight limit - our lab; increasing lifting frequency at maximum weight (24 kg) – Hagen; no change in lifting frequency – our lab.

The cardiorespiratory response to RILL is considerable (Figures 3 and 4 and Table 2), as it places substantial physiological stress on the human body. Muscular strength/endurance (peripheral) and cardiorespiratory (central) may both limit the amount of work that an individual is capable of doing. As the intensity of the lifting is increased, by increasing either the load or frequency, the demand on the central and peripheral structure of the body will increase. At the onset of RILL both the aerobic and anaerobic energy system are utilized to supply the needed energy to the working muscles, and as the intensity of work increases this will be reflected in the proportion of the energy systems being used. Oxygen consumption and the respiratory exchange ratio (RER) can be used as indicators of whole body metabolic stress and energy system utilization [60]. The aerobic energy system supplies energy by means of oxidative metabolism (oxygen), and produces energy at a relatively slow to moderate rate, while the anaerobic energy system produces energy at a relatively high to very high rate when compared to the aerobic system [7]. Repetitive incremental lifting and lowering to VO_{2peak} necessitates the use of both energy systems [40, 45, 98, 181], just as a VO_{2max} test does in other modes of exercise [50, 143, 153]. However, due to the mix of both strength and aerobic capacity needed to achieve a long duration in the repetitive incremental lifting and lowering test, the limiting factor(s) is difficult to discern.

Petrofsky and Alexander [135] suggest that handgrip fatigue, as well as erector spinae fatigue at heavier weights may limit lifting endurance. This study was not a RILL test, but used boxes weighting between 0.91-and 36.36-kg and lifting frequencies from 4-

to 70-lifts/min to a height of 60 cm for a 4-min period. One method of discerning variations in the location of fatigue is by using the Borg scale for RPE [28]. The scale is commonly used to measure overall fatigue during many different activities, from whole body vibration [147] to cycling [134]. However, Pandolf et al. [132] suggested that the RPE scale might be more effective when differentiated, such as measuring fatigue in various body parts. Using 60-mins of arm cranking and leg cranking (N = 9, male) at similar absolute and relative intensities indicated that the RPE in the absolute test was lower for the legs than arms, while during the relative test no difference was found between the legs and arms in RPE [132]. In general, the RPE scores for peripheral – arm and leg musculoskeletal were higher than those for central - ventilatory and circulatory, which is in agreement with results from our lab [86].

Repetitive incremental lifting and lowering research conducted on healthy male and female subjects suggest that low back fatigue is the primary reason for terminating the RILL test [86]. Central and peripheral fatigue was determined using the RPE scale developed by Borg [28], and the results were as follows: Arms/shoulders males = 15.29 ± 3:10, females = 15.35 ± 2.62; back males = 18.43 ± 1.55, females = 18.20 ± 1.79; cardiorespiratory males = 16.36 ± 2.06, females = 15.85 ± 2.43, indicating the greatest perception of exertion and fatigue was in the back muscles for both sexes [86]. In contrast to our research, Hagen et al. [59] (N = 10, male) using a repetitive lifting protocol for both the stoop and squat techniques, with an increasing mass of 2.5-kg every 2-min until VO_{2peak} found the central RPE to be higher than the peripheral RPE. The RPE scores for the squat technique (similar technique to the current study) were as follows: central 16.4 ± 1.9, thigh 6.9 ± 2.0, and low back 3.5 ± 2.3. In the following three studies, Hagen et al.

[59], the recently accepted manuscript [86] and this proposed study consider central RPE to indicate cardiorespiratory strain, and peripheral RPE measures to indicate strain on the musculoskeletal system. The reason for the stark contrast in the RPE values is likely due to differences in protocol. In the Hagen et al. [59] study if subjects did not reach volitional fatigue by 24-kg, the frequency of lift was then increased by 4 lifts/min every 2-min until volitional fatigue, whereas, our protocol [86] and the present study utilizes 1-min increments. Moreover, our protocol begins with an empty basket while Hagen et al. [59] started with a loaded basket (11-to 14-kg).

Thus, the use of the Borg RPE scale in a differentiated fashion (central – cardiorespiratory and peripheral – arms/shoulders and low back) will aid in the determination of cite specific fatigue in a more complete manner. A comparison between groups will help clarify any existing differences between the groups due to location of fatigue. Hypothesis: that all three subject groups will give a higher RPE rating associated with the low back and arms/shoulders as compared to the cardiorespiratory system. However, the sedentary and active ns-LBP subjects will demonstrate higher low back RPE scores compared to the healthy subjects. Also, the sedentary and active ns-LBP subjects will achieve peak peripheral and central RPE scores in a shorter test-time period than the healthy subjects. The reason for this hypothesis is based on the peripheral muscle fatigue that has been suggested to be associated with intense repetitive lifting [135]. Also, research indicates that healthy subjects are less likely to have impaired circulation to the low back, while ns-LBP subjects are likely to have reduced or occluded low back blood supply [80, 82, 84]. Reduced blood supply to the low back may cause ischemia, increased fatigue and pain, which would be especially

aggravated during increased muscle contractions during physical activity [84]. The higher level of fatigue and pain associated with the erector spinae muscle mass of the ns-LBP subjects may be associated with an earlier and higher peripheral RPE score, as perceptual cues from smaller muscle masses are likely to be detected by a differentiated RPE [132].

Presently, a review of repetitive lifting research indicates that there is only one published study that has evaluated the cardiorespiratory and low back Mox and Mbv responses simultaneously in male and females [112], with another study citing unpublished results [103]. The exercise bout consisted of 60-mins of submaximal lifting, which revealed a steady increase in Mox and Mbv during the first 20-min followed by a plateau [112]. This indicates that NIRS is capable of monitoring Mox and Mbv changes within the erector spinae muscles during repetitive lifting [103, 112]. The concurrent use of NIRS, open circuit spirometry and RPE should enable the examination and comparison of Mox and Mbv trends throughout the RILL test to volitional fatigue, as well as delineate the location of the most severe fatigue (centrally and peripherally) which may have terminated the test. Examples of typical healthy male and female Mox and Mbv trends during a RILL test to volitional fatigue are shown in Figures 5 and 6 [86].

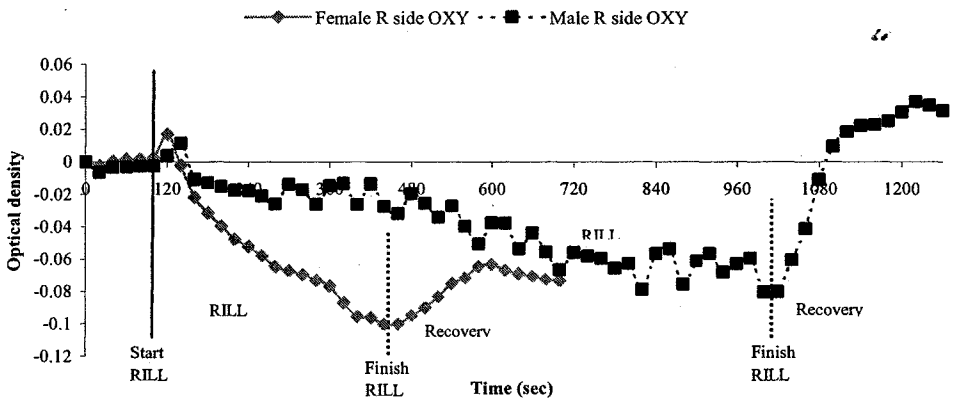


Figure 5. A typical healthy male and female Mox trend during a RILL test to volitional fatigue as measured by NIRS.

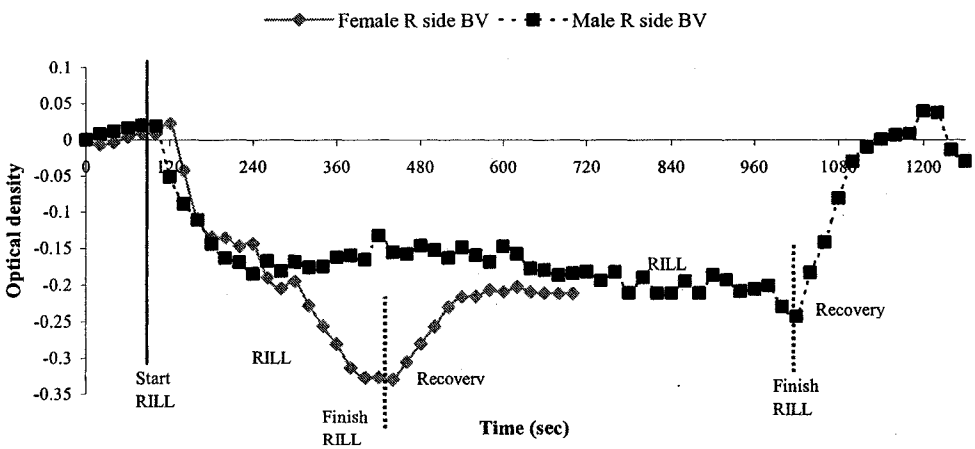


Figure 6. A typical healthy male and female Mbv trend during a RILL test to volitional fatigue as measured by NIRS.

Figure 5 is an example of a Mox trend for a typical healthy male and female subject. At the onset of RILL there is an initial increase followed by a systematic decrease throughout the majority of exercise with a small increase in deoxygenation just prior to the subject terminating the test. At the termination of the RILL there is a rapid re-oxygenation that takes place in most subjects, as seen in the male subject in Figure 5. The initial increase in Mox is a result of the initial increase in Mbv delivering oxygen to the exercising muscle, as well as due to a redistribution of blood from other surrounding and deeper muscle tissue [14, 35]. The systematic decrease in Mox is generally due to increased muscle cell uptake of oxygen that is greater than the amount of oxygen delivered via the blood. Once work intensity exceeds ~50% of VO_{2max} the muscle deoxygenation is also facilitated by metabolic acidosis resulting from increasing H^+ concentration (lactate formation) enhancing the release of oxygen from hemoglobin by the Bohr effect [177]. The recovery of Mox is influenced by the time for resaturation of the exercise desaturated hemoglobin and myoglobin following exercise [35]. Hemoglobin and myoglobin signals are indistinguishable by NIRS, however the bulk of the NIRS signal is made up of hemoglobin (75%) with myoglobin a distant second (25%) [35].

The Mbv response in Figure 6 demonstrates the initial increase in Mbv at the onset of RILL followed by a systematic decrease to a plateau or a plateau with a quick decrease in Mbv just prior to the termination of the RILL. In recovery Mbv increases rapidly typically to levels greater than resting baseline. The trends for Mox during RILL are similar to other forms of dynamic exercise [18, 33], however the trend in Mbv is different from that of other dynamic exercise modes [35, 71]. The reason for the variation in the trend in Mbv is likely due to the intermittent isometric contraction of the erector spinae and its

impact on blood flow changes in the muscle. In a study of speed skating (N = 8, male, elite speed skaters) Rundell et al. [150] found that speed skating in a low position (as determined by joint angle) attenuated the typical hyperemic effect seen in most dynamic exercise. The authors felt that the even though the isometric contraction of the leg muscles was only between 20-to-30% of MVC it was sufficient to impair blood flow during exercise. This line of thought was bolstered by a near doubling of the post-exercise blood lactate concentrations, without a corresponding increase in VO_2 [150]. Although NIRS does not measures changes in blood flow, it does provide trends in Mbv which is considered to reflect changes in blood flow into and out of the area of muscle under investigation [66].

With the inclusion of three subject groups (healthy, sedentary ns-LBP, active ns-LBP) the analysis of back fatigue can be taken one step further. Hypothesis: the trends in Mox and Mbv will be visually similar between all groups, with decreasing Mox and Mbv trends. However, differences will be evident between the groups in the time-course and amplitude of the trends. The healthy subjects will have a slower, more gradual time course in Mox and Mbv as compared to the active and sedentary ns-LBP subjects, achieving lower Mox and Mbv min values and greater delta change values. The ½ recovery time for Mox and Mbv will be quicker for healthy subjects in contrast to active and sedentary ns-LBP subjects. The rationale for this hypothesis is that the healthy subjects will have greater blood supply to the working musculature and greater oxygen extraction ability. The greater blood supply and oxygen extraction ability may be due to the fact that the sedentary and active ns-LBP subjects have missing or occluded arteries in the low back [80, 82]. If the healthy subjects have a more substantial blood supply (e.g.,

more arteries, greater capillary density), they will have the capacity to continue for a longer duration during the RILL before being limited by peripheral fatigue (in the low back). A longer test time will enhance the opportunity to deliver more blood and extract a more oxygen in the low back region (Mox and Mbv), as well as achieve higher cardiorespiratory values.

Hypothesis: the active ns-LBP subjects will demonstrate greater VO_{2peak}, VT, V_E, and HR responses than the sedentary ns-LBP subjects simply due to their higher level of physical activity [64, 72, 171]. With increasing fitness level there are corresponding positive changes in left ventricular function [152]. Schulman et al. [152] found (N = 10 sedentary and 8 age matched endurance trained) a significant training effect (24-32 wks of training) on cardiovascular function that was similar in magnitude, but directionally opposite to those of the detraining group. Across the wide range of fitness levels (VO_{2max} of 26 to 58 $mL \cdot kg^{-1} \cdot min\text{-}1$) before and after the change in training status, cardiac index, stroke volume index, end-systolic volume index, ejection fraction, and the left ventricular contractility index were all linearly correlated with VO_{2max} [152].

With respect to peripheral changes associated with training numerous studies have indicated significant increases in capillary density and enzymes [64, 166] as well as increases in mitochondrial density [171]. Hepple et al. [64] studied the affect two training modes, aerobic (AT) and resistance (RT) training, in older adults (age 65-74 yr) to examine changes in VO_{2peak} and capillary supply. Twenty healthy males used either 9 wks of lower body RT followed by 9 wks of AT on a cycle ergometer (RT-->AT group) or 18 wks of AT on a cycle ergometer (AT-->AT group). RT was performed 3 days/wk and consisted of 3 sets of 6-12 repetition maximum on four exercises. AT was performed

3/dayswk for 30 min at 60-70% heart rate reserve. VO_{2peak} increased after both RT and AT (*P* 0.05), and the vastus lateralis showed an increase in the capillaries per fiber perimeter length after both AT and RT (*P* 0.05), paralleling the changes in VO_{2peak}. However, capillary density was increased only after AT (*P* 0.01). Detraining is typically associated with decreases in these parameters, for example decreases in capillary density (within 2-3 wk of inactivity), a decline in arterial-venous oxygen difference (3-8 wk), as well as rapid reduction in oxidative enzyme activity bring about a reduced mitochondrial ATP production [127]. Klausen et al. [92] trained 6-male subjects 30-min/day 3-times/week for 8 weeks and measured the changes following 8-weeks of training and 8-weeks of detraining. Following 8 weeks of detraining decreases in the number of capillaries per fiber and the number of capillaries around each fiber type were found, as well as decreases in enzyme activities towards pre-training levels. Hortobagyi et al. [68] investigated the effects of 14 days of resistive exercise detraining on power athletes (N = 12). Results indicated that the percentages of muscle fiber types and the Type I fiber area remained unchanged, but the Type II fiber area decreased significantly by -6.4% (*P* = 0.05).

Thus, the influence of training status will affect cardiac output and thus blood and oxygen supply to working muscle, which in turn will influence VO_{2peak}, and Mox and Mbv min, max and delta change as hypothesized earlier. However, the healthy group will still show significantly greater cardiorespiratory values than the active ns-LBP subjects, as the blood supply to the low back of active ns-LBP subjects will still likely be reduced as compared to the healthy subjects [80, 82], which will be associated with earlier peripheral fatigue and termination of the RILL test.

This will be the only study to date that will examine a RILL test to volitional fatigue on ns-LBP subjects using NIRS to monitor trends in Mox and Mbv. The RILL test to volitional fatigue will allow a further comparison and analysis of the ns-LBP and healthy subjects with a more comprehensively coverage of peripheral and central fatigue. Using two distinct ns-LBP groups, sedentary ns-LBP and active ns-LBP, will assist in removing the influence of a decreased fitness level on ns-LBP. Using VO_{2peak} as a covariate will assist in the adjustment for any differences in cardiorespiratory fitness that may exist between the subjects due to differences in fitness level. As a reduced level of fitness for even a short length has been associated with a negative affect on many body systems, cardiovascular and/or muscular [56, 64, 72, 152, 155], which increases the difficulty in determining if a difference between groups (healthy and ns-LBP) is due to the effect of a reduced fitness level, or the actual affect of the injury (ns-LBP).

Psychophysical Evaluation

In the pursuit of safer Manual Material Handling guidelines (MMH), psychophysics has contributed to a substantial accumulation of literature since the 1970's [9, 58, 123, 160-165, 175]. Psychophysics is a branch of psychology concerned with the relationships between stimuli and the resulting sensation. The psychophysical scheme is used to obtain the maximum acceptable weight that one can perform repeatedly for an extended period of time (e.g., 1-to 8-hours) without excessive strain or becoming unusually tired, weakened, overheated, or out of breath.

The psychophysical approach is based on the principle that an individual can perceive the various strains during MMH and judge the differences between each level of

effort and predict the level of exertion over time [161]. The psychophysical handling capacity can be influenced by many variables, such as, age, strength/fitness, gender, lifting frequency, task duration, object size, and environmental temperature [161]. However, if the above variables are held constant across a group of individuals, theoretically all individuals would self-select a workload that each could handle for an 8-hour workday. However, some research suggests that the psychophysical evaluation method is inaccurate in determining the maximum amount of weight that an individual can lift for an 8-hour workday. Mital [122] using 5 males and 5 females (age = 24-55 yrs) and a 25-min psychophysical evaluation (box size-frequency-height were randomly selected) found that the males could only manage 65% and females 84% of their estimated weight for an 8-hour workday. However, Ciriello et al. [39] disputed these findings showing that if the instruction were properly and consistently administered no overestimation would occur for tasks equal to 4-hours. Thus, good subject cooperation, consistent instructions and firm experimental control is the cornerstone of the psychophysical scheme [97].

The majority of psychophysical studies have been completed on healthy populations, such as college students, soldiers and industrial workers. The psychophysical approach has been shown to be reproducible in both males and females, as workloads selected by subjects across replications elicited a similar physiological response (e.g., heart rate) [164, 165]. However, in a case study of ns-LBP patients, the psychophysical lifting capacity was found to be less repeatable [58] and a poor predictor of future ns-LBP [58, 175]. Research suggests that subjects currently suffering from ns-LBP [58, 175] and those who previously suffered from ns-LBP [175] demonstrated lower values for

psychophysical lifting capacities than healthy subjects. Some psychophysically determined values have been recognized to be inconsistent with the biomechanical criteria for low frequency tasks and the physiological criteria for high frequency tasks (>6 lifts/min) [8, 9, 161]. However, these inconsistencies are based on the assumption that the biomechanical and physiological criteria are correct, which to some extent is unknown [161].

A study by Petrofsky and Lind [136] suggested that when levels of work exceed 50% of lifting specific VO_{2peak}, which was proportional to 25% of VO_{2max} on the cycle ergometer, excessive fatigue would ensue. This was based on the maintenance of lifting for 1-to 4-hours and is in agreement with research by Astrand [6]. Other studies indicate that from a physiological perspective, individuals can work at only 33% of their VO_{2max} for whole-body repetitive lifting tasks between 2-and 8-hours [121, 179]. Lifting from the floor to a vertical distance ≤75 cm is considered to be whole-body work. Thus, the repetitive lifting and lowering tests in the present study would both be considered whole body, as the table height for both the RILL and the psychophysical tests is 67 cm. The 33% criteria that is recommended by the National Institute for Occupational Safety and Health (NIOSH) is based on a treadmill VO_{2max} test to volitional fatigue [179]. Some feel that the criterion 33% of a treadmill VO_{2max} (10.5 kcals/min) overestimated the actual capacity of repetitive lifting. As a result, NIOSH [128] adjusted the criteria to account for the differences between treadmill data and repetitive lifting data, suggesting that for whole-body repetitive lifting tasks between 2-and 8-hours in duration the work intensity should not surpass 33% of 9.5 kcals/min (or 4000 kcals/day for a 420-min work period).

The 9.5 kcals/min criterion is based on the 1991 committees assumed mean (50th percent) lifting capacity of a female 40 years of age [179].

An interesting question is, will subjects self-select (psychophysically) a lifting load that elicits 33%, 40% or 50% of their own lifting VO_{2peak}. The terminology lifting VO_{2peak}, not VO_{2max}, will be used, as higher VO_2 values would be achieved during other exercise modes [135, 154]. By using open circuit spirometry we will be able to determine the percentage of VO_{2peak} individuals self-select during the psychophysical test based on the previous RILL test to volitional fatigue. Further, we will be able to observe the relationship between the self-selected weight (kg) and VO_2 during the psychophysical evaluation and the percentage of the peak values determined during the RILL test. For example, if a subject self-selects a work level of 40% of their lifting VO_{2peak}, will the self-selected weight be 40% of the peak mass achieved during the RILL test. Additionally, we will examine the subjects self-selected work level to see if it is below VT (an indicator anaerobic threshold). Monitoring the work intensity may be best accomplished via VT or heart rate [30], as blood lactate concentrations fluctuate substantially during endurance performance (90-min) and cannot accurately predict the highest work intensity that can be maintained during prolonged exercise without fatigue [30]. It would be expected, physiologically, that people attempting to determine a long-term (≥50-min) work level would select a work output below their anaerobic threshold, or their work intensity would not be maintained over a prolonged period [29, 42, 100, 168]. It has been shown that attempting to do prolonged work (≥50-min) at too great of an intensity will be associated with a build-up of lactic acid, and the premature termination (mean = 14.4 +/- 6.3 min) of the work/exercise [168]. It is important for subjects to choose a work

intensity below their own individual anaerobic threshold [168]. Hypothesis: all subjects will self-select a work intensity below their individual anaerobic threshold, as determined by VT, at approximately 50% of RILL VO_{2peak}.

By employing NIRS technology we can analyze Mox and Mbv trends throughout extended (20-min) submaximal exercise. Currently, little research exists in the monitoring of skeletal muscle oxygenation and blood volume responses via NIRS to extended duration exercise [15, 37, 38, 85], with very little research on extended submaximal work of the erector spinae muscle [112], and no research on extended work of the erector spinae muscle of ns-LBP subjects. By viewing the trends in Mox and Mbv of the healthy, sedentary ns-LBP and the active ns-LBP we may be able to identify differences in general trends between the three groups. For example, we can determine if the percent change in Mox and Mbv levels during the psychophysical evaluation are comparable to the self-selected percentage of VO_{2peak}. If the Mox during the psychophysical evaluation is at 80% of the maximum delta change value while the VO_2 throughout the test is 40% of the RILL VO_{2peak} then one could speculate that the fatigue from long duration lifting and lowering work activities would be peripheral in nature, not central. This knowledge would provide a direction in addressing fatigue issues in extended lifting and lowering work situations. Additionally, if a significant difference was determined in the delta change Mox or Mbv values between the sedentary ns-LBP subjects and the other two subject groups (healthy and active ns-LBP) various associations may be speculated upon. For instance, one may suggest an association between activity level and low back Mox and Mbv, and that pain may not be associated with Mox and Mbv (i.e., blood supply), which has been suggested [81].

Canadian Physical Activity And Lifestyle Appraisal (Cpafla) Manual And Modified Schober Test

The CPAFLA test battery [31] includes several tests to measure health related fitness in the general population, and if necessary, make recommendations to aid in the improvement of overall health. The CPAFLA has a back health component, which is composed of measures of abdominal muscular endurance via the partial curl-up test and low back/hamstring flexibility via the trunk forward flexion (TFF) test [4]. Also of importance in the assessment of ns-LBP are the measures of waist-girth (WG) and body mass index (BMI), which are used primarily as an assessment of body fat distribution [31]. The Modified Schober test as well will be discussed in this section, which is considered to be indicative of previous or current low back (lumbosacral) flexibility [12], will also be discussed in this section.

Reduced abdominal endurance and low back flexibility have been associated with ns-LBP [22]. The partial curl-up has been demonstrated to be a reliable measure of abdominal endurance [51], and abdominal endurance has been implicated in ns-LBP due to its affect on core stability [4]. The TFF test (also known as the sit and reach test), has been questioned as a measure of low back flexibility [69] as it may be a better indicator of hamstring flexibility. Payne et al. [133] studied healthy-related fitness and its association with ns-LBP in 233 males and 287 females and found that TFF was positively related to back health in both sexes. Thus, whether the TFF test is a measure of hamstring flexibility, erector spinae flexibility or both is not of principal consequence, but of primary importance is that TFF is association with ns-LBP [133].

The Modified Schober test is considered to be a test of lumbosacral flexibility [13,

[23]. A study by Battié [13] indicated that the Modified Schober test correlated poorly with other flexibility measures (e.g., sit and reach, side bending), but this may indicate that it is measuring another, or a different, component of flexibility. Biering-Sørensen [23] using a prediction equation found that first-time occurrence of LBP may be predicted with the inclusion of the Modified Schober score. Interestingly there appear to be sex differences in the Modified Schober test with males demonstrating greater flexibility than females [23], as well as over time women seem to show less of a decrement in Modified Schober score between the ages of 40-and 50-years [13]. However, the Modified Schober test is not without its criticisms. Miller et al. [120] used 50 healthy males and females to study the inter-rater reliability of the Modified Schober test. The study revealed that systematic error, or variation in repeated test scores, might be a concern due to inconsistency in skin landmarks. However, it is suggested that variation between test scores can be due to a subject learning effect [23].

The use of the BMI and waist-girth by the CPAFLA are used to provide an indication of obesity and abdominal fat [31]. The rationale for these measures is somewhat instinctive, from the perspective that if you carry excessive fat in the abdominal region it will put greater stress on the lower back. Additionally, there may intuitively be an association between a greater proportion of abdominal fat and weak abdominal muscles, from the perspective that heavier people may be less physically fit. Studies have demonstrated an association between excessive abdominal weight and low back pain [62]. However the study cited [62] indicated that the back pain was a result of disc herniation, not musculoskeletal soft tissue pain. More recently, a study by Payne et al. [133] found that both males and females with a history of ns-LBP had a significantly greater WG as compared

to subjects with no history of ns-LBP. However, the use of BMI was not found to be a good discriminator between those with ns-LBP and those without [133]. Considering the above information, as well as a review of ns-LBP prevention by Carpenter and Nelson [32], which found that better hamstring flexibility and abdominal muscular endurance would reduce the risk of chronic ns-LBP, the inclusion of the partial curl-up, TFF, and WG in this study is warranted.

Summary

During the RILL and psychophysical tests the cardiorespiratory variables were used to examine similarity and differences in central stress between subject groups and tests in coordination with the RPE-central (cardiovascular), and to note level of conditioning of subjects. Near infrared spectroscopy was used to assess peripheral stress via trends in erector spinae hemodynamics in combination with RPE-peripheral (arms/shoulders and back) during the two forms of muscle contractions. The rationale in the application of NIRS to ns-LBP was based on research suggesting that chronic low back pain may be related to an absence or occlusion of arteries in the low back region. Kauppila has studied the number and pattern of arteries in the lumbar and sacral region of normal healthy [79] and ns-LBP subjects [80, 82-84]. The research suggests that LBP may be associated with missing or occluded arteries, which may reduce low back blood flow. The reduced oxygen delivery may result in lower Mox delta change values, and lower cardiorespiratory variables due to peripheral (low back muscular) fatigue, or pain due to ischemia. However, if pain (skeletal) or effort becomes a limiting factor during an exercise test it should be able to be identified during the exercise test [177], as well as noted

by lower RPE scale values and questioning by the research post-test. If NIRS is able to detect these variations in the hemodynamic trends between the subject groups then it may be a useful non-invasive tool for the identification of ns-LBP of a soft tissue nature.

By incorporating 3 distinct subject groups to compare and combine the results from the BSME, RILL and the psychophysical test we will attempt to note any significant differences between groups in: (1) cardiorespiratory measures, (2) erector spinae hemodynamics, and (3) other basic physical tests that have previously demonstrated an association with ns-LBP (i.e., partial curl-up, TFF, Modified Schober, and WG). Following the analysis of the results we attempted to determine if: a significant difference exists between groups in time to exhaustion, RPE or erector spinae hemodynamics during a static muscle contraction of the low back; the BSME endurance time is positively correlated with RILL endurance time; RILL is limited by a central or peripheral fatigue; ns-LBP (sedentary or active) subjects have greater peripheral fatigue during lifting and lowering than healthy subjects; subjects naturally self-select (psychophysical) a submaximal work level below VT and what percent of VO_{2peak} does it represent; variation between groups exist on the percent of VO_{2peak} to complete extended submaximal work (psychophysical test); ns-LBP subject groups (i.e., sedentary and active) differ on time to exhaustion, central-cardiorespiratory values or peripheral-local muscle values during the RILL or psychophysical tests and; similar associations have been found between the partial curl-up, TFF, Modified Schober, WG and ns-LBP subjects and determine variability between subject groups. Determining the above relationships will help develop a better overall understanding of central and peripheral limitations during

fatiguing work and variability between subject groups (healthy, sedentary ns-LBP, and active ns-LBP) during these types of muscle contractions.

REFERENCES

1. Abdel-Moty, E., D. A. Fishbain, T. M. Khalil, S. Sadek, R. Cutler, R. S. Rosomoff, and H. L. Rosomoff. Functional capacity and residual functional capacity and their utility in measuring work capacity. *Clin J Pain.* 9:168-173., 1993.
2. Addison, R. and A. Schultz. Trunk strength in patients seeking hospitalization for chronic low-back disorders. *Spine.* 5:539-544, 1980.
3. Alaranta, H., H. Hurri, M. Heliovaara, A. Soukka, and R. Harju. Non-dynamometric trunk performance tests: reliability and normative data. *Scand J Rehab Med.* 26:211-215, 1994.
4. Albert, W. J., J. Bonneau, J. M. Stevenson, and N. Gledhill. Back fitness and back health assessment considerations for the Canadian Physical Activity, Fitness and Lifestyle Appraisal. *Can J Appl Physiol.* 26:291315, 2001.
5. Albert, W. J., G. G. Sleivert, J. P. Neary, and Y. N. Bhambhani. Monitoring individual erector spinae fatigue responses using electromyography and near infrared spectroscopy. *Can J Appl Physiol.* 29:363-379, 2004.
6. Astrand, I. Aerobic work capacity in man and women. *Acta Physiol Scand.* 49:64-70, 1960.
7. Astrand, P. O. and K. Rodahl. *Textbook of Work Physiology: Physiological basis of exercise.* Second ed. New York: McGraw-Hill Book Company, 1977
8. Ayoub, M. M. Problems and solutions in manual materials handling: state of the art. *Ergonomics.* 35:713-728, 1992.

9. Ayoub, M. M. and P. G. Dempsey. The psychophysical approach to manual materials handling task design. *Ergonomics*. 42:17-31., 1999.

10. Barnes, W. S. The relationship between maximum isometric strength and intramuscular circulatory occlusion. *Ergonomics*. 23:351-357, 1980.

11. Battié, M. C., S. J. Bigos, L. D. Fisher, T. H. Hansson, M. E. Jones, and M. D. Wortley. Isometric lifting strength as a predictor of industrial back pain reports. *Spine*. 14:851-856., 1989.

12. Battié, M. C., S. J. Bigos, L. D. Fisher, D. M. Spengler, T. H. Hansson, A. L. Nachemson, and M. D. Wortley. The role of spinal flexibility in back pain complaints within industry A Prospective Study. *Spine*. 15:768-773, 1990.

13. Battié, M. C., S. J. Bigos, A. Sheehy, and M. D. Wortley. Spinal flexibility and individual factors that influence it. *Phys Ther*. 67:653-658, 1987.

14. Belardinelli, R., T. Barstow, J. Porsasz, and K. Wasserman. Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. *Eur J Appl Physiol*. 70:487-492, 1995.

15. Belardinelli, R., T. J. Barstow, J. Porszasz, and K. Wasserman. Skeletal muscle oxygenation during constant work rate exercise. *Med Sci Sports Exerc*. 27:512-519., 1995.

16. Belardinelli, R., D. Georgiou, and T. J. Barstow. NIRS and changes in skeletal muscle oxygenation during incremental exercise in chronic heart failure: a comparison with healthy subjects. *Giornale Italiano di Cardiologia*. 25:715-724, 1995.

17. Bhambhani, Y., S. Buckley, and T. Susaki. Detection of ventilatory threshold using near infrared spectrometry in men and women. *Med Sci Sports Exerc.* 29:402-409, 1997.

18. Bhambhani, Y., R. Maikala, and S. Buckley. Muscle oxygenation during incremental arm and leg exercise in men and women. *Eur J Appl Physiol Occup Physiol.* 78:422-431., 1998.

19. Bhambhani, Y., R. Maikala, J. Jeon, and G. J. Bell. Reliability of tissue deoxygenation during cuff ischemia in healthy males. *Can J Appl Physiol.* 3:467, 1998.

20. Biedermann, H.-J., G. L. Shanks, and J. Inglis. Median frequency estimates of paraspinal muscles: reliability analysis. *Electromyogr Clin Neurophysiol.* 30:83-88, 1990.

21. Biering-Sorensen, F. A one-year prospective study of low back trouble in a general population. The prognostic value of low back history and physical measurements. *Danish Medical Bulletin.* 31:362-375., 1984.

22. Biering-Sorensen, F. Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine.* 9:106-119, 1984.

23. Biering-Sorensen, F. A prospective study of low back pain in a general population. *Scand J Rehab Med.* 15:81-88, 1983.

24. Biering-Sorensen, F., C. E. Thomsen, and J. Hilden. Risk indicators for low back trouble. *Scand J Rehab Med.* 21:151-157, 1989.

25. Bigos, S. J., M. C. Battie, D. M. Spengler, L. D. Fisher, W. E. Fordyce, T. H. Hansson, A. L. Nachemson, and M. D. Wortley. A prospective study of work

perceptions and psychosocial factors affecting the report of back injury. *Spine.* 16:1-6, 1991.

26. Bonde-Petersen, F., A. L. MØrk, and E. Nielsen. Local muscle blood flow and sustained isometric contractions of human arm and back muscles. *Eur J Appl Physiol.* 34:43-50, 1975.

27. Borenstein, D., S. Wiesel, and S. Boden. *Low Back Pain: Medical diagnosis and comprehensive management.* Second ed. Philadelphia: W.B. Saunders Company, 1995, 22-26, 63-170.

28. Borg, G. and B. Noble. Perceived exertion. *Exerc Sport Sci Rev.* 2:131-153, 1974.

29. Boulay, M. R., P. Hamel, J. A. Simoneau, G. Lortie, D. Prud'homme, and C. Bouchard. A test of aerobic capacity: description and reliability. *Can J Appl Sport Sci.* 9:122-126, 1984.

30. Boulay, M. R., J. A. Simoneau, G. Lortie, and C. Bouchard. Monitoring high-intensity endurance exercise with heart rate and thresholds. *Med Sci Sports Exerc.* 29:125-132, 1997.

31. Canadian Society for Exercise Physiology. *The Canadian Physical Activity, Fitness & Lifestyle Appraisal Manual.* Ottawa: The Canadian Society for Exercise Physiology, 1996.

32. Carpenter, D. M. and B. W. Nelson. Low back strengthening for the prevention and treatment of low back pain. *Med Sci Sports Exerc.* 31:18-24, 1999.

33. Chance, B. and W. Bank. Genetic disease of mitochondrial function evaluated by NMR and NIR spectroscopy of skeletal muscle. *Biochemica et Biophysica Acta.* 1271:7-14, 1995.

34. Chance, B., E. Borer, A. Evans, G. Hiltom, J. Kent, M. Maris, and K. McCully. Optical and magnetic resonance studies of hypoxia in human tissue and tumors. *Annals of New York Acad of Sci.* 551:1-16, 1988.

35. Chance, B., M. Dait, C. Zhang, T. Hamaoka, and F. Hagerman. Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. *Am J Physiol.* 262:C766-C775, 1992.

36. Chance, B., S. Nioka, J. Kent, K. McCully, K. Fountain, R. Greenfeld, and G. Holtom. Time-resolved spectroscopy of hemoglobin and myoglobin in resting and ischemic muscle. *Analytical Biochem.* 174:698-707, 1988.

37. Christmass, M. A., B. Dawson, and P. G. Arthur. Effect of work and recovery duration on skeletal muscle oxygenation and fuel use during sustained intermittent exercise. *Eur J Appl Physiol Occup Physiol.* 80:436-447, 1999.

38. Christmass, M. A., B. Dawson, P. Passeretto, and P. G. Arthur. A comparison of skeletal muscle oxygenation and fuel use in sustained continuous and intermittent exercise. *Eur J Appl Physiol Occup Physiol.* 80:423-435, 1999.

39. Ciriello, V. M., S. H. Snook, A. C. Blink, and P. L. Wilkinson. The effect of task duration on psychophysically-determined maximum acceptable weights and forces. *Ergonomics.* 33:187-200, 1990.

40. Commissaris, D. A. and H. M. Toussaint. Dissociated oxygen uptake response to an incremental intermittent repetitive lifting and lowering exercise in humans. *Eur J Appl Physiol Occup Physiol.* 74:264-273, 1996.

41. Cooper, R. G., W. S. C. Forbes, and M. Jayson. Radiographic demonstration of paraspinal muscle wasting in patients with chronic low back pain. *Br J Rheum.* 31:389-394, 1992.

42. Costill, D. L., H. Thomason, and E. Roberts. Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports.* 5:248-252, 1973.

43. Cresswell, A. G. and A. Thorstensson. Changes in intra-abdominal pressure, trunk muscle activation and force during isokinetic lifting and lowering. *Eur J Appl Physiol.* 68:315-321, 1994.

44. De Blasi, R. A., M. Ferrari, A. Natali, G. Conti, A. Mega, and A. Gasparetto. Noninvasive measurement of forearm blood flow and oxygen consumption by near-infrared spectroscopy. *J Appl Physiol.* 76:1388-1393, 1994.

45. de Looze, M. P., H. M. Toussaint, D. A. Commissaris, M. P. Jans, and A. J. Sargeant. Relationships between energy expenditure and positive and negative mechanical work in repetitive lifting and lowering. *J Appl Physiol.* 77:420-426., 1994.

46. Dedering, A., G. Nemeth, and K. Harms-Ringdahl. Correlation between electromyographic spectral changes and subjective assessment of lumbar muscle fatigue in subjects without pain from the lower back. *Clin Biomech (Bristol, Avon).* 14:103-111., 1999.

47. Dieen, J. H., H. H. E. O. Vrielink, and H. M. Toussaint. An investigation into the relevance of the pattern of temporal activation with respect to erector spinal muscle endurance. *Eur J Appl Physiol Occup Physiol.* 66:70-75, 1993.

48. Dolan, P. and M. A. Adams. Repetitive lifting tasks fatigue the back muscles and increase the bending moment acting on the lumbar spine. *J Biomech.* 31:713-721, 1998.

49. Edwards, A. D., C. Richardson, P. Van der Zee , C. Elwell, J. S. Wyatt, M. Cope, D. T. Delpy, and E. O. R. Renynolds. Measurement of Hb flow and blood flow by NIRS. *J Appl Physiol.* 75:1884-1889, 1993.

50. Faina, M., V. Billat, R. Squadrone, M. De Angelis, J. P. Koralsztein, and A. Dal Monte. Anaerobic contribution to the time to exhaustion at the minimal exercise intensity at which maximal oxygen uptake occurs in elite cyclists, kayakists and swimmers. *Eur J Appl Physiol Occup Physiol.* 76:13-20, 1997.

51. Faulkner, R. A., E. J. Sprigings, A. McQuarrie, and R. D. Bell. A partial curl-up protocol for adults based on an analysis of two procedures. *Can J Sport Sci.* 14:135-141., 1989.

52. Ferrari, M., T. Binzoni, and T. Quaresima. Oxidative metabolism in muscle philosophical transactions of the Royal Society of London. *Biological Sci.* 352:677-683, 1997.

53. Fitts, R. H. Cellular Mechanisms of Muscle Fatigue. *Physiological Reviews.* 71:49-93, 1994.

54. Foster, C., K.W. Rundell, A.C. Snyder, J. Stray-Gundersen, G. Kemkers, N. Thometz J. Broker, E. Knapp. Evidence for restricted muscle blood flow during speed skating. *Med Sci Sports Exerc.* 31:1433-1440, 1999.

55. Fox, E., R. Bowers, and M. Foss. *The Physiological Basis for Exercise and Sport.* Fifth ed. ed. Madison: WCB Brown & Benchmark, 1993

56. Germain, P., A. Guell, and J. F. Marini. Muscle strength during bedrest with and without muscle exercise as a countermeasure. *Eur J Appl Physiol Occup Physiol.* 71:342-348, 1995.

57. Grassi, B., V. Quaresima, C. Marconi, M. Ferrari, and P. Cerretelli. Blood lactate accumulation and muscle deoxygenation during incremental exercise. *J Appl Physiol.* 87:348-355., 1999.

58. Griffin, A. B. and J. D. G. Troup. Tests of lifting and handling capacity, their repeatability and relationship to back symptoms. *Ergonomics.* 27:305-320, 1984.

59. Hagen, K. B., J. Hallen, and K. Harms-Ringdahl. Physiological and subjective responses to maximal repetitive lifting employing stoop and squat technique. *Eur J Appl Physiol Occup Physiol.* 67:291-297, 1993.

60. Halpern, M. Prevention of low back pain: basic ergonomics in the workplace and the clinic. *Clin Rheum.* 6:706-730, 1992.

61. Hamaoka, T., T. Katsumura, N. Murase, S. Nishio, T. Osada, T. Sako, H. Higuchi, Y. Kurosawa, and T. Shimomitsu. Quantification of ischemic muscle deoxygenation by near infrared time-resolved spectroscopy. *J Biomed Opt.* 5:102-105, 2000.

62. Heliovaara, M. Body height, obesity, and risk of herniated lumbar intervertebral disc. *Spine.* 12:469-472, 1987.

63. Hemborg, B. and U. Moritz. Intra-abdominal pressure and trunk muscle activity during lifting. II. Chronic low-back patients. *Scand J Rehabil Med.* 17:5-13, 1985.

64. Hepple, R. T., S. L. Mackinnon, J. M. Goodman, S. G. Thomas, and M. J. Plyley. Resistance and aerobic training in older men: effects on VO2peak and the capillary supply to skeletal muscle. *J Appl Physiol.* 82:1305-1310, 1997.

65. Hicks, A., S. M. McGill, and R. L. Hughson. Tissue Oxygenation by Near-Infrared Spectroscopy and Muscle Blood Flow During Isometric Contractions of the Forearm. *Can J Appl Physiol.* 24:216-230, 1999.

66. Hiroyuki, H., T. Hamaoka, T. Sako, S. Nishio, R. Kime, M. Murakami, and T. Katsumura. Oxygenation in vastus lateralis and lateral head of gastrocnemius during treadmill walking and running in humans. *Eur J Appl Physiol.* 87:343-349, 2002.

67. Hölmstrom, E., U. Moritz, and M. Andersson. Trunk muscle strength and back muscle endurance in construction workers with and without low back disorders. *Scand J Rehab Med.* 24:3-10, 1992.

68. Hortobagyi, T., J. A. Houmard, J. R. Stevenson, D. D. Fraser, R. A. Johns, and R. G. Israel. The effects of detraining on power athletes. *Med. Sci. Sports Exerc.* 25:929-935, 1993.

69. Hui, S. S. and P. Y. Yuen. Validity of the modified back-saver sit-and-reach test: a comparison with other protocols. *Med Sci Sports Exerc.* 32:1655-1659, 2000.

70. Humphreys, P. W. and A. R. Lind. The blood flow through active and inactive muscles of the forearm during sustained handgrip contractions. *J Physiol.* 166:120-135, 1962.

71. Im, J., S. Nioka, B. Chance, and K. W. Rundell. Muscle oxygen desaturation is related to whole body VO2 during cross-country ski skating. *Int J Sports Med.* 22:356-360, 2001.

72. Ingjer, F. Capillary supply and mitochondrial content of different skeletal muscle fiber types in untrained and endurance-trained men. A histochemical and ultrastructural study. *Eur J Appl Physiol.* 40:197-209, 1979.

73. Ito, T., O. Shirado, H. Suzuki, M. Takahashi, K. Kaneda, and T. E. Strax. Lumbar trunk muscle endurance testing: an inexpensive alternative to a machine for evaluation. *Arch Phys Med Rehabil.* 77:75-79, 1996.

74. Jensen, B. R., K. Jorgensen, A. R. Hargens, P. K. Nielsen, and T. Nicolaisen. Physiological response to submaximal isometric contractions of the paravertebral muscles. *Spine.* 24:2332-2338, 1999.

75. Jørgensen, K. Human trunk extensor muscles physiology and ergonomics. *Acta Physiol Scand.* 160:5-58, 1997.

76. Jørgensen, K. and T. Nicolaisen. Trunk extensor endurance: determination and relation to low-back trouble. *Ergonomics.* 30:259-267, 1987.

77. Kankaanpaa, M., D. Laaksonen, S. Taimela, S. M. Kokko, O. Airaksinen, and O. Hanninen. Age, sex, and body mass index as determinants of back and hip extensor fatigue in the isometric Sorensen back endurance test. *Arch Phys Med Rehabil.* 79:1069-1075., 1998.

78. Kankaanpaa, M., S. Taimela, D. Laaksonen, O. Hanninen, and O. Airaksinen. Back and hip extensor fatigability in chronic low back pain patients and controls. *Arch Phys Med Rehabil.* 79:412-417., 1998.

79. Kauppila, L. I. Blood supply of the lower thoracic and lumbosacral regions. Postmortem aortography in 38 young adults. *Acta Radiol.* 35:541-544, 1994.

80. Kauppila, L. I. Can low-back pain be due to lumbar-artery disease? *Lancet.* 346:888-889, 1995.

81. Kauppila, L. I. Low back pain. Consider compromised blood supply. *Bmj.* 306:1267, 1993.

82. Kauppila, L. I. Prevalence of stenotic changes in arteries supplying the lumbar spine. A postmortem angiographic study on 140 subjects. *Ann Rheum Dis.* 56:591-595, 1997.

83. Kauppila, L. I. Studying low back pain (LBP). *Spine.* 21:527, 1996.

84. Kauppila, L. I. and K. Tallroth. Postmortem angiographic findings for arteries supplying the lumbar spine: their relationship to low-back symptoms. *J Spinal Disord.* 6:124-129, 1993.

85. Kawaguchi, K., M. Tabusadani, K. Sekikawa, Y. Hayashi, and K. Onari. Do the kinetics of peripheral muscle oxygenation reflect systemic oxygen intake? *Eur J Appl Physiol.* 84:158-161, 2001.

86. Kell, R. T. and Y. Bhambhani. Cardiorespiratory & Hemodynamic Responses during Repetitive Incremental Lifting & Lowering in Healthy Males & Females. *Eur J Appl Physiol.* 90:1-9, 2003.

87. Kell, R. T., M. Farag, and Y. Bhambhani. Relationship between Erector Spinae Hemodynamics and Static Back Endurance in Healthy Males Edmonton, 2002, pp. 1-22 (unpublished).

88. Kell, R. T., M. Farag, and Y. Bhambhani. Reliability of erector spinae oxygenation and blood volume responses using near-infrared spectroscopy in healthy males. *Eur J Appl Physiol.* 91:499-507, 2004.

89. Keller, A., J. Hellesnes, and I. B. a. a. Jens. Reliability of the Isokinetic Trunk Extensor Test, Biering-Sorensen Test, and Astrand Bicycle Test: Assessment of Intraclass Correlation Coefficient and Critical Difference in Patients With Chronic Low Back Pain and Healthy Individuals. *Spine.* 26:771-777., 2001.

90. Keppel, G. *Design and Analysis: A Researcher's Handbook.* New Jersey: Prentice-Hall, INC., 1973

91. Kishino, N. D., T. G. Mayer, R. J. Gatchel, M. M. Parrish, C. Anderson, L. Gustin, and V. Mooney. Quantification of lumbar function. Part 4: Isometric and isokinetic lifting simulation in normal subjects and low-back dysfunction patients. *Spine.* 10:921-927., 1985.

92. Klausen, K., L. B. Andersen, and I. Pelle. Adaptive changes in work capacity, skeletal muscle capillarization and enzyme levels during training and detraining. *Acta Physiol Scand.* 113:9-16, 1981.

93. Kovacs, K. M., W. S. Marras, A. S. Litsk, P. Gupta, and S. A. Ferguson. Localized oxygen use of healthy and low back pain individuals during controlled trunk movements. *J Spinal Disord.* 14:150-158, 2001.

94. Kunimune, Y., Y. Harada, Y. Kabuto, K. Takeuchi, M. Senda, and H. Inoue. Recovery from exercise-induced desaturation in the paraspinal muscles in idiopathic scoliosis. *Spine.* 24:2019-2024, 1999.

95. Latimer, J., C. G. Maher, K. Refshauge, and I. Colaco. The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. *Spine*. 24:2085-2089; discussion 2090., 1999.

96. Lee, J. H., Y. Ooi, and K. Nakamura. Measurement of muscle strength of the trunk and the lower extremities in subjects with history of low back pain. *Spine*. 20:1994-1996., 1995.

97. Legg, A. J. Maximum acceptable repetitive lifting workloads for an 8-hour work-day using psychological and subjective rating methods. *Ergonomics*. 24:907-916, 1981.

98. Legg, A. J. and C. M. Pateman. A physiological study of the repetitive lifting capabilities of healthy young males. *Ergonomics*. 27:259-272, 1984.

99. Lentini, A. C., R. S. McKelvie, N. McCartney, C. W. Tomlinson, and J. D. MacDougall. Left ventricular response in healthy young men during heavy-intensity weight-lifting exercise. *J Appl Physiol*. 75:2703-2710, 1993.

100. Loat, C. E. and E. C. Rhodes. Relationship between the lactate and ventilatory thresholds during prolonged exercise. *Sports Med*. 15:104-115, 1993.

101. MacDonald, M. J., M. A. Tarnopolsky, H. J. Green, and R. L. Hughson. Comparison of femoral blood gases and muscle near-infrared spectroscopy at exercise onset in humans. *J Appl Physiol*. 86:687-693, 1999.

102. Maikala, R. and Y. Bhambhani. Low-back muscle oxygenation trends during simple postural variations-intersession reliability using near infra-red spectroscopy. In *IEA2000/HFES Congress*, pp. 5-9 to 9-12, 2000.

103. Maikala, R. and Y. Bhambhani. Muscle oxygenation trends using near-infrared spectroscopy (NIRS). In *CD-ROM Proceedings of CybErg: The Second International Cyberspace Conference on Ergonomics*: The International Ergonomics Association Press, pp. 542-557, 1999.

104. Mancini, D., L. Bolinger, L. Li, K. Kendrick, B. Chance, and J. Wilson. Validation of near-infrared spectroscopy in humans. *J Appl Physiol.* 77:2740-2745, 1994.

105. Mannion, A. F., B. Connolly, K. Wood, and P. Dolan. The use of surface EMG power spectral analysis in the evaluation of back muscle function. *J Rehabil Res Dev.* 34:427-439, 1997.

106. Mannion, A. F. and P. Dolan. Electromyographic median frequency changes during isometric contraction of the back extensors to fatigue. *Spine.* 19:1223-1229, 1994.

107. Mannion, A. F., G. A. Dumas, R. G. Cooper, F. J. Espinosa, M. W. Faris, and J. M. Stevenson. Muscle fibre size and type distribution in thoracic and lumbar regions of erector spinae in healthy subjects without low back pain: normal values and sex differences. *J Anat.* 190 (Pt 4):505-513, 1997.

108. Mannion, A. F., G. A. Dumas, J. M. Stevenson, and R. G. Cooper. The influence of muscle fiber size and type distribution on electromyographic measures of back muscle fatigability. *Spine.* 23:576-584., 1998.

109. Mannion, A. F., L. Kaser, E. Weber, A. Rhyner, J. Dvorak, and M. Muntener. Influence of age and duration of symptoms on fibre type distribution and size of the back muscles in chronic low back pain patients. *Eur Spine J.* 9:273-281, 2000.

110. Mannion, A. F., M. Meier, D. Grob, and M. Muntener. Paraspinal muscle fibre type alterations associated with scoliosis: an old problem revisited with new evidence. *Eur Spine J.* 7:289-293, 1998.

111. Mannion, A. F., B. R. Weber, J. Dvorak, D. Grob, and M. Muntener. Fibre type characteristics of the lumbar paraspinal muscles in normal healthy subjects and in patients with low back pain. *J Orthop Res.* 15:881-887, 1997.

112. Maronitis, A. B., K. M. Kovacs, R. E. Splittstoesser, and W. S. Marras. The effectiveness of whole body localized measures of fatigue. In *HFES*: Proceedings of the IEA, pp. 5-91-95-94, 2000.

113. Marras, W. S. and K. P. Granata. Changes in trunk dynamics and spine loading during repeated trunk exertions. *Spine.* 22:2564-2570., 1997.

114. Matthijsse, P., P. Hendrich, W. Rijnsburger, R. Woittiez, and P. Huijing. Ankle angle effects on endurance time, median frequency and mean power of gastrocnemius EMG power spectrum: a comparison between individual and group analysis. *Ergonomics.* 30:1149-1159, 1987.

115. May, A. G., L. V. DeBerg, J. A. DeWeese, and C. G. Rob. Critical arterial stenosis. *Surgery.* 54:250-253, 1963.

116. Mayer, T., R. Gatchel, J. Betancur, and B. Elizabeth. Trunk muscle endurance measurement. *Spine.* 20:920-927, 1995.

117. Mayer, T., G. Kondraske, V. Mooney, T. W. Carmicheal, and R. Butsch. Lumbar myoelectric spectral analysis for endurance assessment. *Spine.* 14:986-991, 1989.

118. McGill, S. M., R. L. Hughson, and K. Parks. Lumbar erector spinae oxygenation during prolonged contractions: implications for prolonged work. *Ergonomics*. 43:486-493., 2000.

119. McNeill, T., D. Warwick, G. Andersson, and A. Schultz. Trunk strength in attempted flexion, extension and lateral bending in healthy subjects and patients with low back disorders. *Spine*. 5:529-538, 1980.

120. Miller, S. A., T. Mayer, R. Cox, and R. J. Gatchel. Reliability problems associated with the modified Schober technique for true lumbar flexion measurement. *Spine*. 17:345-348, 1992.

121. Mital, A. Comprehensive maximum acceptable weight of lift database for regular 8-hour work shifts. *Ergonomics*. 27:1127-1138, 1984.

122. Mital, A. The psychophysical approach in manual lifting--a verification study. *Hum Factors*. 25:485-491., 1983.

123. Mital, A. Psychophysical capacity of industrial workers for lifting symmetrical and asymmetrical loads symmetrically and asymmetrically for 8 h work shifts. *Ergonomics*. 35:745-754., 1992.

124. Miyake, M., Y. Harada, M. Senda, K. Oda, and H. Inoue. Oxygen dynamics at paraspinal muscles during exertion using near-infrared spectroscopy in patients with degenerative lumbar scoliosis. *J Orthop Sci*. 81:187-191, 2003.

125. Moffroid, M. T. Endurance of trunk muscles in persons with chronic low back pain: Assessment, performance, training. *J Rehabil Res Dev*. 34:440-447, 1997.

126. Moffroid, M. T., S. Reid, S. M. Henry, L. D. Haugh, and A. Ricamato. Some endurance measures in persons with chronic low back pain. *Journal of Orthopaedics and Sports Physical Therapy*. 20:81-87, 1994.

127. Mujika, I. and S. Padilla. Muscular characteristics of detraining in humans. *Med Sci Sports Exerc*. 33:1297-1303, 2001.

128. National Technical information Service. *Scientific Support Documentation for the revised 1991 NIOSH Lifting Equation.* Springfield, VA: US Department of Commerce, Publication PB91-226274, 1991.

129. Newton, M., M. Thow, and D. Somerville. Trunk strength testing with isomachines: Part 2. Experimental evaluation of the Cybex II back testing system in normal subjects and patients with chronic low back pain. *Spine*. 18:812-824, 1993.

130. Nicolaisen, T. and K. Jorgensen. Trunk strength, back muscle endurance and low-back trouble. *Scand J Rehab Med.* 17:121-127, 1985.

131. Nindl, B. C., M. A. Sharp, R. P. Mello, V. J. Rice, M. M. Murphy, and J. F. Patton. Gender comparison of peak oxygen uptake: repetitive box lifting versus treadmill running. *Eur J Appl Physiol Occup Physiol.* 77:112-117, 1998.

132. Pandolf, K. B., D. S. Billings, L. L. Drolet, N. A. Pimental, and M. N. Sawka. Differential ratings of perceived exertion and various physiological responses during prolonged upper and lower body exercise. *Eur J Appl Physiol Occup Physiol.* 53:5-11, 1984.

133. Payne, N., N. Gledhill, P. T. Katzmarzyk, and V. Jamnik. Health-related fitness, physical activity and history of back pain. *Can J Appl Physiol.* 24:236-249, 2000.

134. Perez-Landaluce, J., B. Fernandez-Garcia, M. Rodriguez-Alonso, F. Garcia-Herrero, P. Garcia-Zapico, A. M. Patterson, and N. Terrados. Physiological differences and rating of perceived exertion (RPE) in professional, amateur and young cyclists. *J Sports Med Phys Fitness*. 42:389-395, 2002.

135. Petrofsky, J. S. and A. R. Lind. Comparison of metabolic and ventilatory responses of men to various lifting tasks and bicycle ergometry. *J Appl Physiol.* 45:60-63, 1978.

136. Petrofsky, J. S. and A. R. Lind. Metabolic, cardiovascular, and respiratory factors in the development of fatigue in lifting tasks. *J Appl Physiol.* 45:64-68., 1978.

137. Piantadosi, C. A. Absorption spectroscopy for assessment of mitochondrial function in vivo. In: *Methods in Toxicology*: Academic Press, 1993, pp. 107-126.

138. Piantadosi, C. A., T. M. Hemstreet, and F. F. Jobsis-Vandervliet. Near-infrared spectrophotometric monitoring of oxygen distribution to intact brain and skeletal muscle tissues. *Crit Care Med.* 14:698-706, 1986.

139. Plowman, S. A. and D. L. Smith. *Exercise Physiology for Health, Fitness, and Performance*. Boston: Allyn and Bacon, 1997

140. Pope, M. H. Risk indicators in low back pain. *Ann Med.* 21:387-392., 1989.

141. Pope, M. H., D. G. Wilder, I. A. Stokes, and J. W. Frymoyer. Biomechanical testing as an aid to decision making in low-back pain patients. *Spine*. 4:135-140., 1979.

142. Potvin, J. R., R. W. Norman, and S. M. McGill. Mechanically corrected EMG for the continuous estimation of erector spinae muscle loading during repetitive lifting. *Eur J Appl Physiol Occup Physiol.* 74:119-132, 1996.

143. Pripstein, L. P., E. C. Rhodes, D. C. McKenzie, and K. D. Coutts. Aerobic and anaerobic energy during a 2-km race simulation in female rowers. *Eur J Appl Physiol Occup Physiol.* 79:491-494., 1999.

144. Quaresima, V., W. N. Colier, M. van der Sluijs, and M. Ferrari. Nonuniform quadriceps O2 consumption revealed by near infrared multipoint measurements. *Biochem Biophys Res Commun.* 285:1034-1039, 2001.

145. Quaresima, V., A. Pizzi, A. DeBlasi, A. Ferrari, and M. Ferrari. Influence of the treadmill speed/slope on quadriceps oxygenation during dynamic exercise. *Adv. Exp. Med. Biol.* 388:231-235, 1996.

146. Revuelta, N., A. Dauphin, O. Kowslowski, D. Dubois, and A. Thevenon. Heart rate response to two lifting techniques. *Arch Phys Med Rehabil.* 81:958-959., 2000.

147. Rittweger, J., H. Schiessl, and D. Felsenberg. Oxygen uptake during whole-body vibration exercise: comparison with squatting as a slow voluntary movement. *Eur J Appl Physiol.* 86:169-173, 2001.

148. Roy, S. H., P. Bonato, and M. Knaflitz. EMG assessment of back muscle function during cyclical lifting. *J Electromyogr Kinesiol.* 8:233-245., 1998.

149. Roy, S. H., C. J. De Luca, and D. A. Casavant. Lumbar muscle fatigue and chronic lower back pain. *Spine.* 14:992-1001., 1989.

150. Rundell, K., S. Nioka, and B. Chance. Hemoglobin/myoglobin desaturation during speed skating. *Med Sci Sports Exer.* 29:248-258, 1997.

151. Sako, T., T. Hamaoka, H. Higuchi, Y. Kurosawa, and T. Katsumura. Validity of NIR specroscopy for quantitatively measuring muscle oxidative metabolic rate in exercise. *J Appl Physiol.* 90:338-344, 2001.

152. Schulman, S. P., J. L. Fleg, A. P. Goldberg, J. Busby-Whitehead, J. M. Hagberg, F. C. O'Connor, G. Gerstenblith, L. C. Becker, L. I. Katzel, L. E. Lakatta, and E. G. Lakatta. Continuum of cardiovascular performance across a broad range of fitness levels in healthy older men. *Circulation.* 94:359-367, 1996.

153. Scott, C. B. and G. M. Bogdanffy. Aerobic and anaerobic energy expenditure during exhaustive ramp exercise. *Int J Sports Med.* 19:277-280., 1998.

154. Sharp, M. A., E. Harman, J. A. Vogol, J. J. Knapik, and S. J. Legg. Maximal aerobic capacity for repetitive lifting: comparison with three standard exercise tests and modes. *Eur J Appl Physiol Occup Physiol.* 57:753-760, 1988.

155. Sigaudo, D., J. O. Fortrat, A. Maillet, A. M. Allevard, A. Pavy-Le Traon, R. L. Hughson, A. Guell, C. Gharib, and G. Gauquelin. Comparison of a 4-day confinement and head-down tilt on endocrine response and cardiovascular variability in humans. *Eur J Appl Physiol Occup Physiol.* 73:28-37, 1996.

156. Simonson, S. G. and C. A. Piantadosi. Near-infrared spectroscopy: clinical applications. *Crit Care Clin.* 12:1019-1029, 1996.

157. Sjogaard, G. Muscle energy metabolism and electrolyte shifts during low-level prolonged static contraction in man. *Acta Physiol Scand.* 134:181-187., 1988.

158. Sjogaard, G., G. Savard, and C. Juel. Muscle blood flow during isometric activity and its relation to muscle fatigue. *Eur J Appl Physiol.* 57:327-335, 1988.

159. Smidt, G. L. and P. R. Blanpied. Analysis of strength tests and resistive exercises commonly used for low-back disorders. *Spine*. 12:1025-1031, 1987.

160. Snook, S. H. The design of manual handling tasks. *Ergonomics*. 21:963-985., 1978.

161. Snook, S. H. Future directions of psychophysical studies. *Scand J Work Environ Health*. 25:13-18., 1999.

162. Snook, S. H. and V. M. Ciriello. The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics*. 34:1197-1213, 1991.

163. Snook, S. H. and V. M. Ciriello. Maximal weights and work loads acceptable to female workers. *J Occup Med*. 16:527-534, 1974.

164. Snook, S. H. and C. H. Irvine. Psychophysical studies of the physiological fatigue criteria. *Hum Fac*. 11:291-300, 1969.

165. Snook, S. H., C. H. Irvine, and S. F. Bass. Maximum weights and work loads acceptable to male industrial workers. *Am Ind Hyg Assoc J*. 31:579-586, 1970.

166. Soares, J. M. Effects of training on muscle capillary pattern: intermittent vs continuous exercise. *J Sports Med Phys Fitness*. 32:123-127, 1992.

167. Sparto, P. J., M. Parnianpour, T. E. Reinsel, and S. Simon. The effect of fatigue on multijoint kinematics and load sharing during a repetitive lifting test. *Spine*. 22:2647-2654., 1997.

168. Stegmann, H. and W. Kindermann. Comparison of prolonged exercise tests at the individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol.l(-1) lactate. *Int J Sports Med*. 3:105-110, 1982.

169. Stevenson, J. M., C. L. Weber, J. T. Smith, G. A. Dumas, and W. J. Albert. A longitudinal study of the development of low back pain in an industrial population. *Spine.* 26:1370-1377, 2001.

170. Suni, J. H., P. Oja, S. I. Miilunpalo, M. E. Pasanen, I. M. Vuori, and K. Bos. Health-related fitness test battery for adults: associations with perceived health, mobility, and back function and symptoms. *Arch Phys Med Rehabil.* 79:559-569., 1998.

171. Suter, E., H. Hoppeler, H. Claassen, R. Billeter, U. Aebi, F. Horber, P. Jaeger, and B. Marti. Ultrastructural modification of human skeletal muscle tissue with 6-month moderate-intensity exercise training. *Int J Sports Med.* 16:160-166, 1995.

172. Suzuki, N. and S. Endo. A quantitative study of trunk muscle strength and fatigability in the low-back-pain syndrome. *Spine.* 8:69-74., 1983.

173. Thompson, D. A. Sensitivity of paraspinal EMG spectral analysis to training: two preliminary studies. *Thesis.* Queens, Kingston, 1992.

174. Tran, T., N. Sailasta, U. Kreutzer, R. Hurd, Y. Chung, P. Mole, S. Kumo, and T. Jue. Comparative analysis of NMR and NIRS measurements of intracellular PO2 in human skeletal muscle. *Am. J. Physiol.* 276:R1682-R1690, 1999.

175. Troup, J. D., T. K. Foreman, C. E. Baxter, and D. Brown. 1987 Volvo award in clinical sciences. The perception of back pain and the role of psychophysical tests of lifting capacity. *Spine.* 12:645-657., 1987.

176. Videman, T. and M. C. Batti'e. A critical review of the epidemiology of idiopathic low back pain. In: *Low Back Pain: A scientific and clinical overview.* J. N.

Weinstein and S. L. Gordon (Eds.) Rosemont: American Academy of Orthopaedic Surgeons, 1996, pp. 317-332.

177. Wasserman, K., J. E. Hansen, D. Y. Sue, B. J. Whipp, and R. Casaburi. *Physiology of exercise. Principles of exercise testing and interpretation.* 2nd ed. Malvern, PA: Lea & Febiger, 1994

178. Waters, T. R., V. Putz-Anderson, and S. Baron. Methods for assessing the physical demands of manual lifting: a review and case study from warehousing. *Am Ind Hyg Assoc J.* 59:871-881, 1998.

179. Waters, T. R., V. Putz-Anderson, A. Garg, and L. J. Fine. Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics.* 36:749-776., 1993.

180. Wenger, H. A. and A. T. Reed. Metabolic factors associated with muscular fatigue during aerobic and anaerobic work. *Can J Appl Physiol.* 1:43-48, 1976.

181. Williams, C. A., J. S. Petrofsky, and A. R. Lind. Physiological response of women during lifting exercise. *Eur J Appl Physiol Occup Physiol.* 50:133-144, 1982.

182. Wilson, J., D. Mancini, K. McCully, N. Ferraro, V. Lancoe, and B. Chance. Noninvasive detection of skeletal muscle underperfusion with near-infrared spectroscopy in patients with heart failure. *Circulation.* 80:1668-1674, 1989.

183. Wright, J. R., D. I. McCloskey, and R. C. Fitzpatrick. Effects of muscle perfusion pressure on fatigue and systemic arterial pressure in human subjects. *J Appl Physiol.* 86:845-851., 1999.

184. Yoshitake, Y., H. Ue, M. Miyazaki, and T. Moritani. Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. *Eur J Appl Physiol.* 84:174-179, 2001.

APPENDIX B: *Manuscript published in European Journal of Applied Physiology 2004 91(5-6): 499-507*

Eur J Appl Physiol (2004) 91: 499–507
DOI 10.1007/s00421-003-1014-0

ORIGINAL ARTICLE

Robert T. Kell · Mamdouh Farag · Yagesh Bhambhani

Reliability of erector spinae oxygenation and blood volume responses using near-infrared spectroscopy in healthy males

Accepted: 7 August 2003 / Published online: 14 January 2004

Abstract The purpose of this investigation was to (1) describe the trends in oxygenation (OXY) and blood volume (BV) of the right and left paraspinal muscles during the Biering-Sorensen muscle endurance (BSME) test using near infrared spectroscopy (NIRS), and (2) assess the test-retest reliability of OXY and BV changes during the BSME in healthy males. Seventeen healthy males [age = 28.4 (9.8) years, height = 1.75 (0.05) m, body mass = 82.7 (9.1) kg; mean (SD)] completed two BSME trials within 1 week. NIRS probes were placed bilaterally at lumbar 3. The test was performed with the subject in the prone position using the following protocol: 2 min baseline, BSME, and 4 min recovery. The delta and range values of OXY and BV were used for analysis. Acceptable intra-class correlations were observed for endurance time and all the NIRS variables at the point of fatigue and at each 10% segment of the BSME during the two trials. Bland-Altman plots confirmed the reproducibility of the bilateral NIRS responses of the paravertebral muscles. The BV responses were more reliable than the OXY responses during the two trials. The OXY and BV responses of the paravertebral muscles during static contractions can be measured reliably using NIRS. Future studies should focus primarily on BV for analysis.

Keywords Blood volume · Erector spinae · Near infrared spectroscopy · Oxygenation

R. T. Kell (✉)
Faculty of Kinesiology and Health Studies,
University of Regina, Regina, SK, Canada, S4S 0A2
E-mail: robert.kell@uregina.ca
Tel.: +1-306-5854362
Fax: +1-306-5854854

M. Farag · Y. Bhambhani
Faculty of Rehabilitation Medicine, University of Alberta,
Edmonton, Alberta, T6G 2G4, Canada

Introduction

A common clinical tool for assessment of erector spinae muscle endurance, which is related to low back health, is the Biering-Sorensen test of static muscular endurance (BSME) (Alaranta et al. 1994; Biering-Sorensen 1983, 1984a, 1984b; Jørgensen and Nicolaisen 1987; Latimer et al. 1999; Mayer et al. 1995; Suni et al. 1998). The benefit of using the BSME as a clinical tool for diagnosis of low back muscular endurance is that it is easily administered, inexpensive, and there is a substantial quantity of compiled data.

Previous investigations have used the BSME as a predictor of low-back health, based on endurance time (Biering-Sorensen 1983, 1984a, 1984b; Smidt and Blandpied 1987). However, muscular endurance time is not considered to be objective, and thus a new method of low-back endurance assessment has been sought for obvious reasons. Electromyography (EMG) has been used during the BSME to examine patterns of fatigue in the lumbar musculature, and is considered to be more objective than basic endurance time, as it is not influenced by motivational factors. The reliability of this technique has been documented over both short-and long-term time intervals (Biedermann et al. 1990).

Near infrared spectroscopy (NIRS) is a non-invasive optical technique that has been used to evaluate the relative change in oxygenation (OXY) and blood volume (BV) of the working skeletal muscle located directly beneath the probe. NIRS has been employed during both during static and dynamic contraction and is based on the differential absorption properties of hemoglobin/myoglobin (Hb/Mb) in the near infrared range of 700–1,000 nm. At 760 nm, these chromophores (light-absorbing compounds) are in the deoxygenated form, whereas at 850 nm they occur in the oxygenated state. Hence, by monitoring changes in the tissue absorbency between these two wavelengths, the relative difference in muscle OXY can be obtained. The sum of the absorbency signals at these two wavelengths

indicates the relative change in BV, assuming a constant hematocrit (Chance et al. 1992; Mancini et al. 1994). Hence, the trends observed in OXY and BV are considered to be relative changes occurring at the level of the small blood vessels (arterioles, capillaries and venules) from a reference point during the test (Mancini et al. 1994).

Several recent studies (Jensen et al. 1999; McGill et al. 2000; Yoshitake et al. 2001) have used continuous wave NIRS to examine the trends in erector spinae OXY and BV during isometric contractions of the back. The evidence from these studies suggests that NIRS can be used to objectively evaluate low-back muscular endurance and fatigue. The rationale behind the application of NIRS to low back muscle endurance is that localized blood flow is known to play a prominent role in the termination of muscle contraction due to fatigue (Sjogaard et al. 1988; Yoshitake et al. 2001). Two reasons why fatigue is accelerated during a sustained isometric muscle contraction are: (1) increased intramuscular pressure (IMP) is linked with blood flow restriction to the working muscles (Barnes 1980; Bonde-Petersen et al. 1975), and (2) the metabolic rate of the working muscle is accelerated. A greater intensity of muscular contraction will result in an increased accumulation of fatigue associated byproducts (e.g., hydrogen ions) due to the augmented metabolic rate, and a greater need for oxygen to sustain the muscle contraction (Fitts 1994; Sjogaard et al. 1988; Wenger and Reed 1976). The result of these two circumstances is further exasperated by the recruitment of fast fatiguing motor units as the duration of the contraction increases, thus increasing the rate of hydrogen ion accumulation and onset of fatigue (Fitts 1994).

The BSME is considered to elicit a muscular contraction of 20–75% of maximal volitional contraction (MVC) (Jørgensen and Nicolaisen 1986; Mannion and Dolan 1994; Smidt and Blanpied 1987) which is influenced by body type and conditioning level of the subjects (Jørgensen and Nicolaisen 1986). Muscular contraction between 20% and 75% of MVC should reduce or occlude erector spinae muscle blood flow (Humphreys and Lind 1962; Jørgensen 1997). Since NIRS provides continuous non-invasive measurement of OXY and BV changes in the microcirculation (Mancini et al. 1994), and the spatial resolution of the measurement is sufficient to reflect these changes only in the active musculature (Chance and Bank 1995), the technique is attractive for the evaluation of the metabolic status of the muscle. However, if NIRS is to be an effective technique for evaluating hemodynamic changes in the low back musculature during exercise, its test-retest reliability in different postures must be established. To date, the OXY and BV trends of the erector spinae muscles during back extension in the standing and sitting postures have been examined and the reproducibility of these measurements has been established (Maikala and Bhambhani 2000). The purpose of this investigation was to (1) describe the trends in OXY and BV of the right and left erector spinae muscles during the BSME, and (2) assess the test-retest reliability of OXY and BV changes during the BSME in healthy males.

Methods

Subjects

Seventeen active, healthy male volunteers were recruited from the University of Alberta and surrounding area. The inclusion criteria for subject recruitment were as follows: (1) males between the ages of 18 and 50 years, (2) no previous history of low-back pain, (3) currently asymptomatic for low-back pain, and (4) absence of metabolic, cardiovascular, respiratory and orthopedic disorders. Their physical characteristics were [mean (SD): age = 27.4 (7.74) years, height = 1.75 (0.05) m, weight = 81.8 (11.7) kg, and body mass index (BMI) = 26.8 (4.7)]. All subjects were right-handed males. The subjects met with the researcher individually to discuss the study and provide their written informed consent for participation. Each subject completed two BSMEs to volitional exhaustion within a 1-week period. The Health Research Ethics Board of this institution approved the test procedures described below.

BSME procedures

Upon reporting to the laboratory, the subject's height and weight were recorded using standard procedures. The subject was asked to flex at the waist to allow the researcher to locate the area of the 3rd lumbar vertebra (L3). Previous literature indicates that L3 is frequently used for placing both EMG electrodes (Biedermann et al. 1990; Kankaanpaa et al. 1998; Koumantakis et al. 2001; Moffroid et al. 1993) or NIRS probes (Yoshitake et al. 2001). Pilot testing indicated that placement at L3, approximately 3 cm to the left and right side of the vertebral column, provided a clear NIRS signal which was sensitive to changes during static and dynamic exercise. The two NIRS probes (MicroRunman; NIM, Pa., USA) were then placed bilaterally at the L3 level over the right and left erector spinae muscles on the skin surface. The probes were secured with a tensor bandage around the abdominal region so as to hold the probes in position and block out all background light. Sufficient care was taken not to occlude blood flow to the area under investigation. The subject assumed a prone position on the plinth with the face down, so that the upper half of the body, as discerned by the iliac crest, was at the breakpoint in the plinth. Two straps were lightly fastened around the subject's gluteus maximus and ankles (just superior to the medial and lateral malleoli) for stability during the test. A towel was positioned beneath the ankle straps to reduce the strain on the distal aspect of the tendo calcaneus (Achilles tendon).

The trial was initiated with a 2 min baseline with the subject resting in the prone position on the plinth. An alignment bar whose height could be adjusted was suspended from the ceiling so that it maintained contact with the upper torso while the subject was in the prone (neutral) position. Thereafter, the plinth support to the upper body was removed so as to start the BSME. The subject was asked to maintain the neutral position, as indicated by the alignment bar, by contracting the musculature of the lower back and gluteal regions while folding his arms across the chest throughout the duration of the test. The subject received moderate encouragement during the test but was not informed of the elapsed time. The test was terminated at volitional fatigue or if the subject lost contact with the alignment bar and did not re-establish contact with the bar in 2–3 s following verbal prompting. The time from the onset of the BSME to volitional fatigue was recorded as the endurance time. Thereafter, the subject was allowed to recover for 4 min while lying prone on the plinth. The second trial was completed within 1 week following the same procedures.

NIRS measurements

The NIRS unit (MicroRunman; NIM, Pa., USA) was calibrated prior to each test using the NIRCOM software provided with the instrument. The NIRS unit was calibrated while securely fastened in position over the erector spinae muscles (right and left sides) while the subject lay quietly on the plinth. A moderate penetration depth with the light intensity ranging between 100 mV and 150 mV was applied during calibration and testing. The muscle probe, which had a tungsten light source placed at a distance of 4 cm from the silicone diodes, absorbed the reflected light at 760 nm and 850 nm. The penetration depth was 60% of the optode spacing, which is the physical distance between the light source and sensor, roughly 2–2.5 cm. NIRS measurements were undertaken continuously at a frequency of 60 Hz during the baseline, BSME and recovery periods. A piece of clear plastic was placed over the photodetectors on the probe to prevent distortion of the signal due to sweat from the skin surface.

The equation used to calculate the change in optical density (OD) is based on the Modified Beer-Lambert law as follows (Chance et al. 1992; Mancini et al. 1994):

$$\text{Opticaldensity} = a \times c \times d \times B + G$$

where: a is the absorption coefficient of the chromophore (light-absorbing compound), c is the concentration of the chromophore, d is the distance between optodes on the measuring probe, B is the differential path length factor of the tissue, and G is the geometry of the tissue. One of the limitations of continuous wave NIRS is that the differential path length factor cannot be measured due to the scattering of the photons (Obrig and Villringer 1997), and therefore, the changes in concentration of the chromophores cannot be quantified. The values are presented as relative changes in OD, and thus, the trends can be qualitatively compared during exercise.

From the raw NIRS data, the relative change in OXY was calculated as the difference in OD at 760 nm and 850 nm (760–850 nm). The relative change in BV was calculated as the sum (760 nm + 850 nm) of the change in OD at the two wavelengths. Data were averaged over 5 s intervals for each phase of the test. For each subject, the OXY and BV values at the onset of the baseline period were corrected to zero for each trial. Resting OXY and BV values were determined by averaging the data 20 s prior to the start of exercise. The minimum values during the BSME (OXY_{min} and BV_{min}) and the maximum values during recovery (OXY_{max} and BV_{max}) were recorded. The delta values (OXY_{delta} and BV_{delta}) were calculated from the resting baseline minus the minimum or maximum OXY and BV values depending on the direction (increasing or decreasing) of change during exercise. The range for each of these variables was calculated as the difference between the maximum and minimum values (OXY_{ran} and BV_{ran}) throughout the total time period, including baseline, work and recovery. In order to examine the reliability of the NIRS trends during the BSME, the OXY and BV values at the same relative stage of the test (10–100% of the endurance time) were calculated for each subject and statistically analyzed.

Statistical analysis

A dependent t-test was used to compare endurance time and rating of perceived exertion between trials. A two-way repeated measures analysis of variance (trial by side) was used to compare the means of the following NIRS variables: OXY_{delta}, OXY_{ran}, BV_{delta} and BV_{ran}. Significant F ratios were analyzed using a post hoc Scheffé test. The alpha level was set at 0.05 for all statistical tests. Because numerous multiple comparisons were performed, the Bonferroni adjustment for a P value of 0.05 was applied to minimize type I error for each variable (Ottenbacher 1991). Intra-class correlations (ICCs) were used to examine the reliability of the BSME time and the four NIRS variables on the right and left sides. ICCs were also used to evaluate the reliability of the OXY and BV responses at the same relative stage of the BSME for the two trials on both sides. All statistical analyses were performed using SPSS (SPSS for Windows, version 10.0.7, copyright 1989–1999) computer package. In order to further examine the reliability of the measurements, Bland-Altman plots were used to examine the test-retest reliability (limits of agreement) between the two trials for each of these variables. This was done in the following manner: (1) the difference between the two tests for each subject was plotted against their average value of the two trials, and (2) the plots were examined to see if any data points were beyond two standard deviations (95% confidence limits) above and below the mean of the two trials (Bland and Altman 1986).

Results

Muscle OXY and BV trends

The general trends of a representative subject for right and left side erector spinae OXY (850–760 nm) and BV (850 nm + 760 nm) during the two BSME test trials to volitional fatigue are illustrated in Fig. 1A–D, respectively. The endurance times [mean (SD)] for the two trials are listed in Table 1. After a relatively stable baseline value for 2 min, muscle OXY (Fig. 1B, D) demonstrated a rapid increase during the first 30 s of the BSME and then declined from its peak for the remainder of the test. The initial increase in OXY was due to rapid decreases in both the deoxy-Hb/Mb and oxy-Hb/Mb (850 nm) signals. The decline in OXY during the latter portion of the BSME was due to a continuous decline in deoxy-Hb/Mb and a leveling off in the oxy-Hb/Mb signals. Upon termination of the BSME, muscle OXY on the right side increased very rapidly toward the baseline value within 5–10 s and remained fairly stable for the remainder of the 4-min recovery period. In contrast, generally on the left side OXY rapidly declined toward baseline levels. Muscle BV also demonstrated a rapid increase from the resting baseline value at the onset of the BSME for about 30 s. However, BV continued to increase systematically for the remainder of the BSME even though OXY showed a decline during this period. Upon termination of the BSME, BV demonstrated a sharp decline and recovered towards the resting baseline value in a manner similar to muscle OXY.

Although these overall trends were fairly consistent amongst the subjects during the two trials, there were some subtle differences in these patterns during the test. For example, the subject illustrated in Fig. 1 did not demonstrate the rapid increase in OXY on the right side at the onset of the BSME during trial 2. Instead, there was a rapid decrease in OXY during the first 30 s and a subsequent increase for the remainder of the BSME. A comparison of the OXY trend between the right and left sides for this subject indicated that right side OXY declined to a level that was below the baseline value, whereas left-side OXY remained above the baseline value during the latter portion of the BSME.

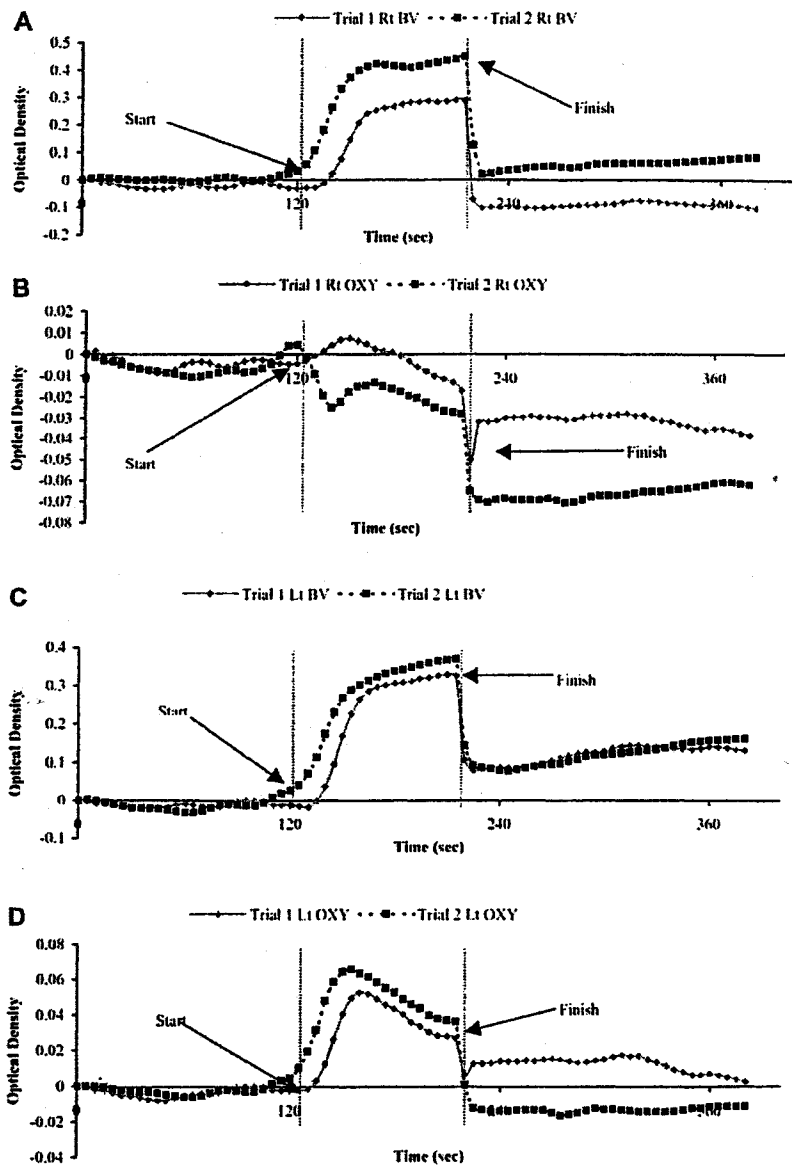


Fig. 1A–D NIRS trends of the right (*Rt*) and left (*Lt*) erector spinae muscles during the three phases of the test protocol in a single typical subject for the two trials: 2 min of baseline, Biering-Sorensen muscle endurance test, and 4 min of recovery

Reliability of muscle OXY and BV measurements

The mean values for the four NIRS variables (OXY_{delta}, OXY_{ran}, BV_{delta} and BV_{ran}) are summarized in Table 1. The *F* ratios for the two-way interactions and main effects of the ANOVA and the ICCs are presented in Table 2. No significant interactions (trial by side) or main effects were observed for each of the four NIRS variables. This implies that there were no significant differences between the two sides or the two trials for the mean values of each of these variables. The lack of significant interaction for each of these variables enabled the calculation of the average ICC for the two trials and two sides. The average ICCs for the NIRS variables ranged from 0.69 to 0.84, indicating a moderate reliability of these measurements between the two trials and sides. The ICC for endurance time was 0.98, indicating strong test-retest reliability.

Table 1 Erector spinae oxygenation and blood volume responses during the Biering-Sorensen muscle endurance test in healthy males ($n=17$). *BV* Blood volume, *OXY* oxygenation

	Side	Trial 1		Trial 2	
		Mean	SD	Mean	SD
Endurance time (s)		140.29	52.28	134.71	47.71
OXY_{delta} (OD units)	Right	0.066	0.054	0.081	0.068
	Left	0.083	0.061	0.096	0.070
OXY_{ran} (OD units)	Right	0.083	0.054	0.107	0.072
	Left	0.103	0.059	0.120	0.069
BV_{delta} (OD units)	Right	0.191	0.117	0.243	0.156
	Left	0.215	0.118	0.216	0.112
BV_{ran} (OD units)	Right	0.239	0.130	0.280	0.139
	Left	0.254	0.101	0.264	0.099

The reproducibility of the OXY and BV range and delta variables during the two test trials according to the methods proposed by Bland and Altman (1995) are presented in Figs. 2 and 3, respectively. According to this method, all the data points should lie within two standard deviations above and below the expected mean difference of the two trials. Since the aim of the study was to examine the test-retest reliability of the NIRS technique, the expected mean difference between the two trials was zero. Examination of the Bland-Altman plots in Figs. 2 and 3 indicates that at 95% confidence there were one to two outliers for the OXY values (delta and range, respectively) and one outlier for the BV values (delta and range). This suggests that there was no systematic error between the two test trials or two sides for each of these NIRS variables.

The reproducibility of the OXY and BV responses at the same relative stage of the BSME during the two trials for the right and left sides is illustrated in Fig. 4. It is evident that the trends were highly reproducible during both trials on either side. The average ICCs for the OXY and BV responses were 0.96 and 0.95, respectively.

Discussion

Muscle OXY and BV trends

The current results indicated that at the onset of the BSME, muscle OXY increased for the first 20–30 s in a majority of the subjects and then demonstrated a systematic decline below the baseline value until a minimum value was attained. In some subjects, there was a leveling off prior to the termination of the test. The changes in OXY during the initial stages of the BSME were accompanied by concomitant increases in BV, which tended to level off with the duration of the contraction. During the recovery phase, both OXY and BV reversed their trends immediately upon cessation of exercise and attained or overshot their resting baseline values during the first minute of recovery. The OXY and BV trends observed in the present study are generally consistent with those reported by other investigators that have used NIRS during static extension of the erector spinae muscles in healthy subjects. McGill et al. (2000) demonstrated that during 30-s contractions ranging between 2% and 30% MVC, there was a decline in muscle OXY which was proportional to the intensity of contraction. Jensen et al. (1999) reported that during 30 s of static back muscle extensions ranging from 5% to 80% of MVC, there was a significant reduction in tissue oxygen saturation (calculated as the ratio between the OXY and BV signals) starting at an intensity of 20% MVC, which corresponded to an IMP of 30–40 mmHg. Moreover, the decrease in tissue oxygen saturation increased with an increasing level of IMP. Neither of these studies cited reported the BV trends during the static contractions. However, Yoshitake et al. (2001) demonstrated a significant reduction in OXY during 60 s of static extension of the erectors spinae muscles, with a concomitant reduction in the BV, a trend which is in contrast to that observed in the present study. The reason for this discrepancy is unclear and needs to be further investigated. It should be noted that in all the studies cited, the investigators predetermined the duration of the erector spinae muscle contraction, whereas in the present study the contractions were sustained to voluntary fatigue.

From a physiological standpoint, we believe that the initial increase in OXY at the onset of exercise is associated with a redistribution of blood to the active motor units and not due to changes in tissue geometry because of the static nature of the contraction. This initial increase in OXY is supported by the localized increase in BV during this period (Fig. 1A, C). The redistribution of blood is controlled both by local tissue factors which

Table 2 *F* ratios and intraclass correlations coefficients (ICCs) between trials and sides for endurance time, muscle OXY and BV during the Biering-Sorensen muscle endurance test measured by near infrared spectroscopy ($n=17$)

Variables	*F* ratio* Trial by side	*F* ratio* Trials	*F* ratio* Sides	ICC
Endurance time (s)		0.106		0.98
OXY_{delta}	0.90	0.446	0.148	0.69[b]
OXY_{ran}	1.70	0.297	0.097	0.75[b]
BV_{delta}	1.21	0.898	0.197	0.84[b]
BV_{ran}	0.66	0.947	0.155	0.82[b]

*None of the *F* ratios were significant at the 0.05 level after applying the Bonferroni correction factor

[b]Average ICC calculated from measurements of two trials on the right and left sides

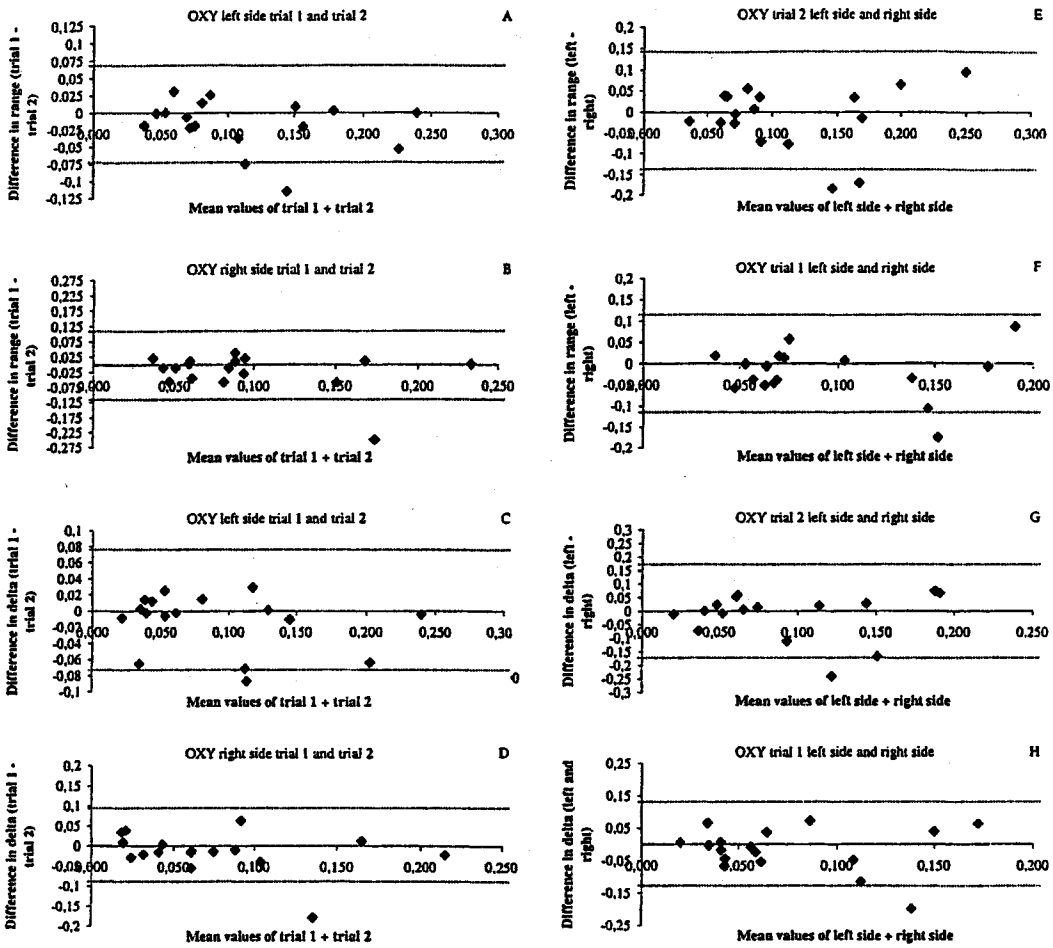


Fig. 2A–H Bland-Altman plots for the absolute sums and differences of the delta and range values in oxygenation between the two trials of the right and left erector spinae muscles during the Biering-Sorensen muscle endurance test. The *dotted lines* indicate two standard deviations above and below the mean value for that variable.

stimulate vasodilation in that area (e.g., nitric oxide, adenosine), and sympathetic neural input to the exercising and non-exercising motor units (Hansen et al. 2000; Marshall 2000; Radegran and Hellsten 2000). Additionally, the increase in BV is likely related to the cardiovascular response associated with static contractions, as noted by an increase in heart rate and blood pressure (Gaffney et al. 1990; Mitchell et al. 1980).

Following the preliminary increase in both BV and OXY, BV plateaus (Fig. 1). The plateau in BV is likely due to IMP equaling intravascular pressure and thus not permitting further vasodilation, at which point OXY begins to decline (Fig. 1). The decline in OXY suggests that oxygen demand in the exercising muscle is greater than oxygen supply (Jensen et al. 1999). Muscle contraction levels of 20% of MVC have demonstrated reduced blood flow in the back extensor muscles (Bonde-Petersen et al. 1975). Since, the BSME elicits a muscular contraction that ranges between 20% and 75% of MVC (Jørgensen and Nicolaisen 1986; Mannion and Dolan 1994; Smidt and Blanpied 1987), it is possible that the decrease in OXY was due to a reduction in BV that is reflected in the NIRS signal (McGill et al. 2000).

Reliability of muscle OXY and BV measurements

In the present study the test-retest ICC for endurance time was 0.98, which is consistent with previous reports on healthy males (Keller et al. 2001; Latimer et al. 1999;

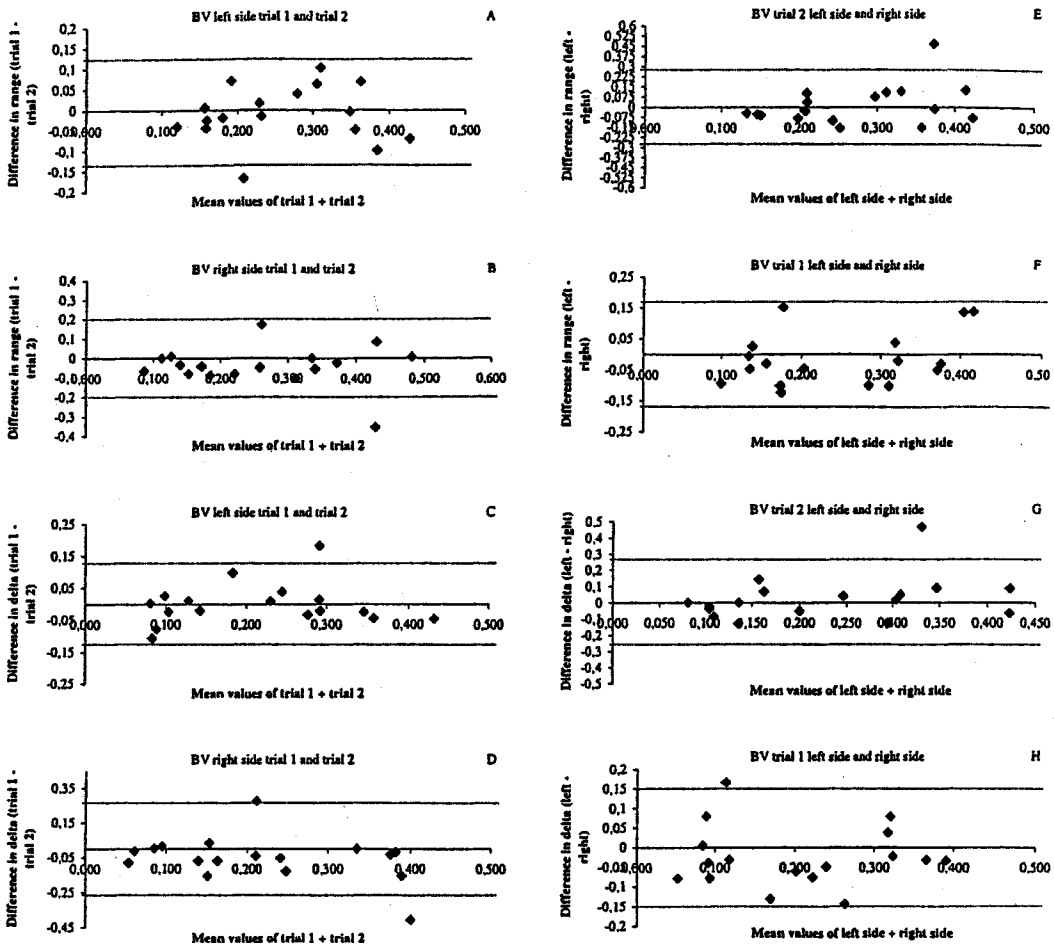


Fig. 3A–H Bland-Altman plots for the absolute sums and differences of the delta and range values in blood volume between the two trials of the right and left erector spinae muscles during the Biering-Sorensen muscle endurance test. The *dotted lines* indicate two standard deviations above and below the mean value for that variable

Moffroid et al. 1994; Moreland et al. 1997). The current results also indicated moderate to high test-retest reliability for the four NIRS variables monitored during the BSME (Table 2). ICCs ≥0.80 are considered to be acceptable, while ICCs ≥0.90 are very strong (Newton et al. 1993). Therefore, the current findings suggest that BV responses during the BSME are more reliable than the OXY responses, and therefore should be the focus of future investigations. Further, of these hemodynamic responses, the delta value is arguably the most important as it measures the amplitude of change from baseline during work, eliminating post-exercise hyperemia. To the best of our knowledge, ICC values for hemodynamic measures of the erector spinae muscle during the BSME have not been published. In related research, Maikala and Bhambhani (2000) reported significant reliability coefficients of 0.83, 0.94, 0.99, and 0.91 for the OXY_{min}, OXY_{ran}, BV_{min} and BV_{ran}, respectively, in healthy males during maximal isometric contractions of the back extensors in the sitting position. Corresponding values in the standing position were 0.84, 0.74, 0.99, and 0.99, respectively.

The reproducibility of these NIRS measurements during the BSME was further supported by the Bland-Altman plots presented in Figs. 2 and 3. As indicated earlier, the BV responses met the reliability criterion, as only one of the 17 data points was an outlier, whereas for the OXY responses one or two outliers were observed. It should be noted that one of these two subjects was an outlier for both the OXY and BV responses. It is also evident from these plots that the OXY responses of

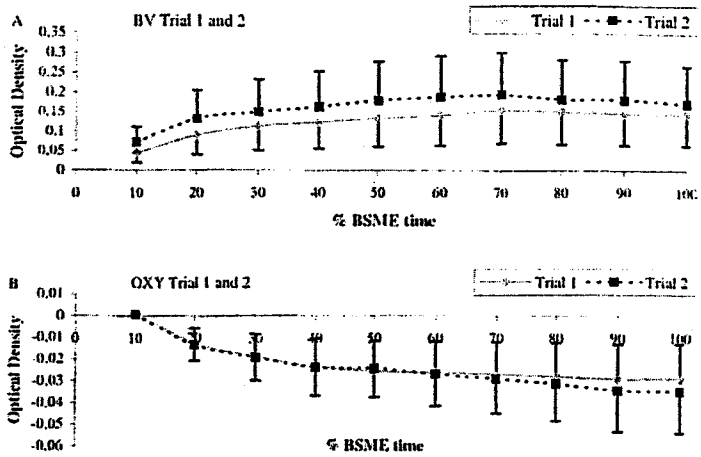


Fig. 4A, B A comparison of the near infrared spectroscopy (NIRS) trends for trials 1 and 2 at the same relative time of the Biering-Sorensen muscle endurance test in the overall group of subjects. The values of the right and left sides were pooled for analysis. The *error bars* indicate values that are one standard error above and below the mean

several subjects were on the borderline. The outlier values consisted of numerous subjects and not one or two in particular thus a physiological explanation for the outliers is difficult to envision. However, closer examination of the raw signals indicates that these were likely physiological in nature and not due to measurement error such as movement of the muscle probe. In saying this, perhaps the outliers in each case had some variation between trials, not related to probe placement, probe movement or physical fatigue, but maybe due to variation in strap tightness or a learning effect causing some change in body position.

Previous studies that have used NIRS to evaluate OXY of the erector spinae muscles during isometric contractions have used different percentages of MVC for durations ranging from 30 to 60 s (Jensen et al. 1999; McGill et al. 2000; Yoshitake et al. 2001). Hence it is important to evaluate the reproducibility of these responses not only at the point of fatigue during the BSME, but also at different stages during the test. The current study clearly demonstrated that the OXY and BV responses at each 10% segment of the two test trials were highly reproducible (Fig. 4). No significant differences were observed between the slopes of the curves for the two trials for each of these variables, implying that the tissue hemodynamic responses could be studied even for short test durations during different types of interventions with confidence. However, further research is needed to evaluate the reliability of these responses at different percentages of MVC during static back muscle contractions.

In conclusion, the results of the current study indicated that NIRS is a reliable technique for evaluating OXY and BV trends of the erector spinae muscles during the BSME in healthy men. No significant differences were observed between the two trials on the right and left sides for these variables at the point of fatigue. As well, these responses were highly reproducible at each 10% segment of the test. In general, the reliability was stronger for the muscle BV compared to the OXY variables. Future research studies that utilize NIRS should focus primarily on this variable for analysis.

Acknowledgements This work was supported by funding from the Alberta Workers' Compensation Board.

References

Alaranta H, Hurri H, Heliovaara M (1994) Non-dynamometric trunk performance tests: reliability and normative data. Scand J Rehabil Med 26:211–215

Barnes WS (1980) The relationship between maximum isometric strength and intramuscular circulatory occlusion. Ergonomics 23:351–357

Biedermann H-J, Shanks GL, Inglis J (1990) Median frequency estimates of paraspinal muscles: reliability analysis. Electromyogr Clin Neurophysiol 30:83–88

Biering-Sorensen F (1983) A prospective study of low back pain in a general population. Scand J Rehabil Med 15:81–88

Biering-Sorensen F (1984a) Physical measurements as risk indicators for low-back trouble over a one-year period. Spine 9:106–119

Biering-Sorensen F (1984b) A one-year prospective study of low back trouble in a general population. The prognostic value of low back history and physical measurements. Dan Med Bull 31:362–375

Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1:307–310

Bland JM, Altman DG (1995) Comparing methods of measurement: why plotting difference against standard method is misleading. Lancet 346:1085–1087

Bonde-Petersen F, Mørk AL, Nielsen E (1975) Local muscle blood flow and sustained isometric contractions of human arm and back muscles. Eur J Appl Physiol 34:43–50

Chance B, Bank W (1995) Genetic disease of mitochondrial function evaluated by NMR and NIR spectroscopy of skeletal muscle. Biochim Biophys Acta 1271:7–14

Chance B, Dait M, Zhang C (1992) Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. Am J Physiol 262:C766-C775

Fitts RH (1994) Cellular mechanisms of muscle fatigue. Physiol Rev 71:49–93
Gaffney FA, Sjogaard G, Saltin B (1990) Cardiovascular and metabolic responses to static contraction in man. Acta Physiol Scand 138:249–258
Hansen J, Sander M, Hald CF (2000) Metabolic modulation of sympathetic vasoconstriction in human skeletal muscle: role of tissue hypoxia. J Physiol (Lond) 527:387–396
Humphreys PW, Lind AR (1962) The blood flow through active and inactive muscles of the forearm during sustained handgrip contractions. J Physiol (Lond) 166:120–135
Jensen BR, Jorgensen K, Hargens AR (1999) Physiological response to submaximal isometric contractions of the paravertebral muscles. Spine 24:2332–2338
Jørgensen K (1997) Human trunk extensor muscles physiology and ergonomics. Acta Physiol Scand 160:5–58
Jørgensen K, Nicolaisen T (1986) Two methods for determining trunk extensor endurance: A comparative study. Eur J Appl Physiol 55:639–644
Jørgensen K, Nicolaisen T (1987) Trunk extensor endurance: determination and relation to low-back trouble. Ergonomics 30:259–267
Kankaanpaa M, Laaksonen D, Taimela S (1998) Age, sex, and body mass index as determinants of back and hip extensor fatigue in the isometric Sorensen back endurance test. Arch Phys Med Rehabil 79:1069–1075
Keller A, Hellesnes J, Jens IB, et al (2001) Reliability of the isokinetic trunk extensor test, Biering-Sorensen test, and Astrand bicycle test: assessment of intraclass correlation coefficient and critical difference in patients with chronic low back pain and healthy individuals. Spine 26:771–777
Koumantakis GA, Arnall F, Cooper RG (2001) Paraspinal muscle EMG fatigue testing with two methods in healthy volunteers. Reliability in the context of clinical applications. Clin Biomech (Bristol, Avon) 16:263–266
Latimer J, Maher CG, Refshauge K (1999) The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. Spine 24:2085–2089; discussion 2090
Maikala R, Bhambhani Y (2000) Low-back muscle oxygenation trends during simple postural variations-intersession reliability using near infra-red spectroscopy. IEA2000/HFES Congress, pp 5–9; 9–12
Mancini D, Bolinger L, Li L (1994) Validation of near-infrared spectroscopy in humans. J Appl Physiol 77:2740–2745
Mannion AF, Dolan P (1994) Electromyographic median frequency changes during isometric contraction of the back extensors to fatigue. Spine 19:1223–1229
Marshall JM (2000) Adenosine and muscle vasodilatation in acute systemic hypoxia. Acta Physiol Scand 168:561–573
Mayer T, Gatchel R, Betancur J (1995) Trunk muscle endurance measurement. Spine 20:920–927
McGill SM, Hughson RL, Parks K (2000) Lumbar erector spinae oxygenation during prolonged contractions: implications for prolonged work. Ergonomics 43:486–493
Mitchell JH, Payne FC, Saltin B (1980) The role of muscle mass in the cardiovascular response to static exercise. J Physiol (Lond) 309:45–54
Moffroid MT, Haugh LD, Haig AJ (1993) Endurance training of trunk extensor muscles. Phys Ther 73:10–17
Moffroid MT, Reid S, Henry SM (1994) Some endurance measures in persons with chronic low back pain. J Orthop Sports Phys Ther 20:81–87
Moreland J, Finch E, Stratford P (1997) Interrater reliability of six tests of trunk muscle function and endurance. J Orthop Sports Phys Ther 26:200–208
Newton M, Thow M, Somerville D (1993) Trunk strength testing with isomachines, part 2. Experimental evaluation of the Cybex II back testing system in normal subjects and patients with chronic low back pain. Spine 18:812–824
Obrig H, Villringer A (1997) Near-infrared spectroscopy in functional activation studies. Can NIRS demonstrate cortical activation? In: Villringer A, Dirnagl W (eds) Optical imaging of brain function and metabolism II. Advances in experimental medicince and biology. Plenum Press, New York, pp 113–127
Ottenbacher KJ (1991) Statistical conclusion validity multiple inferences in rehabilitation medicine. Am J Phys Med Rehabil 70:317–322
Radegran G, Hellsten Y (2000) Adenosine and nitric oxide in exercise-induced human skeletal muscle vasodilatation. Acta Physiol Scand 168:575–591
Sjogaard G, Savard G, Juel C (1988) Muscle blood flow during isometric activity and its relation to muscle fatigue. Eur J Appl Physiol 57:327–335
Smidt GL, Blanpied PR (1987) Analysis of strength tests and resistive exercises commonly used for low-back disorders. Spine 12:1025–1031
Suni JH, Oja P, Miilunpalo SI (1998) Health-related fitness test battery for adults: associations with perceived health, mobility, and back function and symptoms. Arch Phys Med Rehabil 79:559–569
Wenger HA, Reed AT (1976) Metabolic factors associated with muscular fatigue during aerobic and anaerobic work. Can J Appl Physiol 1:43–48
Yoshitake Y, Ue H, Miyazaki M (2001) Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. Eur J Appl Physiol 84:174–179

APPENDIX C: *Manuscript published in European Journal of Applied Physiology 2003 90(1-2): 1-9*

Eur J Appl Physiol (2003) 90: 1–9
DOI 10.1007/s00421-002-0776-0

ORIGINAL ARTICLE

Robert T. Kell · Yagesh Bhambhani

Cardiorespiratory and hemodynamic responses during repetitive incremental lifting and lowering in healthy males and females

Accepted: 12 November 2002 / Published online: 21 May 2003

Abstract The purposes of this study were twofold. First, to evaluate the cardiorespiratory and muscle oxygenation (OXY)/blood volume (BV) responses during repetitive incremental lifting and lowering (RILL) in healthy males and females. Second, to develop a predictive equation for predicting peak aerobic power ($\dot{V}O_{2peak}$) during RILL from the cardiorespiratory, OXY/BV and body composition variables. Fourteen males and 18 females [mean (SD) for age, height and body mass were: 29.6 (8.2) years; 1.75 (0.07) m; 78.9 (10.4) kg and 23.9 (2.1) years; 1.63 (0.06) m; 62.3 (6.3) kg, respectively] completed a RILL from floor to table height at 10 lifts/min to voluntary fatigue. Cardiorespiratory responses were measured using open circuit spirometry and hemodynamic trends were monitored bilaterally at the third lumbar vertebra via near infrared spectroscopy. Significant sex differences ($p<0.05$) were observed for the peak values of oxygen uptake ($\dot{V}O_{2peak}$), ventilation rate ($\dot{V}_E$), oxygen pulse, BV-max and BV-delta. Erector spinae OXY decreased systematically until $\dot{V}O_{2peak}$ was attained, while BV decreased until ~50% of $\dot{V}O_{2peak}$ and then leveled off. Stepwise regression analysis indicated that ~75% of the variance in $\dot{V}O_{2peak}$ was predicted from cardiorespiratory, hemodynamic and body composition variables, with the most important predictors for absolute and relative $\dot{V}O_{2peak}$ being $\dot{V}_E$ ($r=0.75$) and fat mass ($r=-0.63$) respectively. Inclusion of left side OXY/BV responses increased the predictability of the common variance in $\dot{V}O_{2peak}$ from 40% to 74%, implying that muscle hemodynamics play an important role in determining $\dot{V}O_{2peak}$ during RILL.

Y. Bhambhani (✉)
Faculty of Rehabilitation Medicine,
University of Alberta, Edmonton, Alberta, T6G-2G4, Canada
E-mail: Yagesh.Bhambhani@ualberta.ca
Tel.: +1-780-4927248
Fax: +1-780-4921626

R. T. Kell
Faculty of Physical Education and Recreation,
University of Alberta, Edmonton, Alberta, T6J-2H9, Canada

Keywords Erector spinae oxygenation · Incremental lifting/lowering · Metabolic responses

Introduction

Occupational fitness testing is routinely used to assess an individual's physical work capacity to perform jobs that require extensive materials handling. The measurement of the maximal oxygen uptake ($\dot{V}O_{2max}$) is an important part of the fitness assessment battery because of its relationship with endurance work capacity. The current NIOSH guidelines (National Institute for Occupational Safety and Health 1981) recommend that an individual be allowed to work at a time-weighted average of approximately 33% of their individual $\dot{V}O_{2max}$ for an 8-h working day in order to avoid undue fatigue and reduce the risk of work place injury. However, the exercise mode that should be used in the assessment of $\dot{V}O_{2max}$ was not specified in this recommendation. In order to obtain a valid measure of an individual's $\dot{V}O_{2max}$, it is important that the measurement be undertaken when the individual is exercising with large muscle groups, so that the cardiorespiratory system can be maximally stressed. Therefore, these laboratory tests are usually conducted on a treadmill or a stationary cycle ergometer. Although this information is useful in evaluating the overall cardiorespiratory health status of the individual, it has limited application in evaluating a worker's capacity to perform manual material handling tasks.

Repetitive lifting and lowering of loads form an integral part of many jobs that require extensive materials handling. To date, several studies have investigated the maximal cardiorespiratory responses to incremental lifting and compared them with other modes such as cycle ergometry and treadmill running (Commissaris and Toussaint 1996; Legg 1981; Nindl et al. 1998; Petrofsky and Lind 1978b; Revuelta et al. 2000; Sharp et al. 1988). The evidence indicates that the maximal cardiorespiratory responses [oxygen uptake ($\dot{V}O_2$), heart

rate, ventilation rate ($\dot{V}_E$)] during incremental lifting to voluntary fatigue are significantly lower than those attained during incremental cycle ergometry or treadmill running (Petrofsky and Lind 1978b; Sharp et al. 1988). The reasons for this are currently unclear, but could be due to differences in the types of muscle contractions required for these exercise modes. During treadmill running or stationary cycling, blood flow and oxygen availability to the exercising muscles is enhanced due to the isotonic nature of the muscle contractions (McArdle et al. 2001). However, during repetitive lifting and lowering the lower back muscles contract both isotonically and isometrically during the different phases of the task. It is likely that the isometric component of the muscular contractions during this task will attenuate blood flow and oxygen availability to the low back musculature, thereby resulting in premature fatigue (Bondra-Petersen et al. 1975; McGill et al. 2000). In order to increase our understanding of the physiological factors limiting performance during repetitive lifting and lowering, it is important that a study which examines the central and peripheral responses during this task be conducted, and the variables that best predict performance are identified.

Near infrared spectroscopy (NIRS) is a valid non-invasive technique that has been used to measure the trends in muscle oxygenation during a variety of exercise modes (Mancini et al. 1994). NIRS is based on the differential absorption properties of hemoglobin (Hb) and myoglobin (Mb) in the near infrared range of the absorption spectrum (i.e., between 700 nm and 1000 nm). At 760 nm, Hb and Mb are primarily in the deoxygenated state, whereas at 850 nm they occur in the oxygenated form (HbO_2 and MbO_2). The difference in tissue absorbency between these two wavelengths reflects the relative change in oxygen saturation at the small blood vessels, while the sum signal indicates the change in blood volume determined from the total amount of Hb. Some of the limitations of NIRS are that: (1) it is difficult to quantify the absolute amount of tissue oxygen uptake because the path length of the signal cannot be accurately determined, and therefore only qualitative changes in the degree of oxygenation and blood volume can be evaluated; and (2) the technique is unable to differentiate between the contribution of Hb and Mb as the absorption spectra of these two chromophores overlap (Chance et al. 1992; Mancini et al. 1994).

Recently, several studies have used NIRS to examine localized changes in muscle oxygenation and blood volume during isometric contractions of the lower back (Jensen et al. 1999; Kunimune et al. 1999; McGill et al. 2000; Yoshitake et al. 2001). These studies suggest that NIRS is a sensitive technique for measuring tissue oxygenation and blood volume changes during such contractions, and therefore could be useful in the measurement of localized muscle fatigue. Examination of the literature on repetitive lifting indicates that there is only one investigation that has evaluated the cardiorespiratory responses and low back muscle oxygenation trends simultaneously in male and females (Maronitis et al. 2000). This study, however, evaluated the responses during submaximal exercise and did not compare responses between males and females.

The purposes of this study therefore were to: (1) evaluate the maximal cardiorespiratory responses during repetitive incremental lifting and lowering (RILL) in healthy males and females; (2) examine the relative changes in muscle oxygenation and blood volume (hemodynamics) of the erector spinae muscles during RILL, and (3) develop a regression equation for predicting the $\dot{V}O_{2max}$ from the cardiorespiratory, hemodynamic and body composition variables.

Methods

Subjects

Fourteen male and 18 female volunteers, all right side dominant, provided their written informed consent to participate in this investigation. The subject inclusion criteria were: (1) age between 18 and 50 years, (2) absence of any metabolic, cardiorespiratory and neuromuscular disorders, (3) no previous history of low back injury, and (4) currently asymptomatic for low back pain. A Physical Activity Readiness Questionnaire (PAR-Q) was used to screen each participant and identify any contraindications to exercise (Canadian Society for Exercise Physiology 1996). Each subject met with the researcher individually at the onset of the study, during which a written and verbal account of the testing procedures was provided. The study involved one test session during which anthropometric measurements and the RILL test were completed.

Anthropometric measurements

After recording the height and weight of the subjects, the skinfold thickness (SFT) was measured in duplicate at the biceps, triceps, suprailiac and subscapularis sites on the right side of the body. Measurements were made to the nearest 0.2 mm using Lange calipers (Cambridge Scientific Industries, Cambridge, Mass., USA) and the average of the values was calculated for each site. Percent body fat was determined as the sum of the four skinfold sites (Durnin and Womersley 1974), from which the absolute lean body mass (LBM) and fat mass (FM) was calculated for each subject. Skinfold thickness on the left (L) and right (R) erector spinae muscle at the third lumbar vertebra (L3) was also measured in duplicate to determine the adipose tissue thickness at the NIRS probe sites.

Repetitive incremental lifting and lowering (RILL) protocol

Each subject was demonstrated a safe lifting and lowering technique and asked to simulate this technique before starting the test. The metabolic equipment was then properly fitted, following which the subject sat in an upright posture on a chair adjacent to the lifting table for 2-min while baseline-resting data were collected. Thereafter the subject stood in front of the basket that was resting on the floor, approximately 45 cm in front of the lifting table. The basket (33 cm × 33 cm × 29 cm) was fitted with handles on both sides and had a mass of 5 kg. The subject lifted and lowered the basket from the floor to a waist height table (height = 67 cm) using a right foot lead at a cadence of 10 lifts/min (Fig. 1). The load was

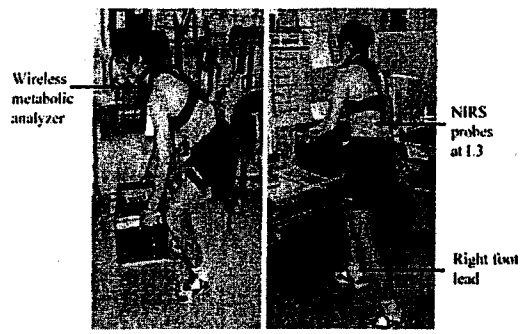


Fig. 1 Experimental setup for the repetitive incremental lifting and lowering protocol

increased by 2.25 kg/min continuously until voluntary fatigue was attained. Towards the end of each stage of the RILL test, the subject was asked if he/she could continue with the test. If the response was positive, the load was increased by 2.25 kg. If the response was negative, the subject was asked to increase the lifting frequency as much as possible until voluntary fatigue. The intent was to stress the cardiorespiratory and muscle mass maximally so as to attain the following criteria (American College of Sports Medicine 2001) for $\dot{V}O_{2max}$: (1) a leveling off (increase of less than 100 ml/min) or a decrease in the oxygen consumption ($\dot{V}O_2$) with increasing workload, (2) age-predicted maximal HR, calculated as (220–age), and (3) a respiratory exchange ratio > 1.10.

At the mid-point of each stage the subject was asked to rate their perceived exertion (RPE) using the Borg Scale (Borg and Noble 1974). The RPE was segmented to the following three regions to obtain a more complete picture of the perceptual responses during RILL: (1) central sensations in the heart and lungs, (2) local sensations in the arms/shoulder, and (3) local sensations in the lower back (L3 region). At the termination of the RILL protocol the subject sat quietly on a chair while 4-min of recovery data were collected. The investigator then asked the subject the reason for terminating the test.

Cardiorespiratory measurements

A portable wireless metabolic analyzer (Vmax*ST* system, SensorMedics, Yorba Linda, Calif., USA) was used to measure the cardiorespiratory responses during RILL on a breath-by-breath basis. The lightweight (570 g), battery-operated metabolic analyzer was fitted snuggly about the subject's shoulders using a breathable Velcro shoulder mount. The unit contained a volume transducer, O_2 and CO_2 analyzers, a temperature sensor and a pressure transducer. The O_2 and CO_2 analyzers were calibrated using commercially available precision gases (16% O_2, 4% CO_2, balance N_2; Sensormedics, Calif., USA) prior to and at the completion of each test in order to ensure data accuracy. The flow meter was calibrated by injecting 3-L of air using a syringe. Heart rate was recorded via a wireless chest monitor (Sport tester) interfaced with the portable metabolic unit. The breath-by-breath data were averaged over 20-s intervals for subsequent analysis.

Near infrared spectroscopic measurements

Tissue absorbency was measured from the right (R) and left (L) erector spinae using two commercially available dual-wavelength NIRS units (MicroRunman, NIM, Pennsylvania, USA). Each NIRS probe had one tungsten light source located at a distance of 4 cm from the silicone diode that absorbed light at 760 and 850 nm. The penetration depth was approximately 60% of the optode distance or 2–2.5 cm. The probes were positioned by having the subject flex at the waist while the investigator located the L3 area. The two probes were secured with a tensor bandage approximately 3 cm to the L and R sides of the vertebral column. Sufficient care was taken when securing the probes to avoid occlusion of blood flow to the muscles. The NIRS unit was calibrated using the NIRCOM software (NIM) available with the instrument. The probes were set at a moderate penetration depth with the light intensity between 120 mV and 150 mV. During calibration and exercise the probes were covered with transparent plastic to avoid any contamination of the light signal due to perspiration. The OXY (850 nm to 760 nm signal) and BV (850 nm + 760 nm signal) data were collected on-line during the baseline, RILL and recovery periods.

The NIRS measurements, expressed in OD units, were averaged over 20-s intervals so as to correspond with the metabolic data obtained during the RILL. These values were subsequently analyzed in the following manner. The change in OXY (OXY-delta) was calculated as the difference between the baseline resting OXY value (20-s prior to the start of RILL) and the minimum OXY observed during the RILL test. The OXY-range was calculated as the difference between the maximum OXY value during recovery and the minimum OXY during the RILL test. The BV-delta and BV-range were calculated in a similar manner.

Statistical analysis

A one-way ANOVA was used to compare the anthropometric characteristics and cardiorespiratory responses of the male and female subjects. A two-way repeated-measures ANOVA (sex by side) was used to compare mean NIRS variables between the R and L sides in males and females. Additionally, a two-way ANCOVA using skinfold thickness (L, R and combined L/R sides) at the probe sites was performed on the mean NIRS variables. A forward stepwise multiple regression analysis, using pooled male and female data ($n = 32$), was used to predict the $\dot{V}O_{2max}$ during RILL from the peak cardiorespiratory, body composition and NIRS variables. Data of the males and females were pooled in order to increase the heterogeneity in the responses and augment the sample size so as to increase the power of the prediction. The independent variables included in the multiple regression were: heart rate (HR, beats/min) and $\dot{V}_E$ (l/min); % body fat, lean body mass (LBM, kg), fat mass (FM, kg), skinfold thickness (SFT) at the probe sites (L, R, combined L/R sides), L- and R-OXY-delta, L- and R-OXY-range, L- and R-BV- delta, and L- and R-BV-range. The alpha level was set at 0.05 ($P < 0.05$). Statistical analyses were performed using the Statistica computer package (Statsoft, '99 edition, copyright 1984–1999).

Results

Anthropometric characteristics

The anthropometric characteristics of the male and female subjects are compared in Table 1. The age, height, body mass and body mass index were significantly higher in males compared to females. The L-SFT and % body fat were significantly lower in males compared to females. No significant gender difference was observed for R-SFT at the probe site. There were no significant differences between the R-SFT and L-SFT at the NIRS probe site in either gender.

Table 1 Anthropometric characteristics [means (SD)] of males and females. (*BMI* Body mass index, *FM* fat mass, *LBM* lean body mass)

Variable	Males ($n=14$)		Females ($n=18$)	
	Mean	SD	Mean	SD
Age (years)	29.6*	8.2	23.9	2.1
Height (m)	1.75*	0.07	1.63	0.06
Weight (kg)	78.96*	10.36	62.30	6.25
1/2 Skinfold right (mm)	9.51	5.56	10.62	2.78
1/2 Skinfold left (mm)	7.98*	3.29	10.49	3.16
Body fat (%)	20.80*	5.43	29.88	4.83
BMI	25.75*	3.23	23.29	1.56
FM (kg)	16.61	5.60	18.81	4.31
LBM (kg)	62.36*	7.64	43.49	3.43

*Significantly ($P<.05$) different

Table 2 Peak perceptual and cardiorespiratory responses [means (SD)] during repetitive lifting and lowering in males and females

Variable	Males ($n=14$)		Females ($n=18$)	
	Mean	SD	Mean	SD
Test duration (min:s)	14:13*	5:01	9:37	2:30
Peak mass lifted (kg)	31.7*	11.6	22.1	5.1
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	2.91*	0.6	2.21	0.3
RPE Back	18.4	1.6	18.2	1.8
RPE Arms/shoulders	15.3	3.1	15.4	2.6
RPE Central	16.4	2.1	15.9	2.4
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	37.2	8.4	35.8	5.5
$\dot{V}O_{2peak}$ ($ml \cdot kg_{LBM}^{-1} \cdot min^{-1}$)	46.90	9.60	50.82	5.44
HR_{peak} ($beats \cdot min^{-1}$)	175.7	26.8	174.2	9.3
$\dot{V}_{Epeak}$ ($l \cdot min^{-1}$)	92.5*	22.2	62.7	12.7
RER_{peak}	1.01	0.1	0.94	0.1
O_2 pulse ($ml \cdot beat^{-1}$)	16.9*	2.4	13.0	1.7

*Significantly ($P<.05$) different

Peak perceptual and cardiorespiratory responses during RILL

The peak perceptual and cardiorespiratory responses during RILL in the male and female subjects are summarized in Table 2. Each subject completed the RILL protocol to voluntary fatigue as described earlier. All the subjects, except one, identified localized low back muscle fatigue as the main reason for terminating the RILL test. The one exception listed weakened handgrip strength as the principal reason for terminating the test. It is evident from Table 2 that the mean RPE for the lower back was higher than that reported for the arms/shoulder and the central cardiorespiratory responses. No significant gender differences were observed for any of the peak RPE values reported.

Examination of the peak cardiorespiratory responses (Table 2) indicated that neither the male or female subjects as a group satisfied the HR and RER criteria for the attainment of $\dot{V}O_{2max}$. Individual results indicated that 92% of the males and 89% of the females achieved their age-predicted maximal heart rate (220–age), while only 25% of the males and 28% of the females reached the RER criterion > 1.10. Only 21% of the males and 22% of the females demonstrated a leveling off in the $\dot{V}O_2$ (i.e., an increase of less than 100 ml/min) with increasing work rate. Because of the small number of subjects satisfying this criterion, the term $\dot{V}O_{2peak}$ has been used to describe the oxygen uptake responses in this study.

The peak values for $\dot{V}O_2$ (l/min), $\dot{V}_E$ (l/min), O_2 pulse (ml/beat) and mass lifted were significantly higher in males compared to females. No significant sex differences were observed for the $\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$), HR_{peak} (beats/min) and RER_{peak}. When the $\dot{V}O_{2peak}$ was expressed as a function of LBM, the values for females exceeded those of males by 7.7%, but the difference was not statistically significant. Significant correlations were observed between the $\dot{V}O_{2peak}$ (absolute and relative) and endurance time ($r=0.75$ and 0.59, respectively) and peak mass lifted (0.67 and 0.52, respectively) in the combined group of males and females.

Hemodynamic responses during RILL

The NIRS data were successfully recorded in all the subjects during the RILL protocol. The OXY and BV trends of the L and R erector spinae muscles in a representative male and female subject are illustrated in Fig. 2. It is evident that at the onset of incremental lifting, there was a systemic decrease in OXY with increasing load. In most individuals, there was a leveling off in OXY as the maximum load was attained. During recovery, there was a rapid increase in OXY during the first 1 to 2-min, followed by a leveling off towards the latter stages. In approximately half the subjects, the value exceeded the resting baseline value observed prior to the onset of lifting. The BV also demonstrated a systematic decrease during the RILL test in both sexes. However, there was no leveling off observed in BV as the peak lifting mass was attained. During recovery, the BV also increased rapidly towards the resting baseline value and in some cases exceeded it (i.e., a hyperemia occurred). Although these overall trends were quite consistent amongst the subjects during the RILL test, they were more varied for L-and R-BV compared to the L-and R-OXY responses.

Comparison between sides and sexes

The two-way ANOVA indicated no significant interaction between sex and side for any of the NIRS responses, implying that the overall trends on the R and L sides were similar in the males and females. Consequently, the main effects of the ANOVA were examined by: (1) combining the mean values of the two sexes to compare the values between the two sides, and (2) combining the values of the two sides to compare the values between

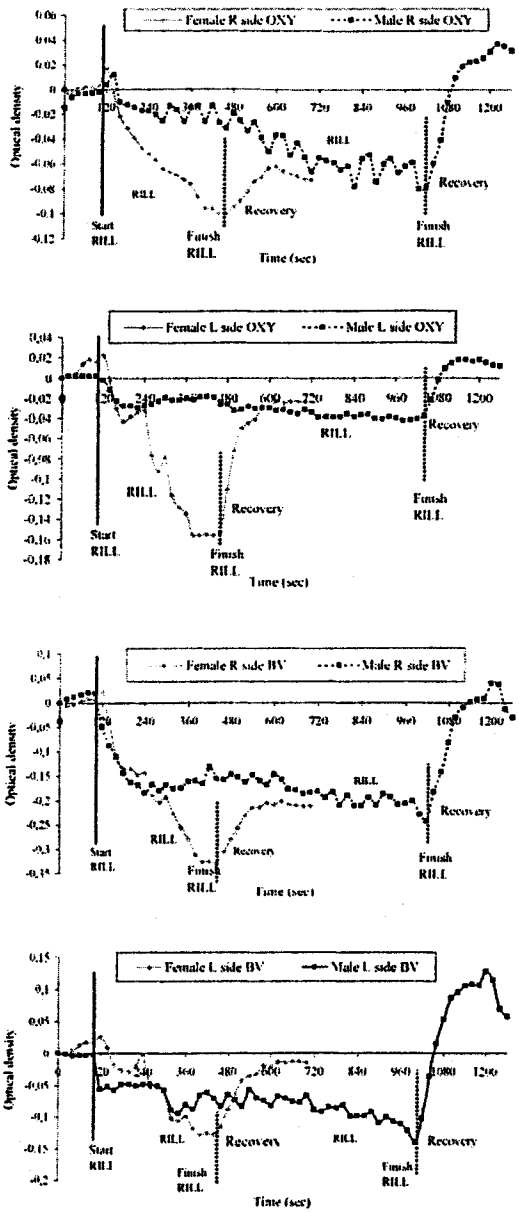


Fig. 2 Oxygenation and blood volume trends of the right and left erector spinae muscles during repetitive incremental lifting and lowering to volitional fatigue in a representative male and female subject

the two sexes. These results are summarized in Table 3. With the exception of OXY-max, no significant main effect for side was observed for OXY-min, OXY-delta, OXY-range, BV-min, BV-max, BV-delta or BV-range. Comparison between the sexes indicated that BV-max and BV-delta were significantly higher in males compared to females. No significant ($p < 0.05$) differences were found between sexes for OXY-min, OXY-max, OXY-delta, OXY-range, BV-min, or BV-range. The use of SFT (L, R and combined L/R sides) at the probe sites as a covariate did not change the significance of any of the hemodynamic variables between the sexes or the sides.

Prediction of $\dot{V}O_{2peak}$ during RILL

The results of the stepwise regression analysis for predicting absolute and relative $\dot{V}O_{2peak}$ using the pooled sample ($n = 32$) are presented in Tables 4 and 5 respectively. It is evident that with absolute $\dot{V}O_{2peak}$ as the dependent variable, $\dot{V}_{Epeak}$ explained ~56% of the common variance ($r = 0.75$) between these two variables. Inclusion of the following variables increased the common variance to 76%: L-OXY-range, LBM, HR, L-SFT and R-BV-delta. The regression equation for predicting the absolute $\dot{V}O_{2peak}$ was:

$$\dot{V}O_{2peak}\left(l \cdot \overset{-1}{\min}\right) - 2.486 + 0.004(\dot{V}_E) + 3.440(L - OXY - range) - 0.001(LBM) + 0.005(HR) - 0.045(L - SFT) - 0.433(R - BV - delta) \quad (1)$$

When using relative $\dot{V}O_{2peak}$ as the dependent variable, FM explained ~40% of the common variance ($r = -0.63$) between the two variables. Inclusion of the following variables increased the common variance to 74%: HR, L-OXY-range, L-BV-range, L-OXY-delta and L-BV-delta. The regression equation for predicting the relative $\dot{V}O_{2peak}$ was:

$$\dot{V}O_{2peak}\left(ml \cdot kg^{-1} \cdot \overset{-1}{\min}\right) = 89.172 + 1.031(FM) + 0.068(HR) + 46.874 \times (L - OXY - range) - 8.433(L - BV - range) - 28.81(L - OXY - delta) - 29.181(L - BV - delta) \quad (2)$$

It is interesting to note that in both the equations, the L-OXY-range was included as a predictor of both absolute and relative $\dot{V}O_{2peak}$. Additionally, in the prediction of the relative $\dot{V}O_{2peak}$, all four left-side NIRS variables were included in the equation. Overall, inclusion of the additional hemodynamic and body composition variables in the multiple regression analysis increased the predictability of the absolute $\dot{V}O_{2peak}$ and relative $\dot{V}O_{2peak}$ by 20% and 34%, respectively.

Table 3 Comparison of hemodynamic responses [means (SD), OD units] between the two sides and sexes

Variable	Right ($n=32$) Mean (SD)	Left ($n=32$) Mean (SD)	Male ($n=28$) Mean (SD)	Female ($n=36$) Mean (SD)
OXY-min	−0.105 (0.120)	−0.098 (0.110)	−0.089 (0.096)	−0.113 (0.134)
OXY-max	0.044 (0.060)	0.112 (0.115)	0.091 (0.098)	0.064 (0.076)
OXY-delta	0.112 (0.121)	0.109 (0.118)	0.096 (0.105)	0.125 (0.134)
OXY-range	0.149 (0.138)	0.209 (0.151)	0.180 (0.163)	0.178 (0.126)
BV-min	−0.135 (0.122)	−0.065 (0.082)	−0.059 (0.071)	−0.141 (0.133)
BV-max	0.130 (0.166)	0.165 (0.142)	0.208 (0.179)*	0.087 (0.129)
BV-delta	−0.115 (0.161)	−0.150 (0.135)	−0.192 (0.179)*	−0.073 (0.117)
BV-range	0.265 (0.163)	0.231 (0.122)	0.268 (0.132)	0.228 (0.153)

Note: For the side comparisons, the values of both sexes were pooled. For the sex comparisons, the values of the two sides were pooled
*Significantly ($P<.05$) different between sides or sexes

Table 4 Summary of the forward stepwise regression analysis for $\dot{V}O_{2peak}$ (l/min) with males and females combined ($n=32$)

Variable	Step	+in/−out	Multiple R	Multiple R-square	R-square change	p-level
$\dot{V}_{Epeak}$ ($L \cdot min^{-1}$)	1		0.747	0.558	0.558	0.000
L-OXY range	2		0.782	0.612	0.054	0.054
LBM	3		0.809	0.655	0.043	0.071
HR_{peak} ($beats \cdot min^{-1}$)	4		0.844	0.712	0.056	0.029
L-SFT	5		0.864	0.746	0.035	0.070
R-BV-delta	6		0.871	0.758	0.012	0.276

Table 5 Summary of the forward stepwise regression analysis for $\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) with males and females combined ($n=32$)

Variable	Step	+in/−out	Multiple R	Multiple R-square	R-square change	p-level
FM	1		0.631	0.399	0.399	0.000
HR_{peak} ($beats \cdot min^{-1}$)	2		0.751	0.564	0.165	0.002
L-OXY-range	3		0.789	0.622	0.058	0.047
L-BV-range	4		0.824	0.680	0.058	0.036
L-OXY-delta	5		0.839	0.704	0.024	0.160
L-BV-delta	6		0.861	0.741	0.038	0.068

Table 6 A comparison of peak cardiorespiratory responses [means (SD)] from lifting and lifting and lowering studies. Movement phase = lifts or lift and lower (lift/lower)

Variable	Present Study	Commissaris and Toussiant (1996)		Nindl et al. (1998)		Sharp et al. (1988)
Sex	Male	Female	Male	Male	Female	Male
Subject number	14	18	5	20	20	18
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	2.91 (0.60)	2.21 (0.30)	3.24 (2.80)	3.43 (0.41)	2.32 (0.27)	3.20 (0.42)
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	37.2 (8.4)	35.8 (5.5)	45.9 (4.0)	42.8 (4.1)	39.0 (3.9)	42.2 (5.5)
$\dot{V}_{Epeak}$ ($L \cdot min^{-1}$)	92.5 (22.2)	62.7 (12.7)	86.6 (11.7)	114.5 (16.8)	80.1 (17.5)	109.9 (18.3)
HR_{peak} ($beats \cdot min^{-1}$)	177.3 (26.8)	174.2 (9.3)	170.4 (5.5)	185.7 (5.8)	189.3 (8.4)	181.0 (8.4)
RER_{peak}	1.01 (0.10)	0.94 (0.10)	0.95 (0.07)	0.96 (0.06)	0.94 (0.06)	1.02 (0.08)
O_2 pulse ($ml \cdot beat^{-1}$)	16.37 (2.63)	13.13 (1.79)	18.83 (5.1)	18.47 (6.9)	12.25 (3.2)	17.67 (5.0)
Protocol	continuous	continuous	discontinuous	discontinuous	discontinuous	discontinuous
Movement phase (s)	lift/lower	lift/lower	Lift/lower	lift	lift	lift
Frequency ($mov \cdot min^{-1}$)	10	10	13.6 to 24	15	15	15
Lifting height (m)	0.76	0.76	from 0.20 m to knuckle height	1.32	1.32	1.32

Discussion

Cardiorespiratory response to RILL

The peak cardiorespiratory responses during RILL in the males and females are compared with previous studies in Table 6. It is evident that the absolute and relative values of the $\dot{V}O_{2peak}$ in the present study for both sexes were slightly lower than those reported in the studies cited. This is most likely due to the differences in the test protocols (continuous vs. discontinuous), lifting frequency (10 lifts/min vs. 13.6 lifts/min), movement phase (lifting and lowering vs. lifting only), and lifting height (0.76 m vs. 1.32 m). All the previous lifting

studies cited used a discontinuous protocol to elicit the peak cardiorespiratory responses, which is in contrast to the present study. Commissaris and Toussaint (1996) designed a discontinuous lifting protocol to avoid localized muscular fatigue, which theoretically would enable the subjects to lift a higher load and increase the peak cardiorespiratory responses. Additionally, research has shown that the $\dot{V}O_{2peak}$ achieved during repetitive lifting is dependent on the frequency and the mass of the lift (Fernandez et al. 1987; Petrofsky and Lind 1978a; Sharp et al. 1988). The lower peak O_2 pulse in males observed in this study compared to others (Commisaris and Toussaint 1996; Nindl et al. 1998; Sharp et al. 1988) was due primarily to their lower absolute $\dot{V}O_{2peak}$, as the HR_{peak} was within the range reported by the investigators cited. The slightly higher peak O_2 pulse of the females in this study compared to those evaluated by Nindl et al. (1998) was due to the lower HR_{peak} (15 beats/min) as the absolute $\dot{V}O_{2peak}$ was similar in both groups of subjects.

The present findings demonstrated that the absolute $\dot{V}O_{2peak}$ was significantly higher in males compared to females, but the relative value was not significantly different between the sexes. This observation is not consistent with the findings of Nindl et al. (1998) who reported that both the absolute and relative values were higher in males compared to females. Since both groups of subjects reached a similar percentage of the age-predicted maximum HR during the RILL in the current study (91% and 94% in the males and females, respectively), the results suggest that peripheral factors most likely contributed to a greater proportion of the relative $\dot{V}O_{2peak}$ in the females. Further, the current observations indicated that when $\dot{V}O_{2peak}$ was expressed relative to LBM, the values were 7.7% higher in females compared to males, but this difference was not statistically significant (Table 2). These findings suggest that lean body mass is an important determinant of the $\dot{V}O_{2peak}$ during RILL.

NIRS trends during RILL

The present study is the first to examine the hemodynamic responses (OXY and BV changes) of the erector spinae muscles during a RILL test to volitional fatigue. The lifting and lowering method implemented in this investigation was a squat technique, during which the quadriceps and biceps muscles perform isotonic contractions to lift the load, while the erector spinae perform intermittent isometric contractions to stabilize the body and the load (Nindl et al. 1998). The OXY trend observed in the present study (Fig. 1) is similar to that reported for the vastus lateralis muscle during incremental cycling (Belardinelli et al. 1995; Bhambhani et al. 1998), rowing (Chance et al. 1992), and submaximal lifting (Maronitis et al. 2000). The systematic decrease in OXY observed during the RILL is attributed to the increased cellular oxygen uptake in the mitochondria for aerobic energy production. The leveling off in OXY towards the latter stages of the RILL suggests that the HbO_2 in the small blood vessels had attained its maximum degree of desaturation at this intensity.

It should be noted that the BV trend observed during RILL was opposite to that formerly reported during incremental cycling (Costes et al. 2001; Grassi et al. 1999). Grassi et al. (1999) reported that BV increased during incremental cycle exercise to approximately 60–65% of $\dot{V}O_{2max}$ and then leveled off, whereas the present findings indicated that BV decreased consistently during RILL. The most likely reason for the discrepancy between the two studies is that RILL involves considerable isometric activity in the erector spinae muscles, whereas the muscle contractions during cycling are predominantly isotonic in nature. Previous research that has used NIRS to evaluate erector spinae hemodynamics during isometric exercise suggests that the decrease in BV is due to a reduced blood perfusion (occlusion) that is secondary to the increase in intramuscular pressure (Jensen et al. 1999). McGill et al. (2000) reported that erector spinae OXY decreased systematically during isometric contractions ranging from 2% to 30% maximum voluntary contraction (MVC), and suggested that this decrease was most likely due to a reduction in BV. Other investigations have demonstrated that at low intensities of isometric contraction (~20% MVC) blood flow to the erector spinae muscles increase, but at higher intensities (≥40% MVC) blood flow is occluded (Bondra-Petersen et al. 1975). Therefore, the consistent decline in BV observed during the RILL in the present study suggests a progressive increase in intramuscular pressure during the protocol with no signs of leveling off at the peak loads. Recently, Maronitis et al. (2000) reported that BV during 60-min of steady-state submaximal lifting increased systematically throughout the test with no signs of leveling off. This is in contrast to the present findings, which demonstrated a systematic decline in BV with increasing load to volitional fatigue. This discrepancy between the two studies could be due to several factors including differences in the test protocol, test duration and accumulation of vasodilatory metabolites in the exercising musculature. In the present study, a continuous incremental lifting and lowering protocol to voluntary fatigue at 10 lifts/min was utilized, whereas in the study cited a submaximal protocol which involved only lifting [the fixed load of 30 lbs (equivalent to 13.6 kg) load was lowered by a conveyor belt] was used in three 20-min segments. Although the subjects were asked to maintain a 70% MVC of the erector spinae between the lifting and lowering phases, it is possible that this could have affected the blood flow patterns which could have influenced the localized BV response. In the current study the average test duration for the male and female subjects was 14.2-min and 7.6-min respectively, whereas the test duration in Maronitis et al. (2000) was fixed at 60-min. It is likely that this difference would have resulted in significant differences in intramuscular temperature, as well as the

accumulation of vasodilator metabolites (e.g., adenosine, carbon dioxide, nitric oxide, etc.) (McArdle et al. 2001), both of which could have affected the localized BV measured by NIRS.

During recovery from the RILL, both OXY and BV demonstrated a rapid increase during the first 1 to 2-min which exceeded the resting baseline values in some cases, followed by a leveling off during the final 2-min. These trends were consistent with those reported for the erector spinae muscles subsequent to isometric exercise (McGill et al. 2000; Yoshitake et al. 2001). The rapid increase in OXY during the early stages of recovery reflects the reduced cellular oxygen uptake at the cessation of exercise, while the increase in BV was most likely due to the reduction in intramuscular pressure which allows reperfusion of blood flow to the exercising muscle. The driving force behind the initial reoxygenation during recovery is the need to replenish two phosphate groups, phosphocreatine (PCr) and adenosine triphosphate (ATP) (Chance et al. 1992). The latter phase of reoxygenation was most likely due to the need to oxidize metabolites such as lactate that accumulate during the exercise phase (McArdle et al. 2001).

Prediction of $\dot{V}O_{2peak}$ during RILL

In the current study, two cardiorespiratory variables that influence oxygen transport ($\dot{V}_E$ and HR), eight NIRS variables that reflect tissue hemodynamics (delta and range for the OXY and BV on the right and left sides), and five body composition variables (% body fat, LBM, FM, R-SFT, and L-SFT at the NIRS probe sites) were used in the stepwise regression analysis to predict the $\dot{V}O_{2peak}$ during RILL. Equation 1 indicates that the most important predictor of the absolute $\dot{V}O_{2peak}$ (l/min) is $\dot{V}_{Epeak}$, which explains 56% of the common variance between the two variables. This observation is not surprising because $\dot{V}_E$ is multiplied by the difference in oxygen fraction between the inspired and expired air for the calculation of the $\dot{V}O_2$ using the Haldane transformation (Consolazio et al. 1963). Hence, any increase in $\dot{V}_E$ would result in an increase in the absolute $\dot{V}O_2$ during the exercise protocol. The remaining five predictors, L-OXY-range, LBM, HR, L-SFT and R-BV-delta, individually explained 1.2% to 5.4% of the common variance with the $\dot{V}O_{2peak}$ (Table 4). Sharp et al. (1988) reported that absolute $\dot{V}O_{2peak}$ during discontinuous repetitive incremental lifting was significantly correlated with total body mass and LBM but not related to percent body fat in healthy males. The correlations with cardiorespiratory variables were not examined in their study.

The variables selected for predicting the relative $\dot{V}O_{2pcak}$ (Eq. 2) were quite different from those included for the prediction of the absolute value. In this case, FM, which was inversely related to the $\dot{V}O_{2peak}$, was the strongest predictor explaining 40% of the common variance. This was followed by the HR_{peak}, which increased the common variance by 16%, and all four left side tissue hemodynamic variables (L-OXY-range and-delta, L-BV-range and-delta), which increased the common variance by an additional 18%. The inclusion of the four left side NIRS variables was most likely because most subjects used a right foot lead during the RILL, which would place a greater stress on the left erector spinae muscles. Research has suggested that inconsistencies in trunk rotation during an isometric contraction could result in asymmetrical recruitment of motor units (Tsuboi et al. 1994), which theoretically would be evident in the local tissue hemodynamics observed in this study. Overall, these observations imply that the absolute and relative $\dot{V}O_{2peak}$ during RILL were dependent upon central oxygen transport, peripheral tissue hemodynamics, and body composition variables in healthy males and females. However, the predictors of the absolute and relative $\dot{V}O_{2peak}$ values were quite different, with the localized muscle OXY and BV variables on the left side playing a more important role in determining the relative $\dot{V}O_{2peak}$ during RILL.

Adipose tissue thickness as a limiting factor for NIRS

When assessing muscle OXY and BV using NIRS, the light must penetrate the skin and adipose tissue before it reaches the muscle tissue. In the validation of NIRS in humans, Mancini et al. (1994) indicated that skin blood flow did not significantly influence the measurement of BV and OXY. However, a recent study by van Beekvelt and coworkers (2001) indicated a negative correlation ($r=-0.70$) between adipose tissue thickness and muscle oxygenation uptake of the forearm muscles, implying that the NIRS measurements may be confounded by skinfold thickness at the measurement site. In the present investigation, no significant differences were observed between the R-SFT and L-SFT in either sex, or when the values of the sexes were pooled (Table 1). However, the L-SFT was significantly lower in males compared to females. Although R-SFT was significantly correlated with R-OXY-delta ($r=-0.37$) and R-OXY-min ($r=0.36$), no significant correlations were observed between the L-SFT and any of the NIRS variables on that side. Moreover, the use of SFT as a covariate did not influence NIRS responses between the sexes and the two sides. The implications of these findings are unclear and need to be further investigated.

In summary, the absolute $\dot{V}O_{2peak}$ during RILL was significantly higher in males compared to females. However, these differences were negated when the values were expressed relative to total body mass or lean body mass. Erector spinae OXY and BV decreased systematically during the RILL until the $\dot{V}O_{2peak}$ was attained in both sexes. Cardiorespiratory, tissue hemodynamic and body composition variables were able to predict approximately 74% of the common variance in the $\dot{V}O_{2peak}$, with the NIRS responses on the left side contributing more of the common variance towards the

relative $\dot{V}O_{2peak}$. The NIRS responses were not significantly influenced by SFT at the measurement site in males and females.

Acknowledgements This research was funded by an Operating Grant from the Alberta Workers' Compensation Board and Support for the Advancement of Scholarship, University of Alberta. We would also like to thank all the subjects who volunteered to make the project a success.

References

American College of Sports Medicine (2001) Resource manual for guidelines for exercise testing and prescription. Lippincott Williams Wilkins, Philadelphia

Belardinelli R, Barstow T, Porsasz J (1995) Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. Eur J Appl Physiol 70:487–492

Bhambhani Y, Maikala R, Buckley S (1998) Muscle oxygenation during incremental arm and leg exercise in men and women. Eur J Appl Physiol 78:422–431

Bondra-Petersen F, Mørk AL, Nielsen E (1975) Local muscle blood flow and sustained isometric contractions of human arm and back muscles. Eur J Appl Physiol 34:43–50

Borg G, Noble B (1974) Perceived exertion. Exerc Sport Sci Rev 2:131–153

Canadian Society for Exercise Physiology (1996) The Canadian physical activity, fitness and lifestyle appraisal manual: CSEP'S plan for healthy active living. The Canadian Society for Exercise Physiology, Ottawa

Chance B, Dait M, Zhang C (1992) Recovery from exercise-induced saturation in the quadriceps muscles of elite competitive rowers. Am J Physiol 262:C766–C775

Commissaris DA, Toussaint HM (1996) Dissociated oxygen uptake response to an incremental intermittent repetitive lifting and lowering exercise in humans. Eur J Appl Physiol 74: 264–273

Consolazio CF, Johnson RE, Pecora LJ (1963) Physiological measurements of metabolic function in Man. McGraw Hill, New York

Costes F, Prieur F, Feasson L (2001) Influence of training on NIRS muscle oxygen saturation during submaximal exercise. Med Sci Sports Exerc 33:1484–1489

Durnin JVGA, Womersley J (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br J Nutri 32:77–97

Fernandez JE, Marley RJ, Stubbs NB (1987) Lifting physical work capacity as a function of frequency. Proceeding of the 31st Annual Meeting of the Human Factors Society, pp 1331–1335

Grassi B, Quaresima V, Marconi C (1999) Blood lactate accumulation and muscle deoxygenation during incremental exercise. J Appl Physiol 87:348–355

Jensen BR, Jorgensen K, Hargens AR (1999) Physiological response to submaximal isometric contractions of the paravertebral muscles. Spine 24:2332–2338

Kunimune Y, Harada Y, Kabuto Y (1999) Recovery from exercise-induced desaturation in the paraspinal muscles in idiopathic scoliosis. Spine 24:2019–2024

Legg AJ (1981) Maximum acceptable repetitive lifting workloads for an 8-hour work-day using psychological and subjective rating methods. Ergonomics 24:907–916

Mancini D, Bolinger L, Li L (1994) Validation of near-infrared spectroscopy in humans. J Appl Physiol 77:2740–2745

Maronitis AB, Kovacs KM, Splittstoesser RE, Marras WS (2000) The effectiveness of whole body and localized measures of fatigue. In: Proceedings of the International Ergonomics Association XIVth Triennial Congress Human Factors and Ergonomics Society 44th Annual Meeting. International Ergonomics Association and The Human Factors and Ergonomics Society, San Diego, pp 5–91–95–94

McArdle WD, Katch FI, Katch VL (2001) Exercise physiology: energy, nutrition, and human performance. Lippincott, Williams, Wilkins, New York

McGill SM, Hughson RL, Parks K (2000) Lumbar erector spinae oxygenation during prolonged contractions: implications for prolonged work. Ergonomics 43:486–493

National Institute for Occupational Safety and Health (1981) Work practices guide for manual lifting. US Government Printing Office. DHHS Publication No. 81–122, Washington

Nindl BC, Sharp MA, Mello RP (1998) Gender comparison of peak oxygen uptake: repetitive box lifting versus treadmill running. Eur J Appl Physiol 77:112–117

Petrofsky JS, Lind AR (1978a) Comparison of metabolic and ventilatory responses of men to various lifting tasks and bicycle ergometry. J Appl Physiol 45:60–63

Petrofsky JS, Lind AR (1978b) Metabolic, cardiovascular, and respiratory factors in the development of fatigue in lifting tasks. J Appl Physiol 45:64–68

Revuelta N, Dauphin A, Kowslowski O (2000) Heart rate response to two lifting techniques. Arch Phys Med Rehabil 81: 958–959

Sharp MA, Harman E, Vogol JA (1988) Maximal aerobic capacity for repetitive lifting: comparison with three standard exercise tests and modes. Eur J Appl Physiol 57:753–760

Tsuboi T, Satou T, Egawa K (1994) Spectral analysis of electromyogram in lumbar muscles: fatigue induced endurance contraction. Eur J Appl Physiol 69:361–366

van Beekvelt MC, Borghuis MS, van Engelen BG (2001) Adipose tissue thickness affects in vivo quantitative near-IR spectroscopy in human skeletal muscle. Clin Sci 101:21–28

Yoshitake Y, Ue H, Miyazaki M (2001) Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. Eur J Appl Physiol 84:174–179

APPENDIX D: *CONSENT FORM*

APPENDIX E: *Physical Activity Readiness Questionnaire*

Physical Activity Readiness Questionnaire - PAR-Q (revised 2002)

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 and 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 (for example, back, knee or hip) 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 any other reason 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 all 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. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

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.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: 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.

No changes permitted. You are encouraged to photocopy 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 or GUARDIAN (for participants under the age of majority) _____ WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

Supported by: Health Canada Santé Canada

continued on other side

APPENDIX F: *DATA COLLECTION SHEET*

Title: Prediction of Endurance Performance for an 8-hour Workday in Patients with Work-related low back injuries

Subject Data:

Name: _____ #_____ Code_____

Occupation: _____

Date: _____

Age: _____ Date of Birth: _____

Height: _____ Weight: _____ Body mass index: _____ M. Schober: _____

Telephone number:

(Home) _____ (Work) _____ (e-mail) _____

Percent body fat:

Biceps		1) _____	2) _____	3) _____	
Triceps		1) _____	2) _____	3) _____	
Suprailiac		1) _____	2) _____	3) _____	
Subscapularis		1) _____	2) _____	3) _____	Average Body Fat: _____
Back	Left	1) _____	2) _____	3) _____	
	Right	1) _____	2) _____	3) _____	

Level of physical activity:

- Not physically active
- Vigorous activity 30-min 3-day a week
- Vigorous activity greater than 30-min more than 3-days a week
- Vigorous activity less than 30-min less than 3-days a week

Current health status:

a) Cardiovascular problem _____
b) Neurological problem _____
c) Low back pain (3 month prior lasting more than a day from the day of the test)
   a. Daily _____
   b. Not daily but once a week _____
   c. Not weekly but once a month _____
   d. Several times a year _____
   e. 2-3 times a year _____
   f. Once a year _____
   g. None at all _____

Do you suffer from chronic low back pain:

a) Daily _____
b) Not daily but once a week _____
c) Not weekly but once a month _____
d) Several times a year _____
e) 2-3 times a year _____
f) Once a year _____
g) None at all _____

When was the previous attack of pain _____

Any contraindications to exercise (hypertension, myocardial infarction, cerebrovascular disease, respiratory disease) _____

Current medications _____

Reason for terminating the BSME:

- Fatigue in _____
- Back pain _____
- Discomfort in thighs or legs _____
- Other reasons _____

Reason for terminating the RILL:

- Fatigue in _____
- Back pain _____
- Discomfort in thighs or legs _____
- Other reasons _____

Reason for terminating the Lifting Endurance test:

- Fatigue in _____
- Back pain _____
- Discomfort in thighs or legs _____

Other reasons _____

APPENDIX G: *BORG SCALE*

FOR RATINGS OF PERCEIVED EXERTION

6

7 **VERY, VERY LIGHT**

8

9 **VERY LIGHT**

10

11 **FAIRLY LIGHT**

12

13 **SOMEWHAT HARD**

14

15 **HARD**

16

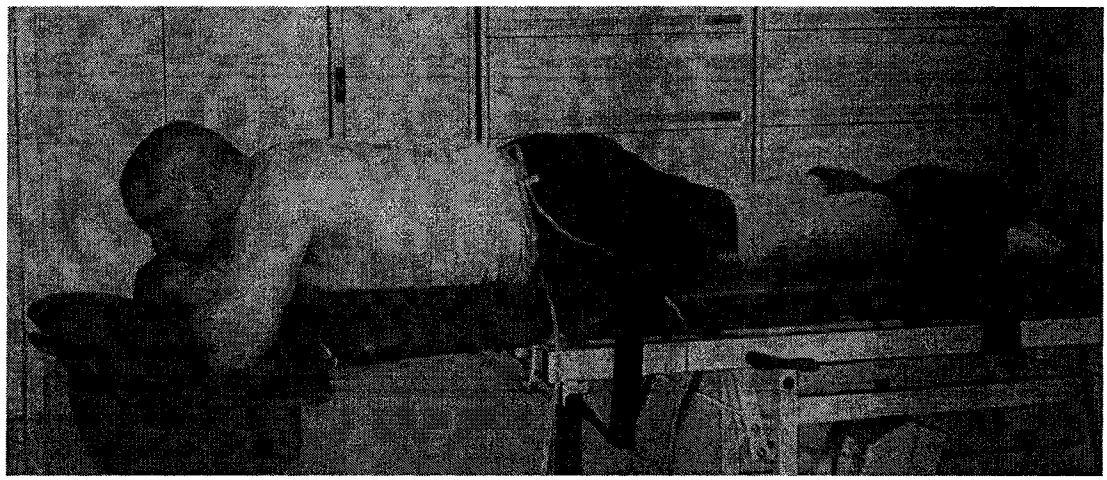
17 **VERY HARD**

18

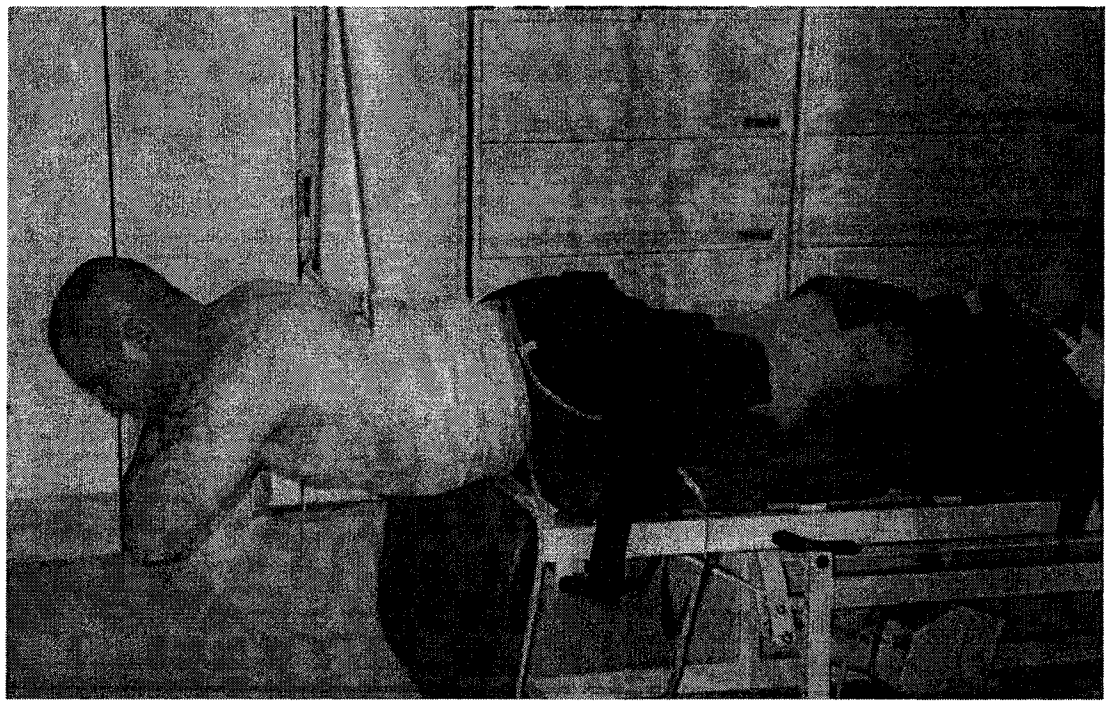
19 **VERY, VERY HARD**

20

APPENDIX H: *PHOTOGRAPH OF BSME*

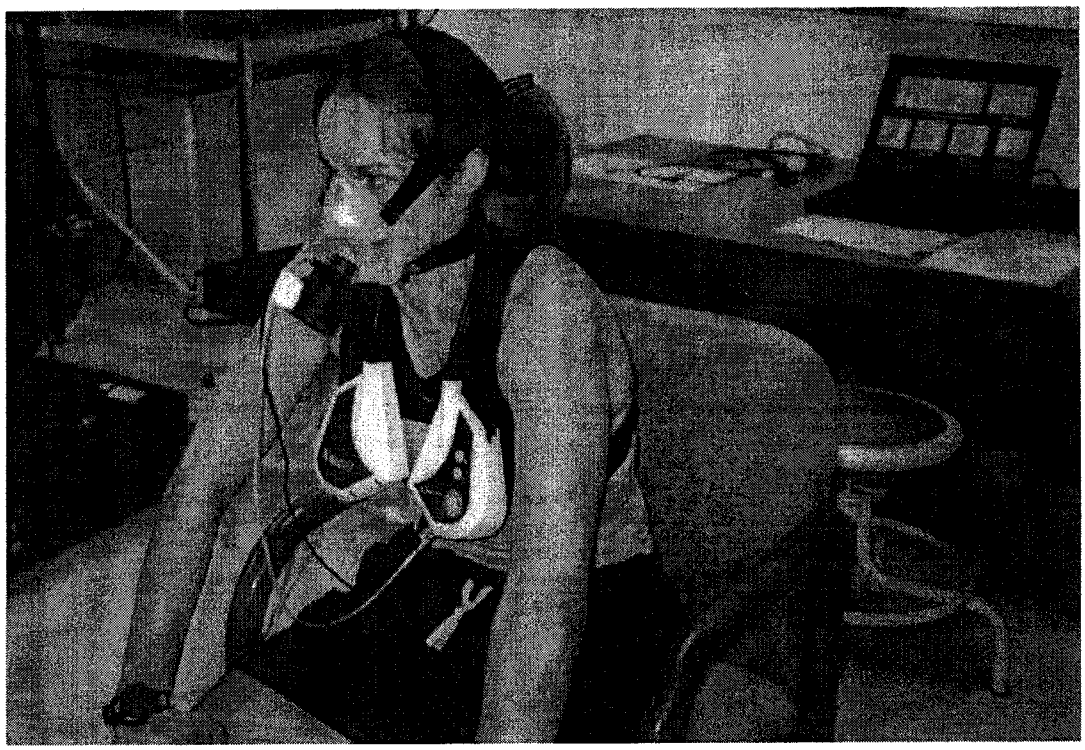


BSME resting position.



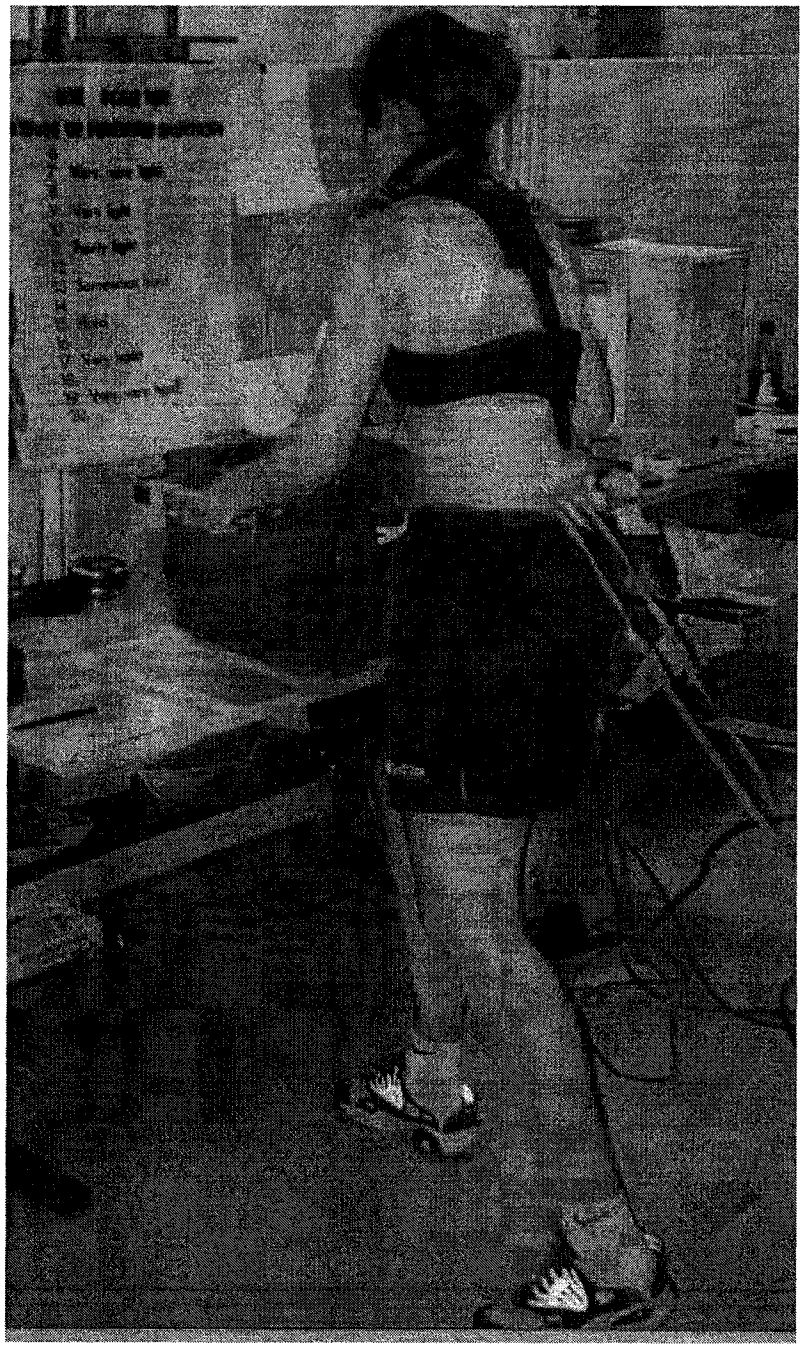
BSME test underway.

APPENDIX I: *PHOTOGRAPH OF VmaxST system*



VmaxST system with chest strap, facemask, turbine, and laptop computer for data display.

APPENDIX J: *PHOTOGRAPH OF RILL*



RILL test underway.

APPENDIX K: *SUBJECT INFORMATION LETTER - BSME*

approximately 3 cm to the left and right of the spinal column on the erector spinae muscles in the lower back. The sensors will be fastened using a tensor wrap (elastic bandage) around the waist (snuggly). The NIRS unit (near infrared spectroscopy) unit will then be switched on to measure the oxygen content of the active muscles. The NIRS unit uses light rays, but there is no radiation involved. Please inform the investigator of any undue discomfort immediately. You will be asked to lie down on the couch (plinth) for 2-minutes and rest. The investigator will fasten 2-straps at your hips and ankles (snuggly). Then the ledge under your upper body will be moved away leaving you to support yourself (in the same neutral position) by contracting your lower back muscles. You will fold your hands across your chest and maintain the neutral position for as long as you are able, the test has started. A stool will be placed approximately 1-foot in front of you so when you are unable to continue the test you can grasp the stool to support your self, thus ending the test. The ledge will then be moved back under your upper body for support. You may end the test whenever you feel too tired to continue or the position is too uncomfortable to maintain. After which you will be given a 4-minute rest. The NIRS sensors will take the 4-minutes of recovery oxygen data while you are resting on the couch. The investigator will ask for the reason you terminated the test. This will conclude the testing session.

Possible Benefits

The study will lead to a better understanding of the physiology that governs the back muscle endurance capacity. As a subject you will be provided with information regarding the endurance of your back muscles.

Possible Risks

This test is not associated with any long-term problems. You may experience some discomfort or fatigue of the back and legs during and shortly following the test, this is a common response following any physical activity or maximal exertion. NIRS has no known risks with the exception of possible redness (sunburn) that can occur on very fair skin. Appropriate adjustment of the light intensity will avoid this problem.

Confidentiality

All information will be kept confidential. No one other than the investigator involved in this study will have access to subject information. All data collection forms will be numbered and this number will then be put beside the subject name on a master list. The list will be locked in a filing cabinet in the Spinal Disorder Research unit at the University of Alberta. The names of the subjects will bit appear in the publication resulting from the research.

Freedom to withdraw

At any time during the study you may choose to stop taking part in the study. There will be no penalty for withdrawing from the study.

APPENDIX L: *SUBJECT INFORMATION LETTER - RILL*

performance, i.e., age, gender, body composition (percent fat), activity level, muscle size, and family and childhood background have been found to influence repetitive lifting. This study will examine one additional factor, oxygen use by the exercising muscle.

Study Requirements

The subject's will attendance one testing session with a time length of approximately 30- to 40-minutes. All subjects will be healthy males and females, with no known back problems (in the past 3-months), or any previous back surgery, heart, or circulatory problems, neurological conditions, or respiratory diseases. If you have any of the above problems please inform the investigator before the test begins.

Procedures

You will first complete a R-PAR-Q (Revised Physical Activity Readiness Questionnaire) and the informed consent to ensure you are a suitable candidate for involvement in the study. The study will then be explained to you, and you will be allowed to ask any questions pertaining to the study. The investigator will then measure your height, weight, and percent body fat (via skinfold calipers). You should bring a pair of shorts (gym) to wear during the test. You will then lift your shirt and be asked to bend over so as to touch your toes, thus allowing the investigator to locate your hip bones and trace (with a finger) to the spot on the back where the NIRS sensors will be attached. The attachment site will be approximately 3 cm to the left and right of the vertebral column on the erector spinae muscles in the lower back. The sensors will be fastened using a tensor wrap (elastic bandage) around the waist (snuggly). The NIRS unit will then be turned on to measure the oxygen content of the active muscles. NIRS uses light rays, thus there is no radiation involved. The investigator will then place the portable metabolic unit on you. This is a lightweight (600g) devise that fits snuggly about the shoulders, with a small mask to cover your mouth and nose allowing the collection of oxygen and carbon dioxide. Once the equipment is properly fitted and attached, you will sit quietly for 2-minutes while baseline data is collected. After which the test will begin, the lifting basket will be placed on the floor in front of you with a starting load of approximately 5-kgs in the basket. The graded protocol will consist of lifting and lowering the basket (from the floor to a waist height table) at a frequency of 10 lifts per minute, and at the end of each minute time frame 2-to 5-kgs will be added to the basket. The lifting and lowering test will continue until the cadence cannot be maintained or until volitional exhaustion (generally about 6-to 16-minutes). Once the lifting and lowering protocol has been terminated you will again sit quietly for 4-minutes while recovery data is collected. Once the recovery data has been collected the investigator will ask for the reason you terminated the test, and then the testing session will be complete.

Possible Benefits

The study will lead to a better understanding of the physiology that governs back muscle endurance capacity. You will also be provided with feedback pertaining to your cardiovascular fitness level. The pilot work will provide important information on the acute effects of lifting and tissue deoxygenation, which is lacking in the literature. The study has a direct application to individuals in specific occupations that are exposed to repetitive lifting on a regular basis.

Possible Risks
This test is not associated with any long-term problems. You may experience some discomfort, fatigue, difficulty in breathing, and sweating, etc. that is normally associated with physical activity. NIRS has no known risks with the exception of possible redness (sunburn) that can occur on very fair skin; however, appropriate adjustment of the light intensity will avoid this problem.

Confidentiality
All information will be kept confidential. No one other than the investigators involved in this study will have access to subject information. All data collection forms will be numbered and this number will then be put beside the subject name on a master list. The list will be locked in a filing cabinet in the Spinal Disorder Research unit at the University of Alberta. The names of the subjects will bit appear in the publication resulting from the research.

Freedom to withdraw
At any time during the study you may choose to stop taking part in the study. There will be no penalty for withdrawing from the study.

APPENDIX M: *SUBJECT INFORMATION LETTER - PSYCHOPHYSICAL*

The differences between the selected loads for each subject has been shown to be unrelated to body weight, lean body mass, maximal lifting capacity or stature, and therefore most likely reflects a true difference between subjects in their perception of what they regard as an acceptable load for an 8-hour workday. However, we do expect to note significant differences between the sexes and groups (i.e., healthy and LBP).

Study Requirements
All subjects will attend one testing session with a time length of approximately 20-min. The subjects will put into one of two groups healthy or LBP. However, persons with previous back surgery, heart, or circulatory problems, neurological conditions, or respiratory diseases with be excluded from participation. If you have any of the above problems please inform the investigator before the test begins.

Procedures
You will first complete a R-PAR-Q (Revised Physical Activity Readiness Questionnaire) and the informed consent to ensure you are a suitable candidate for involvement in the study. The study will then be explained to you, and you will be allowed to ask any questions pertaining to the study. The investigator will then measure your height, weight, and percent body fat (via skinfold calipers). You should bring a pair of shorts or sweat pants to wear during the test. The attached instructions on the last page of this document will be read to you. The lifting and lowering cadence will be set with a metronome at 10 lifts $\cdot$ min^{-1} and it will be played prior to the start of the test for familiarization. An undisclosed amount of weight will be placed in the basket on the floor in front of the table. You have 20-minutes to determine the load you feel that you can lift and lower to and from the table for an 8-hour workday without undue fatigue. An 8-hour workday is defined as 09.00 to 17.00 with two 15-min coffee breaks (10.00 and 15.00) and one 60-min lunch break (12.00). Encouragement will be given to adjust the load by adding or removing weight from the basket. You can stop prior to the 20-min time limit, once 15-min have passed you will be notified that there are 5-min remaining in the test. At 20-min the test will be stopped. At a time that you feel ready you may begin lifting, lowering and adjusting the weight in the basket.

Possible Benefits
The study will lead to a better understanding of maximal acceptable limits for lifting and lowering in both males and females and healthy and LBP populations. The study has a direct application to individuals in specific occupations that are exposed to repetitive lifting and lowering on a regular basis.

Possible Risks
This test is not associated with any long-term problems. You may experience some discomfort, fatigue, difficulty in breathing, and sweating, etc. that is normally associated with physical activity.

Confidentiality
All information will be kept confidential. No one other than the investigators involved in this study will have access to subject information. All data collection forms will be

numbered and this number will then be put beside the subject name on a master list. The list will be locked in a filing cabinet in the Spinal Disorder Research unit at the University of Alberta. The names of the subjects will bit appear in the publication resulting from the research.

Freedom to withdraw

At any time during the study you may choose to stop taking part in the study. There will be no penalty for withdrawing from the study.