The Research of Reoxygenation Time after Muscle Contraction

Academic Dissertation

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March 2017

The Research of Reoxygenation Time after Muscle Contraction

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Presented to the Graduate School of Comprehensive Scientific Research Program in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Biological System Sciences

at the

Prefectural University of Hiroshima

March 2017

Abstract

The prevalence of work-related muscle pain is large in the general population, especially in the caregivers working in elderly institutions. Despite significant advances over recent years in some research areas, the mechanisms of why work-related muscle pain occurs and the pathophysiological mechanisms behind the disorders are still unclear. One suggested explanation is that such pain is caused initially by a limitation of the local muscle circulation, oxidative metabolism and fatigue. There is a lack of objective methods to measure the development and diagnosis of muscle fatigue and the necessary recovery time.

Chapter 1. The purpose of this chapter is to bring a general introduction and literature review about the assessment of erector spinae muscle related to biomechanics and metabolism aspects. Near-infrared spectroscopy (NIRS) is a non-invasive technique that allows for determination of oxygenation and blood flow. The parameters commonly measured by NIRS are oxyhemoglobin/myoglobin (Hb/MbO2), deoxyhemoglobin/myoglobin (Hb/MbR), and total hemoglobin/myoglobin (THb/Mb). Using NIRS, Chance *et al* (1992) reported that recovery time is the balance between oxygen supply and oxygen demand as the bioenergetic resources are restored following determined exercise The purpose of this thesis was to evaluate NIRS (1) as a method for measuring muscle reoxygenation recovery time and hemodynamics for the erector spinae muscle (ESM), and (2) to investigate whether variables measured by NIRS differed between caregiver's movement during different simulated patient-handling tasks. In addition, to contribute for reducing incidences of workers

illness and injury, thereby improving the overall well-being of workers.

Chapter 2. An incremental experiment was conducted to calculate the half time to recovery (hTR), along with its predictors, based on an incremental test using NIRS. As well as, to attempted to examine the interrelationship between the NIRS and EMG variables assessing the metabolic and electrophysiological condition of the ESM during and after isometric task. All eleven subjects (n=11) performed six incremental static trials over time randomly as follows: 10, 20, 30, 40, 50, and 60s, with 15 min rest between each trial. A fast linear decreasing phase of oxygenation index at the beginning and a constant decreasing until the end of exercise was found on the results. The recovery period was followed by systematic increase of oxygenation index with the values being at or near baseline during the final 2 minutes. There were progressive and significant increases in the hTR of ESM related to the incremental time. There was a negative trend for a relationship between MF slope during the BSME test and an increase in hTR after the test. Considering that ischemic muscular activity occurs in this muscle, these results provide information about muscle aerobic and anaerobic function during and after exercise.

Chapter 3. A volitional exhaustion experiment was conducted with aim to assess ESM hTR by NIRS during isometric task. All eleven subjects (n=11) performed one single static task. Two min were measured as a baseline following by an endurance test until volitional exhaustion and subsequently 5 min of recovery period. Fast linear decreasing phase of tissue oxygenation index (TOI) at the beginning and a constant decreasing until the end of exercise. The half time to recovery (hTR) demonstrated to be between about 21 s and 35 s (right and left side pooled). Mean EMG MF decreased progressively to nearly 70% of resting value in both sides. Furthermore, prolonged static posture might diminish oxygenation level and MF, increasing susceptibility to fatigue. The results suggested that the hTR can be an effect evaluations to measure muscle oxygenation after subjective fatigue.

Chapter 4. Simulated experiment with objective to estimate the low back joint moment and calculate the hTR during an isotonic muscle task was conducted. The study subjects were required to perform two distinct transfer tasks: 1) Elevation of the patient from a supine position in bed to a sitting position (SS), and 2) Transferring of the patient from sitting on the bed to sitting in a wheelchair (SW). An additional third task, namely, continuous performance of SS and SW (SS+SW) was also performed. The forces and moments of the L3/L4 joint, hip joints, knee joints, and ankle joints were estimated using the kinematic and inertial properties of the body, together with the process of inverse dynamics and the developed free body diagram (FBD) for motion analysis. Simple main effect analysis showed that the hTR for SS+SW was significantly higher than those for SS and SW ($p < 0.05$), but there were no differences between the right and left lumbar during SS and SW. Low back muscles with their relatively small moment arms in relation to external forces contribute significantly to loading across intervertebral joints. These loads can challenge both tissue and structural tolerance of the spine. Not surprisingly, mechanical factors are often identified as the primary cause in a large proportion of low back disorders. This results suggested an adequate period of rest between patient's transfer movement could avoid ESM fatigue and prevent low back pain.

Chapter 5. General conclusions. The recent advanced of NIRS would help to refine the understanding of skeletal muscle oxygenation in more different pathophysiology conditions. The findings of this study have implications for future investigations on the mechanism of action of the low back muscles. A higher joint moment (i.e., 3D motion capture), a reduction in the strength (i.e., EMG), endurance, and decreased oxygenation levels (i.e., NIRS) of the low back muscles has been implicated as a contributory factor to fatigue. Adequate blood supply is one the most essential component to withstand fatigue and prevent the loss of lumbar muscle function. Therefore, this study could demonstrated an adequate period of rest between caregiver’s movements when transferring patients between bed and wheelchair. This new knowledge results may help understanding the recovery time of the muscle oxygenation after work and further prevent fatigue and low back pain.

Acknowledgments

I wish to express my sincere gratitude to my supervisors Prof. Sumii Hiroshi, Prof. Mitsuhisa Shiokawa, Prof. Ono Takeya, Prof. Horiguchi Toshitaka, Prof. Harada Toshihide for their kind guidance and support throughout the course of my study and for giving me the opportunity to continue to study in this university. I would like to express my heartfelt thanks to Yahata scholarship for providing me a scholarship throughout my life in Japan. I thank all members of Sumii and Shiokawa’s Laboratory for very valuable assistance during my experiments. I deeply thank to my Japanese father Hiroyuki Shinagawa, for sharing with me a happy life with a lot of talk together in Hiroshima. I am grateful to Akiko Masumura for supporting my life in Japan. She has been a volunteer supporting internationals students for more than 50 years.

Last but not least, I am very grateful to my family, even in their absence living in so far from Japan, they could give me energy and incessant encouragement for me to continuing this work. I dedicate this work to my parents (Hissashi Mori and Tokie Mori) my brothers (Fabio and Washington Mori), relatives and friends.

A special thanks to all volunteers that in somehow contributed to this experiment: Yuji Tanada, Yurimi Matsumoto, Yo yo, Mayumi Ishida, Masako Terada, Zhao Qian, Ou meigun, Jun Kawamura, Mai Kondo, Akiko Sakai, Yoshiko Hayasaka, Shumai Ra, Ishida Hiroshi, Uno Machiko, Yuki Sawada, Kana Kageyama and Tatsu Hanada, Sato Saki, Lira Septarina, Adn Feby Abdillah, Miyabe Hikaru, Sasaki Ichiyo, Okano Rie, Meguro Chihiro, Masuda Mie, Ihara Mai, Iwasa Yuri, Kimura Noriko, Takanori Kedo, Shiohama Norika, Tanaka Shouya, Ogura Ayaka, Ichikawa Natsuko, Yoshitake Yuya, Matsumoto Yuka and Xiajing Jiao.

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Chapter 1

General Introduction and Literature Review

1.1 General Introduction

Work-related musculoskeletal disorders affect a large number of people in the world today. The prevalence of work-related muscle pain is large in the general population, especially in the caregivers working in elderly institutions.

The aging of the Japanese population is thought to exceed that of all other nations, with the country purported to have the highest proportion of elderly citizens. According to the statistics of the Japanese Health, Labor, and Welfare Ministry, the proportion of the elderly (65 years or older) reached 20.8% in the fiscal year 2011, and is estimated to increase to 39.6% in 2050 (Figure.1-1). This has induced various health issues among caregivers in nursing homes. The occupational condition is related to the requirement for the caregivers to repeatedly perform activities such as lifting the patients from and to anomalous postures.

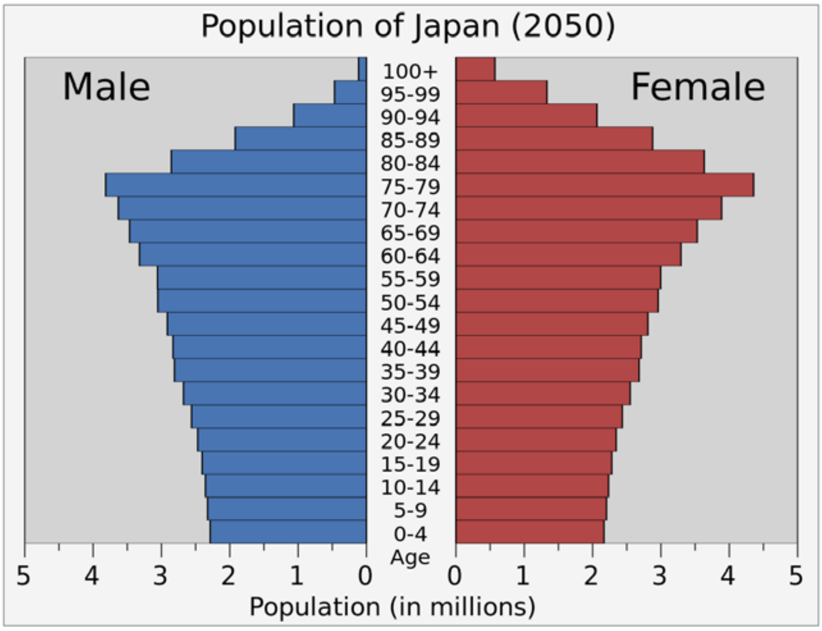


Figure 1-1: Japanese population in 2050. Japanese Health, Labor and Welfare (2011).

Patient transfer has been found to be associated with most low back injuries suffered by caregivers (Russell *et al*. 2007; Schibye *et al*. 2003). Additionally, nurses and caregivers exhibit high rates of low back pain (LBP) and worker compensation claims for back injuries (Daynard *et al*. 2001). In the year 2011, the total annual medical cost of work-related LBP was estimated to be 82.14 billion yen (Itoh, Kitamura, and Yokoyama 2013). A recent systematic review particularly reiterated the prevalence and high risk of work-related LBP in patient-handling and nursing occupations (Daynard *et al*. 2001).

It is thus reasonable to suppress an increase of this medical cost by suppressing the occurrence of work-related LBP.

Identification and preventive procedures related to musculoskeletal disorders (MSDs) have been the major focus of the 12th Occupational Safety and Health Program (Ministry of Health, Labour and Welfare, Japan, 2013). Although knowledge has been gained about the possible causes of work-related LBP, little progress has apparently been made in preventing this critical work-related complaint.

1.2 Literature Review

1.2.1 The Erector Spinae Muscle: Specifications and Assessments

The erector spinae originates from the sacrum, iliac crest, and the erector spinae aponeurosis. It inserts across a number of spinous processes at the lumbar and thoracic region and subdivisions insert across the ribs, cervical spinous processes and skull. It is likely that the muscle functions mainly to produce spine extension and rotation, as well as providing stability. The erector spinae has relatively uniform muscle architecture. The upper and lower fibers of the erector spinae have a similar physiological cross-sectional area (Figure 1-2). Furthermore, their line of action over the lower thoracic and lumbar region is just underneath the fascia, such that forces in these muscles have the greatest possible moment arm and therefore produce the greatest amount of extensor moment with a minimum of compressive penalty to the spine (McGill 2007).

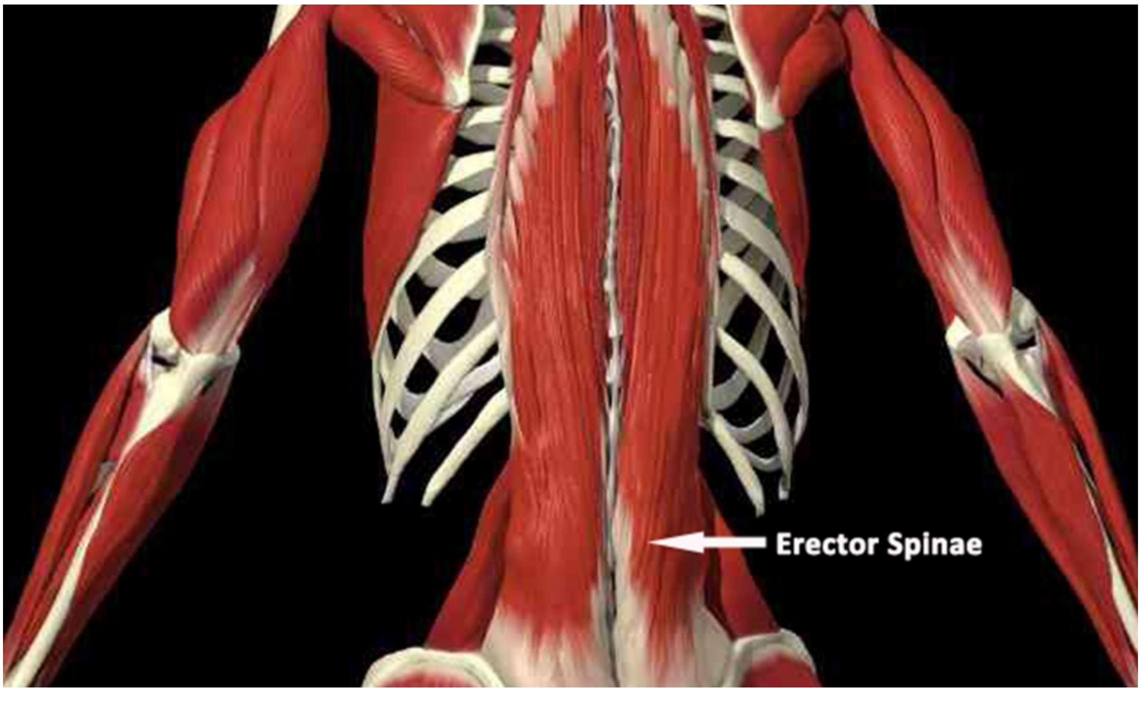


Figure 1-2: Erector spinae muscle. It extends throughout the lumbar, thoracic and vertical regions, and lies in the groove to the side of the vertebral column.

Probably the single most important mechanical function of the spine is to support load that arise from the interaction between external loads and muscular forces. Trunk muscles with their relatively small moment arms in relation to external forces contribute significantly to loading across intervertebral joints. These loads can challenge both tissue and structural tolerance of the spine. Not surprisingly, mechanical factors are often identified as the primary cause in a large proportion of low back disorders.

Consequently, knowledge of loads sustained by the spine and its hemodynamics parameters is necessary for a more rational design of spine injury prevention strategies and rehabilitation programs.

Growing research efforts for low back pain remains a major public health problem in the industrialized world. Tests of trunk muscle performance are essential to understanding the muscle strength/endurance. Assessing muscle dysfunction or increased fatigability have been also suggestive approach based on providing the patients with information on their physical potential and planning an efficacy rehabilitation program. Demoulin *et al* (20129) classified the assessment of trunk in:

✓ Static test; Dynamic tests; Dynamometric tests; Muscle strength tests; Static strength test; Isokinetic test; Static endurance; Dynamic endurance; Muscle fatigue tests

Several studies over the years have shown the flexion-relaxation phenomenon or the apparent myoelectric silence of the low back extensor muscles during a standing-to-full flexion maneuver. As one bends forward, the spine flexes and the extensors undergo eccentric contraction. As full flexion is approached, the passive tissue rapidly take over moment production, relieving the muscle of this role and accounting for myoelectric silence (Hashemirad *et al*. 2009; de Looze *et al*. 1998).

The “passive” of the lumbar extensor muscles appeared to occur only in an electrical sense because they generated substantial force elastically during full spine flexion through stretching.

Mechanical Loading and Field-based Risk Factors

The consequences of high mechanical loading on low back could produce low back pain and injuries attributed to manual lifting activities. It continue as one of the leading occupational health and safety issues facing preventive medicine. Despite efforts at control, including programs directed at both workers and jobs, work-related back injuries still account for a significant proportion of human suffering and economic cost to this nation. The majority of specific risk factors that are addressed in the epidemiological literature are (McGill 2007):

- Static work postures
- Seated work postures
- Frequent bending and twisting
- Lifting, pulling and pushing
- Vibration
- Generation of spine power

The National Institute for Occupational Safety and Health report (Waters *et al*. 1993) provides a good review linking activities requiring lifting, pushing and pulling with increased risk of LBD. Nursing and healthcare workers are annually listed as having the second highest injury and severity rates among listed professions in the United States by the NIOSH.

In aged society, like Japan, various health issues occur in caregivers in nursing homes. Risk factors include physical workload such as the manual lifting and transferring of patients, working conditions such as working time and rest during the night shift, and the working environment. Itoh *et al* (2013) have indicated that in 2011, the total annual medical cost for work-related low back pain was 82.14 billion yen, consisting of 26.48 and 55.66 billion yen for inpatients and outpatients respectively, resulting in a considerable economic burden to Japanese society.

Muscle Contraction by Biomechanical Reactions

ATP provides the energy for this contractions when it is dephosphorylated at the myofibril by ATPase. Next, the ATP is reformed in the creatine kinase reaction when ADP is rephosphorylated by phosphocreatine (PCr). ATP concentration remains constant at the expense of PCr as shown by the sum of these two reactions. This indicated that the net result of muscular contraction is a breakdown of PCr and one molecule of phosphate (Pi) is formed for every molecule of PCr dephosphorylated. Creatine is subsequently rephosphorylated by ATP generated from oxidative phosphorylation. PCr, which undergoes breakdown in the reaction, represents the most immediate energy reserve in skeletal muscle for ATP resynthesis at the onset of muscular contraction (McMahon and Jenkins 2002) (Figure 1-3). PCr represents the most immediate reserve for the rephosphorylation of adenosine triphosphate (ATP). As a fall in the level of PCr appears to adversely affect muscle contraction.

$$\text{ATP myofibrils} \xleftrightarrow{\text{ATPase}} \text{ADP} + \text{PCr} + \text{contraction}$$

$$\text{ADP} + \text{PCr} \xleftrightarrow{\text{Creatine kinase}} \text{ATP} + \text{Cr}$$

$$\text{SUM} \quad \text{PCr} \longleftrightarrow \text{Cr} + \text{Pi}$$

$$3\text{ADP} + 3\ \text{Pi} + \text{NADH} + {}_{1/2}\text{O}_2 + \text{H}^+ \rightarrow \text{NAD}^+ + 3\ \text{ATP} + \text{H}_2\text{O}$$

Figure 1-3. Muscle contraction is derived from the hydrolysis of adenosine triphosphate (ATP) to adenosine diphosphate (ADP) and inorganic phosphate (Pi).

Mechanism of Muscle Fatigue

The common definition of fatigue proposed by Edwards (1983) states that fatigue is a “failure to maintain the required or expected force (or power output).” The definition used in this study are presented by (Gandevia 2001) as the definition of muscle fatigue reflects both peripheral and central fatigue and focuses on the reduction in force that occurs during fatigue:

- ✓ Muscle fatigue: any exercise-induced reduction in the ability of a muscle to generate force or power; it has central and peripheral causes.
- ✓ Peripheral fatigue: fatigue produced by changes at or distal to the neuromuscular junction.
- ✓ Central fatigue: a progressive reduction in voluntary activation of muscle during exercise.

While the fatigue of organism may be described by the progressive reduction of reserve energy or the rate of its expenditures, a similar description for individual tissues is obscure. A variety of methods have been used for measuring localized muscle fatigue.

Fatigue is a complex and multifaceted phenomenon, the underlying mechanisms of which remain somewhat elusive. The lack of clear comprehension regarding the sites and mechanisms of skeletal muscle fatigue is indicative of the complexity of the fatigue process.

1.2.2 Near-infrared Spectroscopy (NIRS)

NIRS is a non-invasive, optical technique that has been widely used to monitor tissue oxygenation through the absorption of light photons in the 700-1000nm spectrum by hemoglobin (Hb), myoglobin (Mb) and cytochrome oxidase (Van Beekvelt *et al.* 2001; Boushel and Piantadosi 2000; Ferrari, Muthalib, and Quaresima 2011; Kell and Bhambhani 2008; Ryan *et al.* 2012).

Measuring Muscle Oxygenation

Over the last few decades, functional near-infrared spectroscopy (NIRS) has been attracting interest from the psychology and medical imaging communities for its ability to non-invasively measure the cerebral hemodynamic changes associated with functional brain activity (Chance *et al.* 1992; Delpy *et al.* 1988; Hamaoka *et al.* 2007; Wolf *et al.* 1997). NIRS is an optical spectroscopy technique, which uses time-resolved, multi-wavelength measurements to infer changes in the optical absorption of tissue and thereby to report changes in oxy- and deoxy-hemoglobin, the two primary absorbing chromophores in biological tissue that vary dynamically with a functional task.

Maybe one of the pioneers to starts experiments on muscle oxygenation in vivo by photoelectrically recording was G. A. Millikan. Until that time, papers had been described how the saturation changes in vivo by chemical specific and time sensitive. By using a soleus muscle of the cat, the findings was a very rapid recovery of the muscle after a maximal tetanic contraction of a few seconds durations, suggesting that a very large fraction of the total oxygen required by normal muscular activity is used up at the moment of contraction and not afterward (Millikan 1937).

However, the ratio of hemoglobin to myoglobin in human skeletal muscle is approximately ten, showing that the majority of the NIRS signals comes more from hemoglobin than myoglobin (Seiyama, Hazeki, and Tamura 1988). More quantitative muscle studies were performed using a three-wavelength NIRSCWS instrument (OM-100A, Shimadzu Co., Japan). This instrument was used in several studies, i.e. to develop a forearm VO_2 method (Kime *et al*. 2003), to investigate the influence of adipose tissue thickness on the NIR measurements (Homma, Fukunaga, and Kagaya 1996).

Quantitation was further improved by combining four-wavelength attenuation data, measured by the NIRO500 (Hamamatsu Photonics, Japan). The NIRO500 was used in several studies, i.e. to develop forearm VO_2 and flow methods (De Blasi *et al.* 1993), to investigate the effect of the treadmill speed and slope on the quadriceps oxygenation (Grassi *et al*. 1999).

One of the methods for assessing muscle oxidative capacity in vivo includes muscle biopsy (Costes *et al*. 2001). Muscle biopsy may be useful and regarded as the gold standard, but the inconvenient to apply in many physiological and clinical conditions because of its invasive patterns. Phosphorus magnetic resonance spectroscopy (P-MRS) can provide a non-invasive and repeated method to measure muscle energy metabolism. The P-MRS device, however, is rather expensive and requires careful maintenance for precise measurements. Furthermore, this methodology has its own limitations in practical use (Brizendine *et al*. 2013; Fulford *et al*. 2014). In 1992, Chance at al revealed a study about the exercising skeletal muscle with NIRS.

NIRS methodology is a useful tool because it is both non-invasive and inexpensive when compared to P-MRS.

Fulford *et al* (2014), reported in their study with P-MRS and NIRS, a good reliability during a spinal muscle function. Ten healthy participants performed exercise involved holding the upper body until fatigue. ICCs indicated a good to excellent reliability of baseline measures and of amplitude changes during fatigue and recovery.

Measurement Principle of NIRS

a) Changes in concentration

- Changes in oxygenated hemoglobin: ΔO_2Hb
- Changes in deoxygenated hemoglobin: ΔHHb
- Changes in total hemoglobin: ΔcHb
- Changes in difference between oxidized and reduced cytochrome oxidase: ΔCtOx

b) Tissue oxygenation index (TOI)

- Ratio of oxygenated to total tissue hemoglobin, expressed in percentage (%).

The detection probe has a light sensor (photodiode) consisting of three small sensors (Figure 1-4). Changes in concentration are calculated from changes in light intensity detected by the center sensor, and TOI values are calculated from the light attenuation slope along the distance (p) from the emitting point, $\delta A/\delta p$, detected by the three sensors.

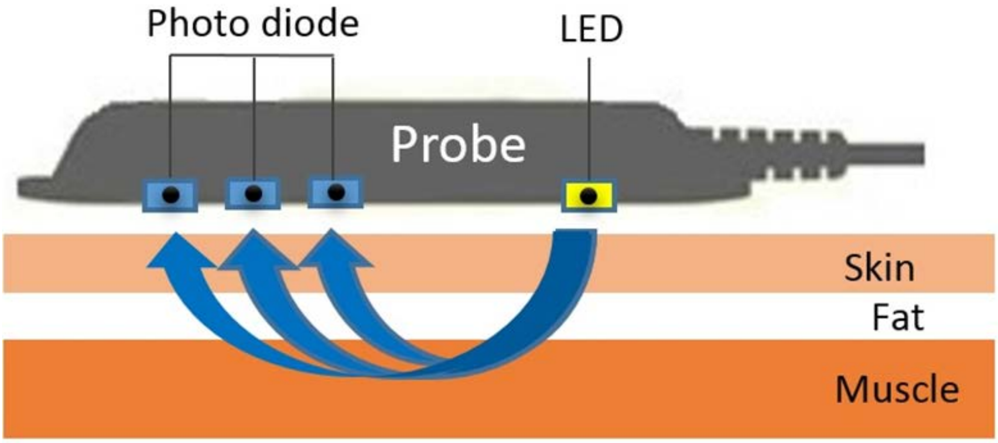


Figure 1-4. Schematic measurement principle and structure of a NIRS probe, consisting of three photo diode sensors.

Until now, there are no "Gold standard" for in vivo measurement with oxygenation monitors using NIRS, because such standards are based upon experience with a variety of devices and/or methods, which do not presently exist in sufficient numbers. This situation makes it difficult to evaluate data measured with NIRS device.

Tissue Oxygenation Index (TOI) as Parameter of NIRS

NIRS method is based upon the relative transparency of biological tissue to light in the near-infrared part of the light spectrum. Signal detection is based on levels of light directed through the muscle and picked up by the detector after the light has travelled through tissue.

TOI indicates the dynamic balance between oxygen supply and oxygen consumption in tissue capillaries, arterioles and venules (Fulford *et al.* 2014; Taelman *et al.* 2011):

$$\mathrm{TOI} = \frac{k.HbO_2}{k.HBO_2 + k.HbR}$$

where **k** = constant scattering distribution; **HbO₂** hemoglobin concentration; **HbR** concentration in reduced hemoglobin.

NIRS monitoring system implemented in this research was performed by NIRO-200NX (Hamamatsu Photonics, Hamamatsu city, Japan), which simultaneously implement BL (Beer-Lambert), and SRS (Spatially resolved spectroscopy) methods (Figure 1-5).

Figure 1-5: NIRO 200NX (Hamamatsu Photonics, Japan).

NIRS parameters provide a measure of concentration changes in oxyhemoglobin, deoxyhemoglobin, and total hemoglobin with respect to an arbitrary initial value, and are expressed in µmol/L.cm. These measures could be converted to µmol/L through multiplication by the interoptode distance (4 cm in this study) and the path-length factor. As for SRS, two parameters are provide, one gives information about tissue oxygenation (TOI, Tissue oxygenation index), it is expressed in % and represents the percentage ratio of oxygenated hemoglobin to total hemoglobin. The other parameter is again a measure of total hemoglobin contents in the tissue (THI, total hemoglobin index) and is expressed in arbitrary units. In this device, cannot discriminate between hemoglobin and cytoplasmatic myoglobin, therefore, all measurements actually refer to [hemoglobin+myoglobin] in the sample volume.

Recovery Time Measured by NIRS

(Luczak and Rohmert 1984), defined recovery as the regeneration of decreased maximal strength and strength reduction as a function of the degree of fatigue. However, the aim of every cell to balance out the capacity of lost (fatigue) by its activity, a process of recovery occurs. According to Chance *et al* (1992), recovery is the time required to restore the intramuscular oxygenation level after exertion may be an indicator for the oxygen-retaining capacity of muscles.

Half time to recovery (hTR) is the index of oxygen demand and delivery measure after exercise, which is also a marker of aerobic-resaturation of exercise-desaturated (Chance *et al*. 1992).

Here we determined hTR as the time takes to reach 50% of the difference between the minimum oxygenation level at the end of the contraction phase and the maximal level at recovery period. Parameters were analyzed using calculations obtained by monoexponential curve fitting (Allart *et al*. 2012; Buchheit and Ufland 2011; Chance *et al*. 1992; Ding *et al*. 2001; Motobe *et al*. 2004; Olivier *et al*. 2013) (Figure 1-6).

(Iotti *et al*. 2004), found oscillation of phosphocreatine re-synthesis during recovery from exercise in humans. In their experiment using P-MRS, a mathematical model implies patterns of PCr recovery othen than mono-exponential ones care conceivable, the mono-exponential pattern being a particular case of function which are solutions of the differential equation upon which the model is based. Phosphocreatine is present in the skeletal muscle and other tissues, where it represents a storage of available energy able to buffer energy requirements of the cell. During muscle contraction phosphocreatine is used and it re-synthesized during recovery. When the metabolic stress is over, phosphocreatine is re-synthesized from ATP which in turn is synthesized by the energy-producing mitochondrial machinery.

Reoxy-rate is now been accepted as a good non-invasive marker of muscle aerobic function after dynamic exercise (Ichimura *et al*. 2006; Puente-Maestu *et al*. 2003). Additionally, Reoxy rate has been shown to present similar recovery kinetic than PCR after submaximal exercise (McCully *et al*. 1994).

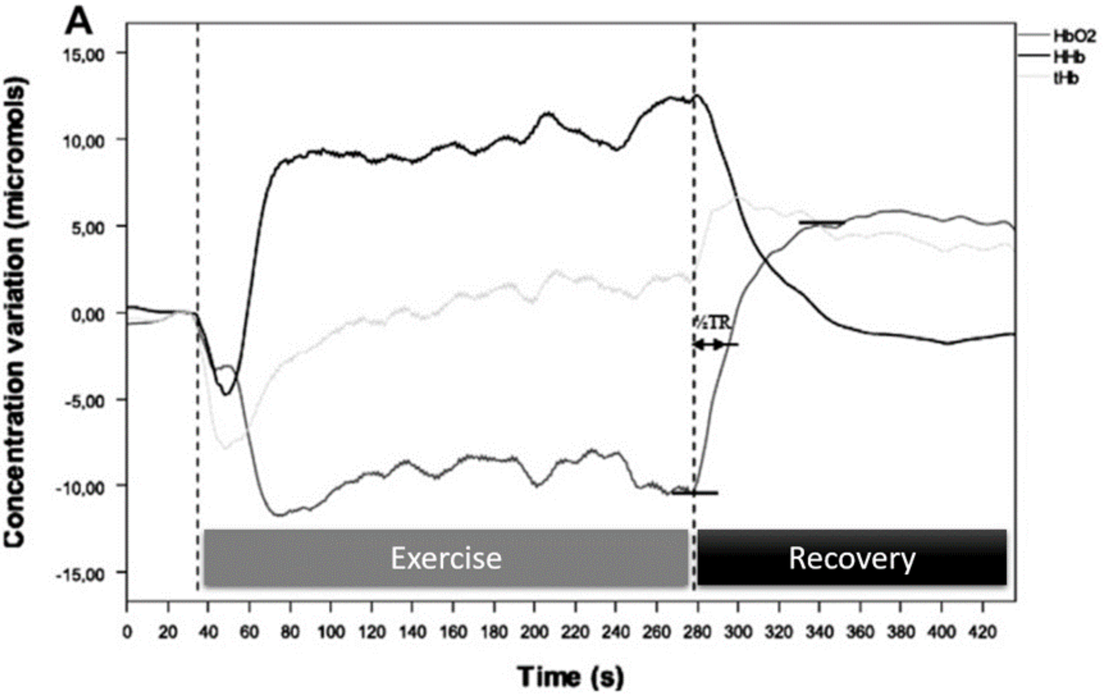


Figure 1-6: Example of a muscle oxygenation recording during and after effort. Change over time in HHb, HbO2 and tHb, 1/2TR (recovery half time). E Allart and others, ‘Evaluation of Muscle Oxygenation by near-Infrared Spectroscopy in Patients with Becker Muscular Dystrophy.’, Neuromuscular disorders : NMD, 22 (2012), 720–27.

1.2.3 Electromyography (EMG)

Muscle force is produced when a group of muscle fiber are activated by their common motor nerve, in a so-called motor unit (MU). Surface electromyography (EMG) registers the electrical activity of a number of motor units being activate and the signal amplitude, typically measured through the root mean square (RMS) value of the EMG signal, is a measure of the extend of muscle activity.

Estimation of Erector Spinae Muscle fatigue with Electromyography

Electromyography has been considered a reliable tool for an indication of localized muscle fatigue (De Luca 1997). In recent years authors have state that the median frequency (MF) of the EMG power spectrum is sensitive to the physiological manifestation of fatigue (De Luca 1997; Tsuboi *et al*. 1994). It was observed by De Luca (1997), a decrease in the MF in the power spectrum (when calculated with a fast Fourier transformation) under sustained isometric contraction, which is interpreted as muscular fatigue (Figure 1-7).

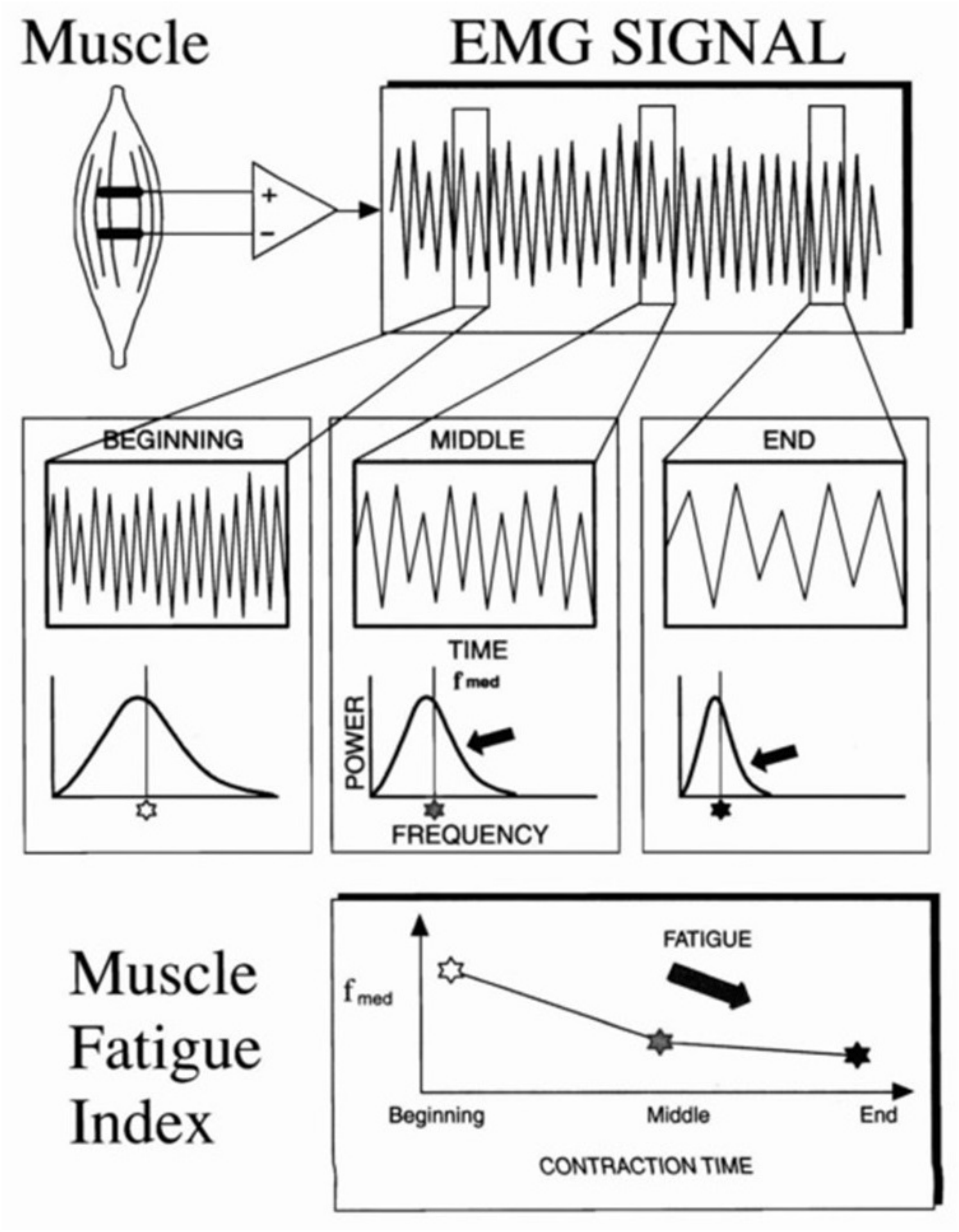


Figure 1-7: Diagrammatic explanation of the spectral modification that occurs in the EMG signal during sustained contractions. The muscle fatigue index is represented by the median frequency of the spectrum. (De Luca, 1997).

Figure 1-8: Multichannel telemetry surface electromyography with wireless electrodes (WEB-7000, Nihon Kohden, Japan)

The WEB-7000 Multichannel Telemetry system EMG (NIHON KOHDEN, Japan) was used to monitor muscle activity in all the experiments in this study. This system primarily consisted of EMG (ZB-150H), EMG transmitters (cordless telemetry electrodes), a BIO Repeater (ZB-700H), receiver antenna (ZR-700H), a receiver, and a personal computer (Figure 1-8).

Applying EMG to assess the state of a group of muscles in the lower back is to detect signals from deepen layers located about the spinal column which contribute to extension and rotation of the trunk. Contractile fatigue is susceptible to subjectivity because contractile force may decrease due to psychological factors as well as to physiological factors. The spectral variables decrease continuously from the onset of contraction, thus providing an indication of the rate of the fatigue process early in the contraction.

De Luca (1997) showed that a decrease in conduction velocity is causally related to a decrease in the pH of a bath fluid surrounding the muscle. During sustained contraction, the pH of the interstitial fluid decreases as lactic acid accumulates in the membrane environment. Thus, the rate of blood flow in the muscle can affect strongly the behavior of the EMG spectral variables. Performing the contraction in an isometric mode where the internal pressure remains reasonably constant and does not alter the rate of blood flow, as is the case in dynamic contraction.

1.2.4 NIRS and EMG

Simultaneous measurements in the right and left ESM using EMG and NIRS have been demonstrated to obtain a reliable quantitative data (van Dieën *et al*. 2009; Kankaanpää *et al*. 2005; Masuda, Miyamoto, and Shimizu 2006; Movahed *et al*. 2012; Shin and Kim 2007; Yang *et al*. 2007). Van Dieen *et al* (2007) have designed whether trunk extensor fatigue occurs during low-level activity with both machines. They are results suggested that even at low-level of EMG activity, fatigue manifestation were found. A similar change of Hb and EMG frequency content was found in ESM contraction at 60% MVC (Kramer *et al*. 2005). We adopted in our study the BSME posture and the mean MVC was found at 40%.

A moderate correlation (r = 0.3) between change in oxygenation and EMG frequency content has also been reported for ESM active ate approximately 50% MVC (Albert *et al*. 2004). Two studies on ESM activity in approximately 50-60% MVC contractions reported substantial between-subjects variations in the pattern of change in hemoglobin (Kell, Farag, and Bhambhani 2004; Kramer *et al*. 2005), while a third study reported a consistent decrease of 60% MVC (Yoshitake *et al*. 2001). These results suggest that blood supply starts to be a limiting factor in these muscles only around these levels of contractions.

Shin & Kim (2007) identified the relationship between the cumulative fatigue of trunk muscles and the recovery time during dynamic lifting and lowering in symmetric and asymmetric postures. They demonstrated that the trunk muscles are physiologically compensated by the good supply of oxygen in spite of the high force generated during dynamic lifting.

1.3 Research Objectives

This research was approached from the standpoint of how muscle contractions affects the myoelectric and hemodynamic manifestations of the erector spinae muscle. Further, three main objectives were developed to outline this results. The first objective was to assess the hemodynamic aspects of erector spinae muscle during and after isometric contraction and additionally finding the relationship between myoelectric and hemodynamic evaluation. The second objective was to assess the erector spinae muscle during and after fatigue task with EMG and NIRS. The third objective was to determine whether caregiver’s movements affect the hemodynamic manifestation during and after patient-handling task on simulated experimental test.

1.4 Research Significance

This research will have implications across multiple activities with the most obvious being related to healthcare. The potential benefit of this research is that it quantified the effects of hemodynamics manifestation of the muscle contraction and clarify the recovery time; it would not only reach the caregivers during patient-handling task, but in athletes in sports and other kinds of workers. Additionally, it is important to evaluate the ratio work/rest and prevent muscle to fatigue and pain.

1.5 Dissertation Organization

This dissertation is organized following the manuscript format. The manuscripts constitute the body of the dissertation. Chapters 1 and 5 are a traditional dissertation introduction and conclusion, respectively. Chapter 2, 3 and 4 are stand-alone manuscripts reporting the results and conclusion of this study by experimental procedures. Chapter 2 is an experimental research paper outlining the incremental test and the influence of myoelectric and hemodynamic manifestations during isometric contractions of the erector spinae muscle. Chapter 3 brings the relationship between myoelectric and hemodynamic manifestations during an isometric contraction until volitional fatigue. Chapter 4 represents the experimental research about the patient-handling task by analyzing the caregivers L3/L4 joint moment and hemodynamic data from the erectors spinae muscle contraction. Chapter 5 represents the overall conclusions and recommend for the future work and limitations.

Chapter 2

Estimation of Muscle Reoxygenation Recovery Time after Static Endurance Test using NIRS

2.1. Introduction

The erector spinae muscle (ESM) plays an important role in providing mechanical stability and controlling movement of the lumbar spine and trunk. Adjusting muscle function in vivo is important for understanding the mechanics and for developing appropriate assessment and training protocols, and treatments to prevent injuries. To prevent injury, it is important to comprehend work/rest schedules (Shin and Kim 2007). To investigate the mechanics related to the condition and recovery of oxygenation level of the muscle, several authors proposed the use of surface electromyography(EMG) and near-infrared spectroscopy (NIRS) to measure the electrical and metabolic activities in the contracting lower back muscles (Albert *et al.* 2004; Kell and Bhambhani 2006; Olivier *et al.* 2013; Yoshitake *et al.* 2001).

Using NIRS, Chance *et al* (1992) reported that recovery time is the balance between oxygen supply and oxygen demand as the bioenergetic resources are restored following determined exercise. On the other hand, it can be interpreted as a measure of the time needed for replenishment of oxygen and energy deficits occurring during exercise by tissue respiration under adenosine diphosphate control. Several studies have investigated the relationship between the exercise rate of Oxy-Hb/Mb and the muscle oxidative capacity (Bangsbo and Hellsten 1998; Buchheit and Ufland 2011; B. Chance *et al.* 1992; Hanada 2000; Kawahara *et al.* 2005; McCully *et al.* 1994; Puente-Maestu *et al.* 2003).

Furthermore, other studies have shown correlations between oxygenation level determined by NIRS and work load, lactic acidosis, and phosphocreatine level (B. Chance *et al.* 1992; Ding *et al.* 2001; Grassi *et al.* 1999; Masuda *et al.* 2005). Yoshitake *et al*. (2001), examined the oxygenation responses of the ESM during static contraction to fundamentally understand the fatigability process of ESM using NIRS. They showed that low back muscle oxygenation decreased during static contractions with an intensity ranging from 2% to 80% of maximum voluntary contraction (MVC) as the endurance time of exercise increased (Kell and Bhambhani 2006, 2008; Yoshitake *et al*. 2001).

One metabolic consequence of high-intensity/short-duration muscle contraction is subsequent impaired performance. While factors such as substrate depletion may strongly contribute to fatigue during prolonged exercise, the precise mechanisms of recovery after brief high-intensity exercise using an incremental time test remain unclear. Thus, a clear understanding of ESM reoxygenation time after static contractions is important for understanding the mechanism of recovery using NIRS.

Another noninvasive electrophysiological method of estimation of muscle activity during contraction is EMG power spectral analysis can be used to show that muscle fatigue is associated with shifts in median frequency (MF) and/or mean power frequency toward lower values (De Luca 1997; Tsuboi *et al*. 2013). Using EMG, studies have shown that a progressive decline in MF is a strong predictor of back muscle endurance (De Luca 1997; Yoshitake *et al*. 2001).

Previous studies have shown that NIRS and EMG can be used to examine low back muscle condition during and after exercise. However, no studies have used NIRS to examine the heterogeneity in the reoxygenation level and recovery time after an incremental over time static endurance test for the ESM.

Therefore, the purpose of this study was to estimate the oxygenation level and calculate the half time to recovery (hTR), along with its predictors, based on an incremental test using NIRS. We also attempted to examine the interrelationship between the NIRS and EMG variables to assess the metabolic and electrophysiological condition of the ESM during and after isometric contraction.

2.2. Methods

2.2.1. Participants

Written informed consent of the understanding of the purpose of the study and potential risks and benefits was obtained from 11 volunteers who were healthy female college students. Inclusion criteria were age between 18 and 20 years; no current low-back pain; no metabolic, cardiovascular, pulmonary, or orthopedic disorders; body mass index <22; and skinfold thickness lateral of the L3 spinous process <18 mm. The protocol (number: MH049, October 22nd 2015) was approved by the Prefectural University of Hiroshima Ethical Committee and complied with the ethical standards of the 1975 Helsinki Declaration, in terms of ethical principles for medical research involving human subjects.

2.2.2. Subcutaneous Adipose Tissue Thickness (ATT) Measurement

Subcutaneous ATT was measured by skinfold calipers at the NIRS measurement site (3 cm right and left from the spinous process at L3 as proposed by Kell *et al* (2008)). Three consecutive measurements were performed and the ATT was defined as the mean ATT as described by (Kankaanpää *et al*. 2005) (Table 2-1).

2.2.3. Exercise Protocol

The protocol was performed in 2 days, with an interval of at least 48 hours. On the first day, instructions were given; participants were familiarized with the procedure, and maximal voluntary contraction (MVC) using EMG was measured in all subjects. MVC was assessed for determination of maximal neuromuscular activity on upper and lower trunk extension (Vera-Garcia, Moreside, and McGill 2010). On the second day, measurements were performed at baseline in the prone position for 2 min. Subsequently, all subjects performed six incremental static trials over time randomly as follows: 10, 20, 30, 40, 50, and 60 s, with 15 min rest between each trial (Figure 2-1).

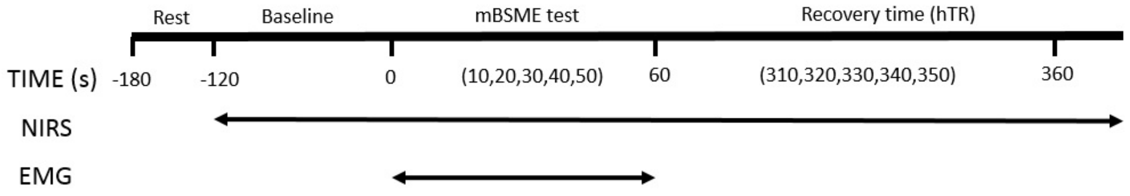


Figure 2-1. Schematic representation of the experimental design. After 1-min rest and 2-min in the prone position at baseline, subjects performed the modified Biering-Sørensen Muscle Endurance (mBSME) test six times before the recovery time of 5 minutes. Around 15 min of rest was allowed between each different time protocol. Electromyography data were extracted only between performance of the mBSME test and near infrared spectroscopy from baseline period to the end of the recovery period.

To perform the modified Biering-Sørensen Muscle Endurance (mBSME) test, the subject lay prone on a plinth with the iliac crest aligned with the edge of the table. Three straps (around the pelvis, knee, and ankles) were used to fix and support the lower body to the table (Figure 2-2). During the mBSME test, the subjects had to place their hands at the side of their heads, with their elbows out to the side at trunk level. They were also instructed to look downward at a visual fixation point (Albert *et al.*

2004; Coorevits *et al*. 2008; Demoulin *et al*. 2006; Moreau *et al*. 2001; Tsuboi *et al*. 2013). Subjects were asked to maintain that position until each trial was completed.

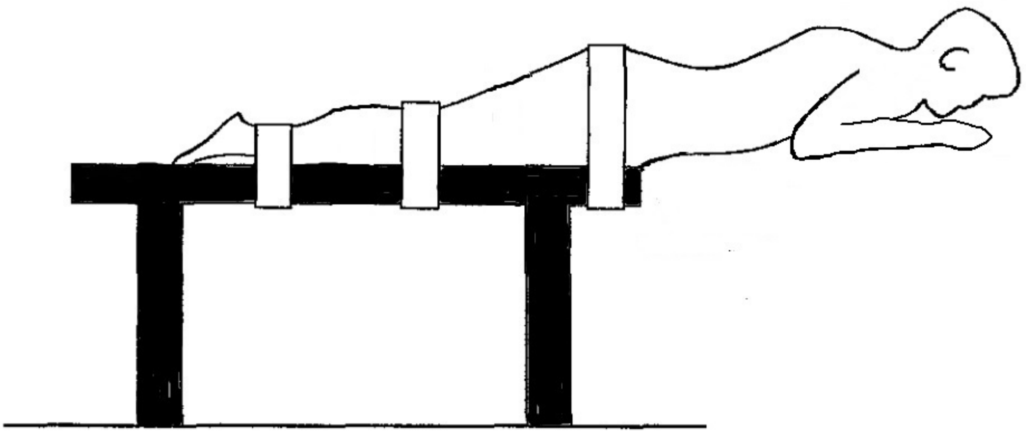


Figure 2-2: Illustration of the modified Biering Sorensen Muscular Endurance test (mBSME) position with the subject strapped at the ankle, legs, and gluteal regions.

2.2.4. Near-infrared Spectroscopy

Two spatial resolved NIRS probes (NIRO-200NX, Hamamatsu Photonics, Japan) were placed (double adhesive tape) using the manufacture's custom-designed optically dense black holder, bilaterally at the third lumbar vertebra over the ESM, 3 cm from the spinous process (Albert *et al.* 2004; Kell and Bhambhani 2006). The interoptode spacing (between the emitter and detector) was 4 cm. The NIRO-200NX provides a ΔO2Hb and ΔOHHb using differences in absorption characteristics of light at 775, 810, and 850 nm. It is not possible to distinguish between the relative contributions of hemoglobin and myoglobin because of the identical spectral characteristics. However, the major signal on NIRS is provided by hemoglobin (B Chance *et al.* 1992). The difference between Oxy-Hb and Deoxy-Hb can be considered the oxygenation index (Grassi *et al.* 1999; Olivier *et al.* 2013), which indicates the relative change in Oxy-Hb and Deoxy-Hb, that is, the change in the oxygenation level in the area of interest.

To improve intersubject comparability, the oxygenation level were expressed as the change from baseline in percentage. The NIRS signals were collected at a sampling frequency of 20 Hz, and the data were stored in a USB memory card before analysis by PC. Data with noises and artifacts collected from NIRS was pre-processed using MATLAB Savitzky-Golay filtering (Mathworks, Massachusetts, USA), before been analyzed by customized Microsoft Excel (Microsoft Corporation, Washington, USA) software program. (Thanh Hai *et al.* 2013).

2.2.5. Calculation of Half Time to Recovery

The hTR was calculated through monoexponential curve fitting as the time taken to reach 50% of the post-exercise maximal value(Allart *et al.* 2012; Buchheit and Ufland 2011; B. Chance *et al.* 1992; Ding *et al.* 2001; Motobe *et al.* 2004; Olivier *et al.* 2013). This was used to provide a comparable variable for evaluating oxidative metabolism in muscles from incremental time trials.

2.2.6. Surface Electromyography

Two wireless electrodes (WEB-7000, Nihon Kohden, Japan) were attached on the back 3 cm from the L3 spinous process bilaterally over the ESM, proximal to the NIRS probes without compromising any evidence. The signal was collected at a sampling rate of 1000 Hz, and was low- and high-pass filtered at 30 Hz and 500 Hz. Power spectral analysis was performed in 1 s epochs for the myoelectric signal from the muscle over the duration of the exercise. Fast Fourier Transform (FFT) of 4096 point (Hamming window processing) was performed. The MF of each task was then calculated using BIMUTAS software (Kissei Comtec Co, Japan).

2.3. Statistical Analysis

All data were analyzed using SPSS version 12.0 (Chicago, USA), with alpha level set at .05 ($p \leq 0.05$). Mean and standard deviation were used to describe all variables. A series of one-way analyses of variance (ANOVA) were used to determine main and interaction effects, while Tukey post hoc comparison was used to detect significant differences when ANOVA effect was significant ($p < .05$). Pearson product moment correlation coefficients (r) were calculated to determine the relationship between EMG MF, hTR, mBSME time, and VAS score. A linear regression analysis was performed to determine the independent variables that best predicted recovery time.

2.4. Results

All participants completed the six trials. The physical characteristics are summarized in Table 2-1.

Table 2-1. Physical characteristics of subjects

Variables	Subjects (*n* = 11)	*p* value
Age (years)	18.8(0.71)	.938
Skinfold left (mm)	15.7(1.85)	.952
Skinfold right (mm)	17.9(1.57)	.652
Height (m)	1.59(0.01)	.899
Body mass (kg)	50.8(4.63)	.961
BMI (kg/m^2)	20.1(1.83)	.995
Right side dominant	11	

Values are reported as mean (±SD).

2.4.1. NIRS Parameters

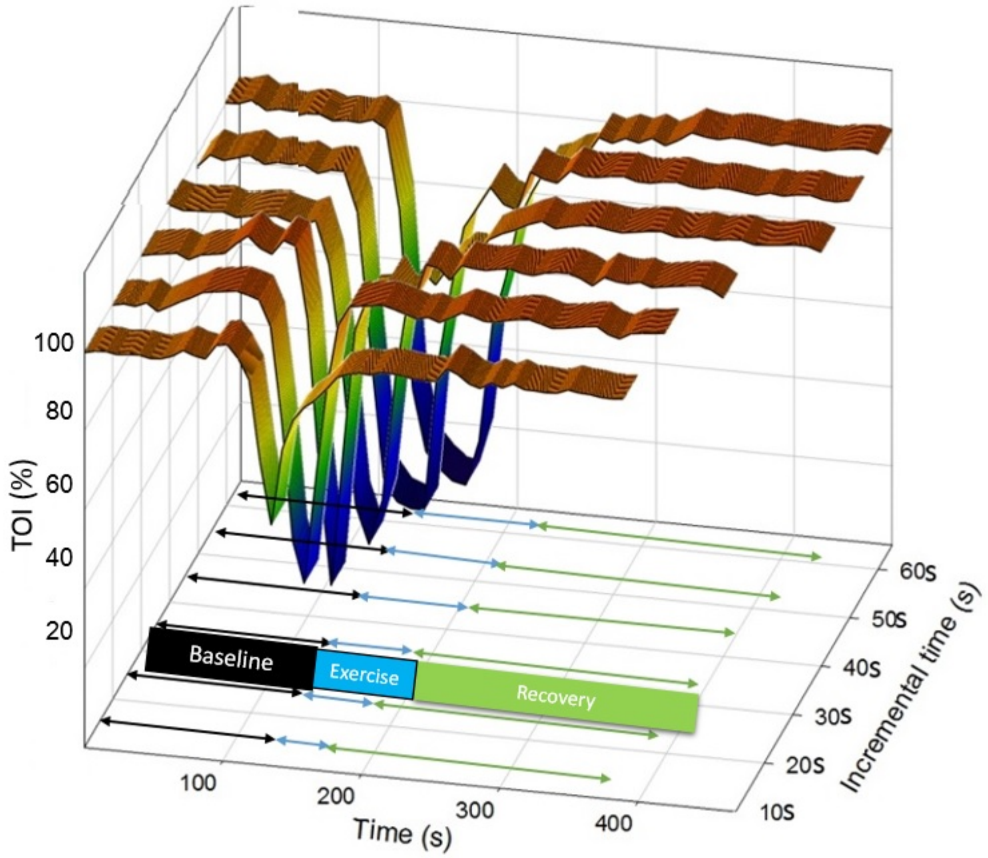


Figure 2-3: 3D ribbon graph showing trend in ESM oxygenation in a single subject during six trials of the mBSME test (10s, 20s, 30s, 40s, 50s and 60s) with NIRS. Two min of baseline, exercise period and 5 min of recovery period. Oxygenation index value was normalized (%).

Figure 2-3 shows the NIRS parameters over one subjects during Baseline, mBSME and Recovery period of each trial. The oxygenation index was normalized in percentage. We found a fast linear decreasing phase of oxygenation index at the beginning and a constant decreasing until the end of exercise. The recovery period was followed by systematic increase of oxygenation index with the values being at or near baseline during the final 2 minutes.

A paired t-test showed no statistically significant differences in the mean hTR for the right and left ESM, t (65) = .437, p = .664.

There were progressive and significant increases in the hTR of ESM of the NIRS related to the incremental time.

On the right ESM, one-way ANOVA was conducted and there was a statistically significant difference between hTR and the duration of the incremental time (F (6,70) = 13.838, p = .001). The effect size of partial ETA squared 0.542. Tukey *post-hoc* test revealed that the hTR after each task statistically significantly increased from the 40s (27.4 ± 10.6s, p = 0.037) to the 50s (32.4 ± 12.7s, p = .001) and 60s (39.9 ± 12.1s, p = .001) trials compared to that for the 10s trial (13.1 ± 2.8s). There were no statistically significant differences between the 10s and 20s (17.5 ± 6.1s, p = .961) and 30s (24.3 ± 7.4s, p = .186) trials (Figure 2-4).

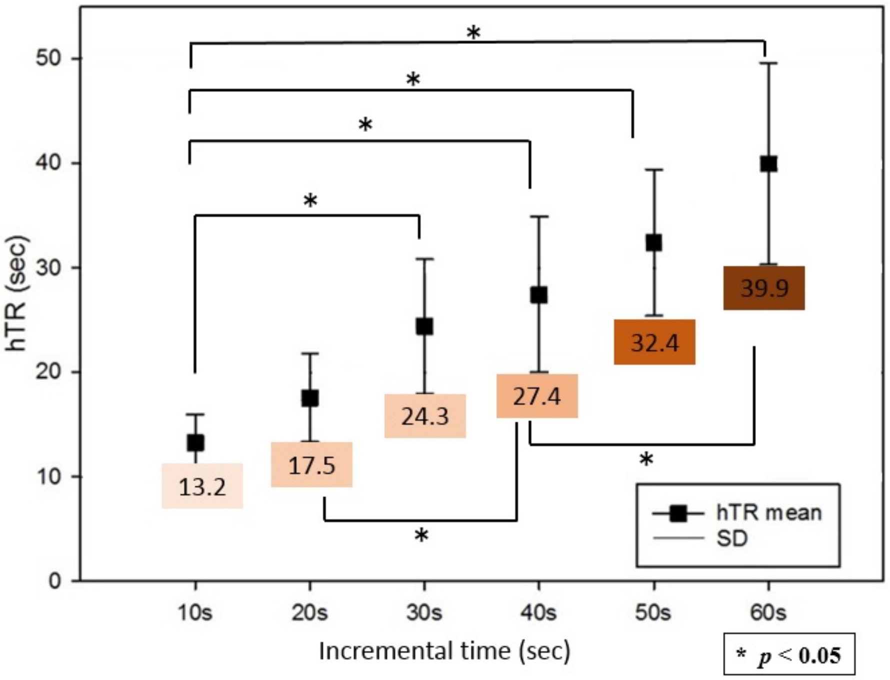


Figure 2-4: Mean and standard deviation of half time to recovery after six trials (10s, 20s, 30s, 40s, 50s, and 60s) of the modified Biering-Sorensen Muscle Endurance test. * indicate a significant difference.

For the left L3, a statistical difference was found by one-way ANOVA (*F*(6,70) = 24.070, *p* = .001). The effect size of partial ETA squared 0.673. Tukey *post-hoc* test revealed that the hTR statistically significantly increased from the 40s (25.8 ± 8.9s, *p* = 008) to the 50s (38.2 ± 7.5s, *p* = .001) and 60s (39.4 ± 9.6s, *p* = .001) trials compared to that for the 10s trial (13.1 ± 2.8s). There were no statistically significant differences between the 10s and 20s (15.3 ± 3.5s, *p* = .979) and 30s (22.3 ± 6.5s, *p* = .110) trials (Figure 2-4).

2.4.2. EMG Parameters

It was found that the MF decreased progressively as an incremental time of exercise from 79.2±13.4Hz (10s) to 63.8±8.3Hz (60s).

A paired t-test showed no statistically significant difference in the mean MF between the right and left ESM, *t* (65) = .1.869, *p* = .067.

There was a statistically significant difference between incremental time trials, as determined by one-way ANOVA (*F*(5,60) = 3.467, *p* = .008), in the mean MF. A Tukey *post-hoc* test revealed that the 50 s and 60 s trials showed statistically significantly lower MF (64.6 ± 7.8 Hz, *p* = .027; and 63.8 ± 7.1 Hz, *p* = .017, respectively) than the 10s trial (79.2 ± 13.4 Hz). There were no statistically significant differences in the MF between the 10s and 20s (74.2 ± 12.1 Hz, *p* = .889), 30s (72.0 ± 12.4 Hz, *p* = .627), and 40s (67.1± 9.8 Hz, *p* = .104) trials (Figure 2-5).

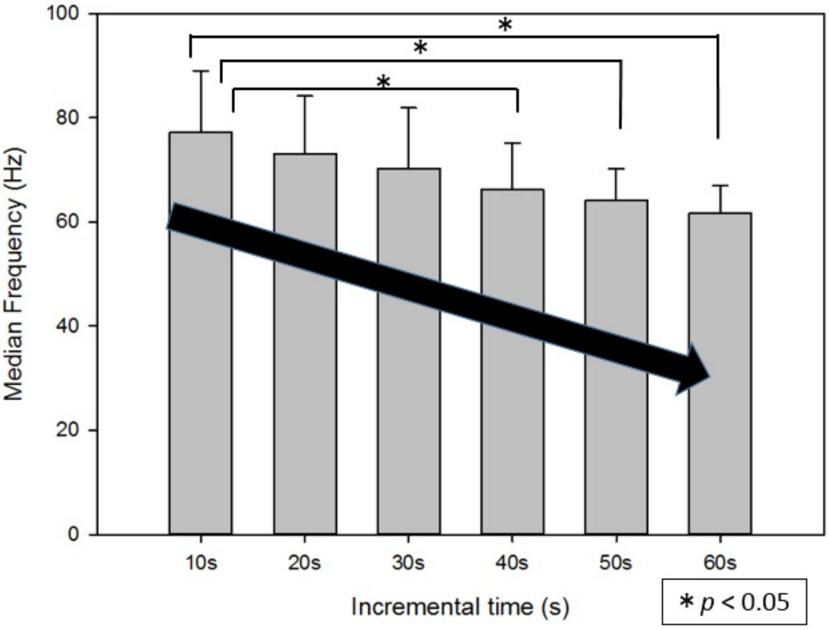


Figure 2-5: Mean and standard deviation of electromyography median frequency (Hz) during the modified Biering-Sorensen Muscle Endurance test. * P<0.05.

2.4.3. Correlations between NIRS and EMG

There was a trend for a relationship between MF slope during the BSME test and an increase in hTR after the test (right r^2 = -0.98, p =.001). The relationship between hTR (right and left sides of ESM are pooled) and MF and VAS are demonstrated on Figure 2-6 and 2-7.

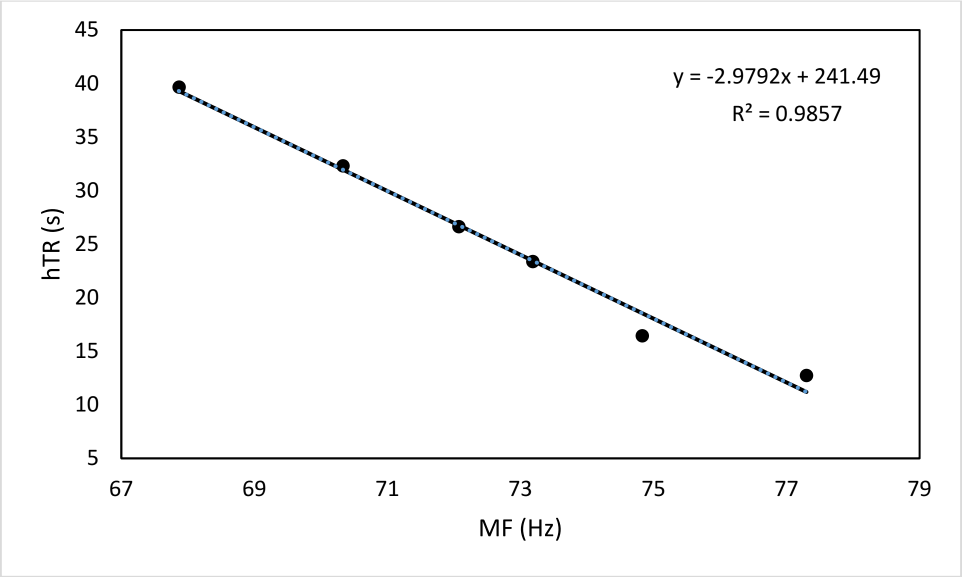


Figure 2-6: Relationship of changing half time to recovery (hTR) measured by NIRS and median frequency (MF) measured by EMG.

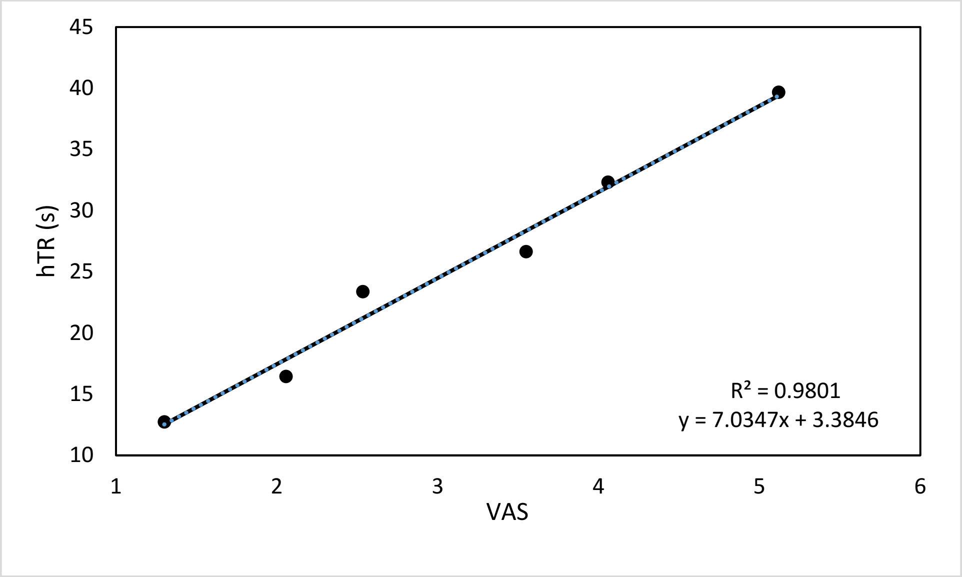


Figure 2-7: Relationship between half time to recovery (hTR) and visual analogue scale (VAS).

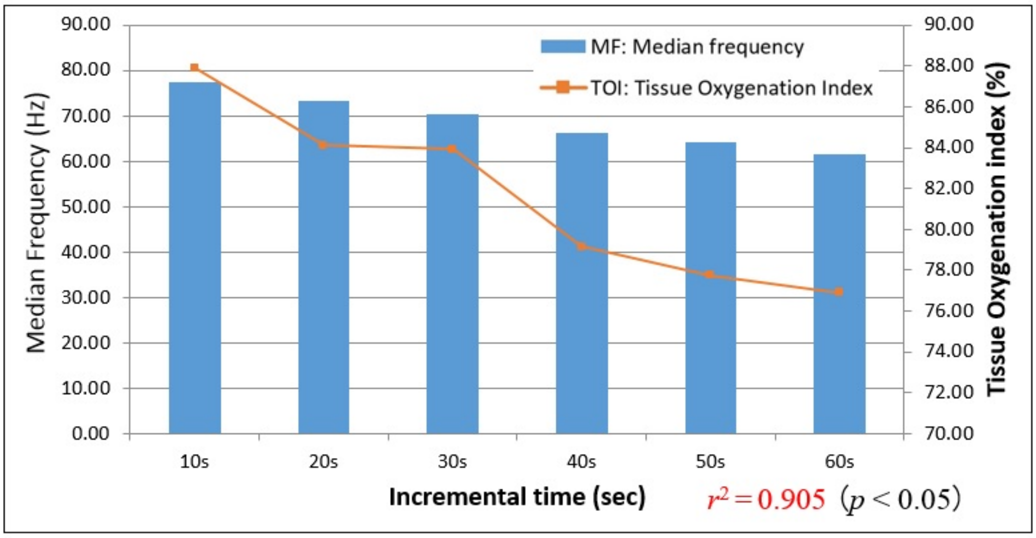


Figure 2-8: Correlation coefficient (Pearson), between MF (EMG) and TOI (NIRS) during exercise.

2.4.4. Prediction of Half Time to Recovery (hTR)

A simple linear regression was calculated to predict ESM (right side) hTR in seconds based on incremental time (s). A significant regression equation was found ($F(1,64) = 62.076$, $p < .001$), with an r^2 of .492. The regression equation developed to predict hTR for the right ESM was:

RL3 hTR (s) = 7.699 + .518 Incremental time (s)

Therefore, .518s was needed for the muscle to recover to half of the reoxygenation level from baseline by adding one second of isometric contraction.

Another simple linear regression to predict hTR (s) from the ESM (left side) was calculated based on incremental time (s). A significant regression equation was found ($F(1,64) = 131.545$, $p < .001$), with an r^2 of .673. The regression equation developed to predict recovery time for the left ESM was:

LL3 hTR (s) = 4.819 + .593 Incremental time (s)

Then, hTR for the left side of the ESM increased to .593s for each second of increment of exercise time.

2.5. Discussion

This is the first report to indicate that longer incremental over time test duration results in a longer reoxygenation time after static muscular test for the ESM, considering the electrophysiological and metabolic responses recorded simultaneously. MF of the myoelectric signals has been shown to be more sensitive to fatigue during sustained isometric contractions such as those during the BSME test(Tsuboi *et al*. 1994). These deoxygenation changes in muscle during exercise that reduce MF are thought to be metabolic acidosis and metabolite deposition(Albert *et al*. 2004; De Luca 1997).

Savitzky-Golay filtering have been used to smooth signals and images with noises as well as artifacts (Thanh Hai *et al*. 2013). In this study, the using a MATLAB software, Savitzky-Golay filtering was applied to reduce spikes noises of NIRS signal. After filtering, data allow us to recognizing the oxygenation level easier compare to raw data.

During a static endurance test, MF could change because of muscle acidosis, but this change might be attenuated if, over the course of the contraction, larger motor units of the muscle were recruited(Albert *et al*. 2004). These factors reduce the conduction potentials that propagate along the sarcolemma, consequently reducing the MF of the myoelectric power spectrum when analyzed by EMG(De Luca 1997).

Our NIRS data indicate that muscle oxygenation level dramatically decreases and then remains low during exercise (Figure 2-3). This observation might be due to the slight interruption of oxygenation during the isometric exercise by increased intramuscular pressure(Hamaoka *et al*. 1996; Yoshitake *et al*. 2001).

Considering that ischemic muscular activity occurs, these results provide information about muscle aerobic function and have good agreement with previous studies(Allart *et al*. 2012; Kell and Bhambhani 2008; Olivier *et al*. 2013; Yoshitake *et al*. 2001). Specifically, we demonstrated that as the duration of the incremental test over time increases, the hTR needed for the ESM to return to baseline level, as determined by NIRS, after the mBSME test increases. Kell(Kell and Bhambhani 2008) *et al* reported a similar result. Oxygen availability is important for the maintenance of muscle contraction. Correspondingly, increase in oxygen consumption decreases the ability to maintain muscle contraction.

Decreased muscle oxygenation may be attributable to increased oxygen demand and metabolic rate of the contracting muscle and increased intramuscular pressure, which may restrict oxygen supply via blood flow.

Although blood volume was not measured in the present study, it is possible that blood volume increases throughout exercise to provide more oxygen to the ESM as the demand for oxygen increases as a result of prolonged incremental exercise. Then, slowly recuperated its level during the recovery period(Kell and Bhambhani 2006; Shang, Gurley, and Yu 2013).

Prolonged isometric exercise time increases the time to recovery of the muscle during the reoxygenation period. From the onset of muscle contraction, high intramuscular pressure was observed, leading to decreased oxygenation change instead. The subject's time to perform the isometric exercise test needs to be considered.

Here, we demonstrated the incremental over time of the similar position as Biering-Sorensen test. During the exercise period, an average of 40% MVC was noted in the ESM, which is relatively in agreement with that reported by Jørgensen(Jørgensen 1997). However, we could not conclude that more than 30% MVC indicated blood flow occlusion. NIRS uses a specific illumination type, but high ATT may strongly limit penetration and consequently influence NIRS amplitude measurements(Ferrari, Muthalib, and Quaresima 2011; Kankaanpää *et al*. 2005).

Furthermore, we selected subjects with similar and low ATT to minimize this possible limitation (Table 2-1). An emitter-photo detector spacing of 4 m was used in this study, guaranteeing adequate penetration of the light beam in the tissue.A limitation of our study would be the sample size. For small sample sizes NIRS evaluation standards have not been established(Kell and Bhambhani 2006). Our calculations were based on the availability and similarity of subject's characteristics.

Human strain in response to external stress is usually a multi-dimensional manifestation because of variations in the physiological system. Because the present study assessed physiological responses during incremental over time exercise, future research focusing on the relationship of these responses should assess whether there are any inherent differences between oxygenation level change and tissue oxygenation index during the endurance test. Replication of our simulation in different activities, either in the laboratory or in the field, is important to increase the impact of this research.

NIRS could play an important role to enhance scientific understanding of oxygenation level in healthy muscle as well as the incremental effects on isometric exercises. To combine future studies with focus on fatigue protocol and isotonic contraction of ESM valuable insights into muscle energetic and mechanisms could contribute to prevent muscle fatigue.

2.6. Conclusion

In this study, we reiterated the importance of maintaining muscle oxygenation between tasks after static contraction of the ESM. It was shown that MF decrease as the oxygenation level declines during the all tasks, which should taken into account in future studies to understand the mechanisms of fatigue. Understanding of the time to recovery after exercise might help comprehend the mechanisms of work/rest to prevent injury.

Chapter 3

The influence of oxygenation level on erector spinae muscle and fatigue during and after isometric contraction.

3.1. Introduction

Identifying physical limitations has long been the focal point of analysis in sport, exercise, rehabilitation, and ergonomics. It is crucial to identify the potential mechanism/sources of exhaustion to prevent musculoskeletal damage. Muscle fatigue, from static and repetitive tasks, is one process that can be implicated as a potential source of injury. The Biering-Sørensen muscle endurance test (BSME), an isometric back endurance test, is commonly used to measure the endurance capacity and fatigue of the back muscles (Biering-Sørensen, Thomsen, and Hilden 1989). Procedures for the test have been previously reported in subjects with and without back pain to determine their muscle potential (Biering-Sørensen, Thomsen, and Hilden 1989; Coorevits *et al.* 2008; Kell and Bhambhani 2006, 2008) .

Near-infrared Spectroscopy (NIRS) was developed as a noninvasive method to examine muscle oxygenation and oxidative metabolism. NIRS quantifies the changes in hemodynamics by changes in the absorption of near-infrared light by oxyhemoglobin and deoxyhemoglobin. By using this technique, tissue organization can be measured in a discrete region in a working physiological setting, which enhances the specificity of the test(Buchheit and Ufland 2011; Kell and Bhambhani 2006). Several studies have used NIRS to examine trends in erector spinae oxygenation and blood volume during isometric contraction of the lumbar extensors (Albert *et al.* 2004; Kankaanpää *et al.* 2005; Kell and Bhambhani 2008; McKeon, Albert, and Neary 2006; Shin and Kim 2007; Yoshitake *et al.* 2001). They revealed that low back muscle oxygenation decreased during static contraction with the intensity ranging from 2% to 80% of the maximum voluntary contraction (MVC) (Kell and Bhambhani 2006, 2008; Yoshitake *et al.* 2001).

Using NIRS, Chance *et al.* (1992) reported that recovery time is the balance between oxygen supply and oxygen demand as bioenergetic resources are restored following an exercise interval. Recovery time can also be interpreted as a measure of the time required for repayment of oxygen and energy deficits accumulated during exercise by tissue respiration under ADP control. In relation to recovery time, Kell *et al.* (2006) demonstrated a systematic decrease in oxygenation towards the baseline in the initial phase of the test with values at or near baseline after about 2 minutes in the erector spinae muscle (ESM). Furthermore, other studies have shown a correlation between recovery time, work load, and lactic acidosis (Chance *et al.* 1992; Ding *et al.* 2001; Masuda *et al.* 2005).

In assessing the effects of ESM fatigue, surface electromyography (EMG) has proven its utility in describing the power spectrum and amplitude changes that occur during volitional exhaustion exercises (van Dieën *et al.* 2009; T. Tsuboi *et al.* 1994). EMG power spectral analysis has indicated that muscle fatigue is associated with shifts in the median frequency (MF) and/or mean power frequency (MPF) towards lower values (De Luca 1997; H. Tsuboi *et al.* 2013). Additionally, EMG has well established that progressive decline in MF is a strong predictor of back muscle endurance(De Luca 1997; Yoshitake *et al.* 2001).

Neuromuscular fatigue response to voluntary effort can be defined as the reduced ability to exert force or power, regardless of whether or not the task can be performed successfully (Frey-Law, Looft, and Heitsman 2012; McNeil, Murray, and Rice 2006). Sustained isometric contractions pose particular challenges to muscle perfusion because the increased demand for blood flow is opposed by increased intramuscular pressure, which will limit its delivery (Dupeyron *et al*. 2009; Yoshitake *et al*. 2001).

Previous studies focused only on the exercise period and not on the recovery period. Furthermore, to the best of our knowledge, the relationship between BSME time and half-time to recovery after exercise, from a NIRS perspective, has not yet been investigated in vivo.

Therefore, the purpose of the current study was to: (1) examine the relationship between EMG MF and the NIRS tissue oxygenation index (TOI) during performance of the BSME test for the ESM, and (2) calculate the half-time to recovery (hTR) from the TOI after exercise.

We hypothesized that both EMG and NIRS can be used to examine low back muscle fatigue by understanding their behavior, which could lead to additional information for improved assessment of muscle fatigue.

3.2. Methods

3.2.1. Participants

The purpose of study and potential risks and benefits was explained to all participants and written informed consent was obtained from 11 healthy female college students who volunteered for the study. The inclusion criteria were: age between 18 and 20; no current low-back pain; no metabolic, cardiovascular, pulmonary, or orthopedic disorders; BMI below 22; and skinfold thickness lateral to the L3 spinous process below 18 mm. The protocol was approved by the Prefectural University of Hiroshima Ethical Committee and complied with the ethical standards of the 1975 Helsinki Declaration detailing ethical principles for medical research involving human subjects. Descriptive information for all participants is presented in Table 1.

Table 3-1. Physical characteristics of subjects. Values are mean (±SD).

Variables	Subjects (*n* = 11)	*p* value
Age (years)	18.8 (0.71)	.938
Height (m)	1.59 (0.01)	.899
Body mass (kg)	50.8 (4.63)	.961
BMI (kg/m^2)	20.1 (1.83)	.995
BSME time (s)	155.5 (33.0)	.997
VAS	7.32 (1.7)	.566
Right-side dominant	11	-

3.2.2. Subcutaneous Adipose Tissue Thickness (ATT) Measurements

The subcutaneous adipose tissue thickness was measured by skinfold calipers at the NIRS measurement site (bilaterally, 3 cm from the L3 spinous process as proposed by Kell *et al*. (2008)). Three consecutive measurements were taken and the ATT was defined as the mean value of the subcutaneous tissue thickness (Kankaanpää *et al*. 2005; Kell and Bhambhani 2008). The results are given in millimeters (mm) (Table 3-2).

Table 3-2: Mean (±SD) values of Skinfold (mm), half time to recovery (hTR), ΔTOI(%) and Reoxy-rate (%/s) variables with the sides compared.

Variables	*n*=11	
Side	Right	Left
Skinfold (mm)	17.9 (1.57)	15.7 (1.85)
hTR (s)	28.80 (8.8)	28.06 (6.9)
ΔTOI (%)	12.18 (4.8)	12.10 (4.2)
Reoxy-rate ($\%^{-s}$)	0.35 (0.1)	0.36 (0.1)

3.2.3. Exercise Protocol

The protocol was intended to be performed in two days, with each measurement separated by at least 48 hours. On the first day, instructions and familiarization were provided, and EMG maximal voluntary contraction (MVC) was measured in all subjects. Maximal neuromuscular activity of the trunk extensors was determined by MVC and evaluated following posterior analysis as proposed by Vera-Garcia, Moreside, and McGill (2010). On the second day, subjects performed the endurance test (i.e., the BSME test) until volitional exhaustion. A baseline of 2 min was measured and subsequently 5 min for the recovery period. All subjects performed one single static test (Figure 3-1).

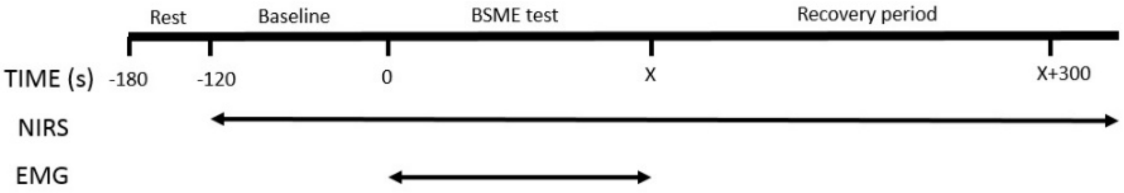


Figure 3-1. Schematic representation of experimental design. After one-minute rest and 2 min of Baseline measurements in the prone position, subjects perform the BSME test (Biering-Sorensen Muscle Endurance), followed by a recovery period of 5 minutes. EMG data is extracted only between the BSME test periods. Near infrared spectroscopy (NIRS) parameters are obtained from the Baseline period.

To perform the BSME test, each subject lay prone on a plinth, aligning their iliac crest with the edge of the table. Three straps (located around the pelvis, knees, and ankles) were used to fix and support the lower body on the table. During the BSME test, the subjects were required to position their hands at the side of their head, with their elbows to the side and level with the trunk (Figure 3-2). They were also instructed to look downward at a visual fixation point (Albert *et al*. 2004; Coorevits *et al*. 2008; Demoulin *et al*. 2006; Kell and Bhambhani 2006; Moreau *et al*. 2001; H. Tsuboi *et al*. 2013). After the recovery period, subjects were asked to rate their perceived discomfort using a 10 cm Visual Analog Scale (VAS). The scores ranged from 0 (no discomfort) to 10 (greatest discomfort). The VAS is a simple and valid index to assess low back discomfort (Rajaee *et al*. 2015).

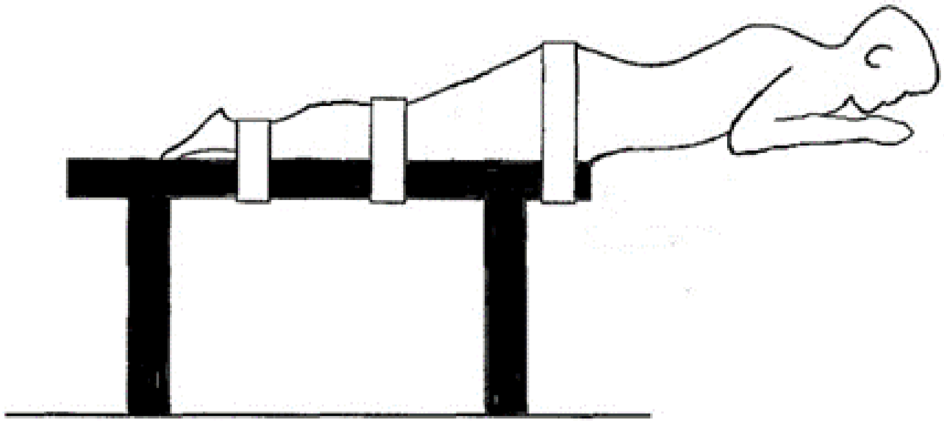


Figure 3-2: Illustration of the Biering-Sorensen Muscular Endurance (BSME) test position with the subject strapped at the ankle, leg, and pelvic regions.

3.2.4. Near-infrared Spectroscopy (NIRS)

Using the manufacturer's custom-designed optically dense black holder, two Spatially Resolved NIRS probes (NIRO-200NX, Hamamatsu Photonics, Japan) were placed (via double-sided adhesive tape) bilaterally at the level of the third lumbar vertebra over the ESM, 3 cm lateral from the spinous process (Albert *et al*. 2004; Kell and Bhambhani 2006).

The NIRO-200NX provides a TOI (expressed in percentage) and displays relative changes in oxyhemoglobin (O2Hb) and deoxyhemoglobin (HHb) (expressed in ΔμM). The NIRO-200NX performs calculations based on the modified Beer-Lambert law and spatially resolved spectroscopy parameters. Hence, the TOI value is a measure of dynamic balance between the distribution and consumption of oxygen (Janssens *et al*. 2013).

To calculate ΔO2Hb and ΔHHb, the NIRO-200NX uses differences in light absorption characteristics at 775, 810, and 850 nm. The interoptode spacing (between the source and detector) was set to 4 cm. It is not possible to distinguish the relative contributions of hemoglobin and myoglobin because they have identical spectral characteristics. However, it has been reported that the major signal from NIRS comes from hemoglobin (Chance *et al*. 1992).

3.2.5. Calculation of Half Time to Recovery (hTR) by Tissue Oxygenation Index (TOI)

The hTR is the time it takes to reach 50% of the difference between TOI at the end of the contraction phase and the recovery period. All TOI parameters were analyzed using calculations obtained by monoexponential curve fitting (Allart *et al.* 2012; Buchheit and Ufland 2011; Chance *et al.* 1992; Ding *et al.* 2001; Motobe *et al.* 2004; Olivier *et al.* 2013).

3.2.6. Surface Electromyography (EMG)

Two wireless electrodes (WEB-7000, Nihon Kohden, Japan) were attached to the back 3 cm lateral to the L3 spinous process over bilateral ESM, and proximate to the NIRS probes, without compromising any evidence. The signal was collected at a sample rate of 1000 Hz, and low- and high-pass filtered at 30 Hz and 500 Hz. EMG MF was calculated using BIMUTAS software (Kissei Comtec Co., Japan).

3.2.7. Data and Statistical Analysis

All of the raw NIRS-derived responses were filtered using MATLAB Savitzky-Golay filtering prior to analysis by a customized Microsoft Excel program. Baseline values were recorded during the initial test. Baseline tissue oxygenation and MF values were normalized to 100% to improve inter-subject comparability.

Data were analyzed using the statistical software SPSS version 20.0 for Windows (IBM Corp., Armonk, NY, USA). Data normality was verified by the Shapiro–Wilk test. Repeated measures analysis of variance (ANOVA) was used to evaluate the NIRS TOI and EMG MF values for the protocol for the right and left sides.

The Bonferroni test was used when significant differences were found, as well as interactions between the effects. The relationship between EMG MF and NIRS TOI was determined using a Pearson product moment correlation analysis. Similar analyses were conducted to determine relationships between the BSME test time and half-time to recovery (hTR), as well as the ΔTOI. A significance level of $p < 0.05$ was adopted. Data are expressed in the results, tables, and graphs as mean ± standard deviation.

3.3. Results

Physical characteristics and variables are summarized in Tables 1 and 2. Figure 3-3 shows the mean value for right and left side erector spinae TOI parameters during baseline, BSME test, and recovery period. The exercise time scale was normalized. Considerable inter-individual variations were observed for NIRS responses during the analyzed test. A fast linear decreasing phase for the TOI was observed at the start of the exercise followed by a constant decreasing phase until the end of the exercise (from 100% to 84.8% with the right and left sides pooled). Mean BSME test time was 155.5 ± 33.0 s.

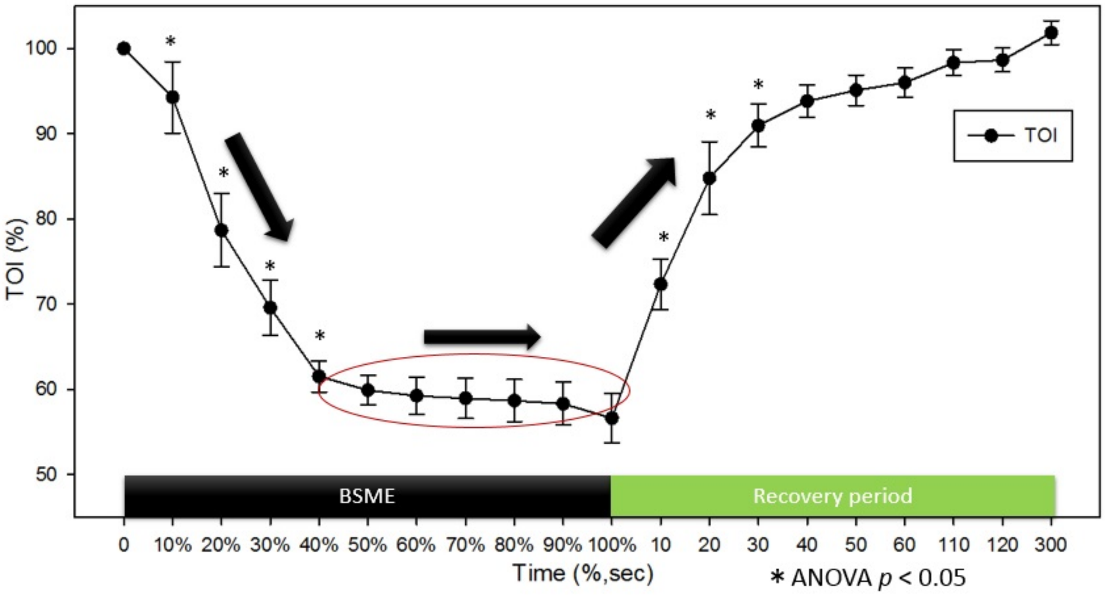


Figure 3-3: Mean Tissue Oxygenation index (TOI) normalized trends during the Baseline, BSME (%) and recovery period (seconds). A dramatic decrease of TOI at the start of the exercise, which leveled off at approximately 40% of the time to fatigue during the BSME test and remained at this level until the test was ended.

The recovery period was followed by a systematic increase in the TOI with values at or near baseline during the final 2 minutes. The half-time to recovery (hTR) was between 20 to 38 s and 22 to 32 s for the right and left sides of the assessed ESM, respectively.

The NIRS TOI for the right-sided ESM at the third lumbar vertebrae (RL) differed significantly between the stages of the protocol when repeated measures ANOVA with a Greenhouse-Geisser correction was performed ($F(1.684, 16.840) = 55.762$, $p < 0.0001$). Post hoc tests using the Bonferroni correction revealed that TOI level increased after exercise from the measure at 100% of the BSME test time to 10 s of the Recovery period (85.52 ± 4.93% vs. 86.40 ± 4.73%, respectively) which was statistically significant ($p = 0.03$).

NIRS TOI for the left-sided ESM at the third lumbar vertebrae (LL) also differed significantly between the stages of the protocol when repeated measures ANOVA with a Greenhouse-Geisser correction were performed (F (2.278, 22.784) = 78.963, p < 0.0001). Post hoc tests using the Bonferroni correction revealed that TOI level increased after exercise from the 10 s of Recovery period to 20 s (85.58 ± 4.16% vs. 88.57 ± 3.67%, respectively) which was statistically significant (p = 0.04) (Figure 4).

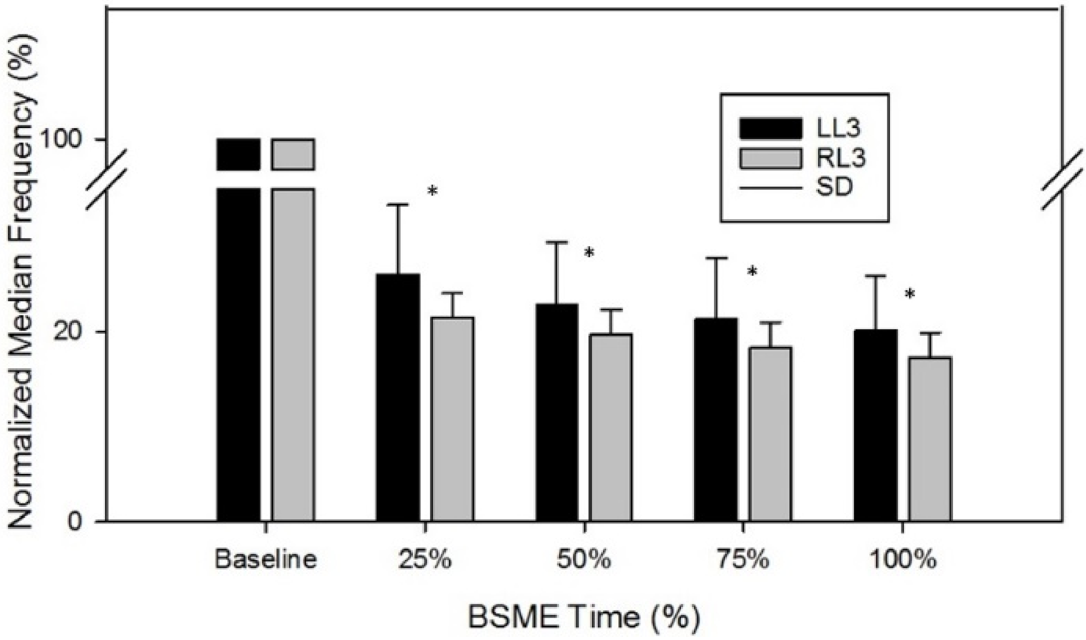


Figure 3-4: Mean changes and standard deviation in EMG Media Frequency from right (RL3) and left (LL3) erector spinae muscle during BSME. EMG spectral variables are expressed as percentage of baseline value (average of first 5 s of BSME test). * p<0.05 for significance of difference between means

Mean EMG MF decreased progressively to nearly 70% of the resting value on both sides. There was no time and side interaction, thus the data from the left and right sides were pooled for subsequent correlation analysis. A positive strong correlation was found between BSME time and hTR, as well as ΔTOI when the values of the two sides were pooled. The correlation coefficient for ΔMF values and BSME time indicated low to moderate correlation (Table 3-3).

Table 3-3: Pearson's correlation coefficient between BSME time and half-time to recovery (hTR), change level of tissue oxygenation index (ΔTOI), and change level of median frequency (ΔMF) variables with right and left side pooled.

Variables	*n*=11	*p* value
hTR	0.845	0.001
ΔTOI	0.894	0.001
ΔMF	0.593	0.055

Table 3-4 shows the correlation matrix between TOI and MF over the period of muscle contraction. There was a strong positive correlation between mean TOI RL and MF RL ($r = 0.78$, $p < 0.05$), and between TOI LL and MF LL ($r = 0.90$, $p < 0.05$).

Table 3-4: Correlation coefficient between TOI and MF during the BSME test. *Correlation is significant at the 0.05 level

	TOI RL	TOI LL
MF RL3	$.781^*$	-
MF LL3	-	$.905^*$

3.4. Discussion

In the present study, we used the NIRS TOI to measure erector spinae muscle oxygenation simultaneously with EMG MF measurements during BSME, as well as the half-time to recovery after the BSME test. The main findings suggested that the relationship between EMG and NIRS is somehow related to the time of muscle contraction as reported by the Chapter 2. Despite of these above described findings, it was obvious to find in this study the time of hTR were much more longer than the previous protocol. We could not find the relationship of fatigue process, whether it starts and where it ends. For EMG, the MF starts declining it values as the muscle isometric contraction begins. However, it was observed that after 40% of time to exhaustion, the TOI trend remained fairly consistent and showed a plateau until the end of the exercise. As for NIRS, the lowest value of its oxygenation could indicate the muscle could not maintain the contraction and lacking of oxygenation, the muscle starts fatiguing.

NIRS TOI and EMG MF decreased progressively as a function of time during the BSME test. This trend is in agreement with previous studies (Coorevits *et al*. 2008; van Dieën *et al*. 2009). Moderate to strong correlation between TOI and MF was demonstrated ($r = 0.78$ and $r = 0.90$, for the right and left sided ESM respectively). Albert *et al*. (2004) suggested a low to moderate correlation between NIRS and EMG, but in their study, muscle oxygenation values were presented in optical density units, which only describe the oxygen concentration change. Therefore, in our study, NIRS TOI (ratio of $HbO2/ (HbO2+HHb)$) was given. It was possible to obtain this by using a spatially resolved spectroscopy system.

With this system, it was also possible to measure the Reoxygenation rate (i.e., Reoxy rate). The Reoxy rate reflects the change in post-exercise muscle oxygenation levels over time. It has been reported to be a good marker of aerobic muscle function. According to McCully (1994), the Reoxy rate has been shown to have similar recovery kinetics to phosphocreatine (PCr) resynthesis after exercise. It may be possible that a faster Reoxy rate is indicative of an improved ability to supply oxygen at a higher rate during the post-exercise period. Future studies focusing on the relationship of these responses should assess whether there are any inherent differences between the Reoxy rate and the burden related to different types of exercises, which would suggest that this index of oxygen demand and delivery is a marker of aerobic resaturation after exercise (Chance *et al*. 1992).

3.4.1. NIRS Parameters

We calculated hTR of 28.33 ± 9.5 seconds and 28.06 ± 6.9 seconds for the right and left ESM, respectively by NIRS tissue oxygenation index. Kell *et al*. (2008), reported a value of 51.17 (29.8) seconds and 58.42 (37.1) seconds for right and left ESM recovery time, respectively, after the BSME test. Although they utilized similar equipment, in their study, muscle oxygenation was calculated as the difference between the concentration change of oxyhemoglobin and deoxyhemoglobin.

In accordance with Albert *et al*. (2004), the TOI for the ESM demonstrated a rapid decrease at the onset of the BSME test, with a more gradual decrease during the middle and later stages. The average ESM response reflected continued utilization of oxygen as illustrated by the decline in oxygen saturation by greater than 10% throughout the test, in order to provide sufficient energy to perform the protocol. These findings are consistent with previous findings, and can be explained by increased cellular oxygen uptake in the mitochondria due to the increased metabolism of the working motor units, or increased intramuscular pressure (Albert *et al*., 2004; Yoshitake *et al*., 2001). The duration of this decline seems parallel with the use of phosphocreatine (PC) as an energy source for muscle contraction (Fulford *et al*. 2014). The energy source during the final phase of the contraction is likely supplied by glycogen in anaerobic glycolysis due to the deficit in oxygen caused by the mechanical obstruction of blood flow to the muscle.

3.4.2. EMG parameters

The electrode locations were selected to incorporate the activity of the multifidus, iliocostalis, and longissimus muscles, although it is questionable whether the signal from each underlying muscle was picked up at any of the sites.

The estimated value of the conduction velocity affects the frequency scaling of the spectrum and consequently, the value of the spectral parameters (De Luca 1997). A decrease in conduction velocity is thought to be caused by an increased concentration of extracellular potassium and metabolic acidosis. Cumulative fatigue develops as isometric contraction time increases, as was observed in this study (Kell and Bhambhani 2006). For bilateral ESM, the MF started to decrease from the moment the muscle contraction was initiated until the end of contraction. This is in line with findings from Tsuboi *et al*. (1994); the downward trend in MF is related to an increase in endurance, suggesting that smaller muscle fibers were recruited at high contraction forces. Mannion *et al*. (2000) suggested a predominance of type I over the II fibers in the ESM of women.

As such, greater oxidative potential and decreased production of metabolic byproducts would result in a slower decline of the EMG MF. No significant difference was found on the right side, which might be explained by the fact that all study subjects had a dominant right side. Nicolaisen and Jorgensen (1985) suggested that the force of the muscle contraction needs to be higher than approximately 50% of the MVC for blood flow to be occluded. During the BSME test, a 40% MVC was recorded. Therefore, we could not assume blood flow occlusion.

3.4.3. Muscle Fatigue Responses

Yoshitake *et al.* (2001) has examined the oxygenation responses of the ESM during static contraction in order to fundamentally understand the fatigability process of the ESM with NIRS. They assumed that the restriction of blood flow due to high intramuscular mechanical pressure was one of the most important factors underlying low back muscle fatigue. Fatigue during static contraction has been attributed to increased intramuscular pressure (van Dieën *et al.* 2009; Yoshitake *et al.* 2001).

Gerr *et al.* (2002), demonstrated a link between musculoskeletal symptoms and disorders and occupational ergonomic exposures, such as sustained static muscle contraction, highly repetitive movements, and insufficient recovery time. According to Chance *et al.* (1992) the hTR is related to a reduction in oxygen concentration and high-energy phosphoric acid level in the muscles. Thus, it is a comprehensive representation of intramuscular capillary density, myoglobin concentration, size and density of mitochondria oxidative enzyme activities, and oxygen transport capacity, and it serves as an index for the oxygen-retaining capacity of muscles. Therefore, in our study, hTR was used to represent the compromised oxygen-retaining capacity in the ESM during the isometric endurance test.

Intramuscular pressure is positively related to contraction intensity(Dupeyron *et al*. 2009; Kimura *et al*. 2006). Thus, it is held that there is a critical force threshold beyond which mechanical pressure occluding muscle blood flow and below which flow will be affected to varying degrees depending on the contraction intensity and anatomical location (Yoshitake *et al*. 2001).

Metabolic factors may be the primary determinant of muscle fatigue in these situations, whereas in low intensity exercise, electrophysiological processes appear to be the limiting factor. Recovery of metabolic supplies is dependent on circulation. Therefore, it can take considerable time for full recuperation of the rest values.

3.4.4. BSME Responses

The BSME test times were moderately variable and ranged between 117.5 and 194.7 s (148.5 ± 26.0 s). These values are slightly lower than has been reported by Albert *et al*. (2004), but they are within the ranges reported by others (Dupeyron *et al*. 2009; Kell and Bhambhani 2006).

3.4.5. Limitations

It should be noted that the sample size presented in this study could have played a prominent role in the lack of detectable differences in physiological responses. However, since sample-size calculations for NIRS-specific investigations have not yet been established (Kell and Bhambhani 2006), the calculations in our investigation were performed according to subject availability and similarity. The examination of muscle oxygenation allowed us to speculate on perfusion, NIRS itself does not approach the precision of Doppler ultrasound or PET, which can show the distribution of blood in a muscle during a sustained isometric contraction (Gurley, Shang, and Yu 2012).

3.5. Conclusion

The findings of this study have implications for future investigations on the mechanism of action of the low back muscles. A reduction in the strength (i.e., EMG), endurance, and oxygenation levels (i.e., NIRS) of the low back muscles has been implicated as a contributory factor to fatigue. Adequate blood supply is obviously the most essential component to withstand fatigue and prevent the loss of lumbar muscle function. Furthermore, prolonged static posture might diminish oxygenation level and MF, increasing susceptibility to fatigue.

Chapter 4

Recovery Time Analysis and Kinematic Load after Patient-handling Simulated Task from Caregiver's Low Back Muscle

4.1 Introduction

The aging of the Japanese population is thought to exceed that of all other nations, with the country purported to have the highest proportion of elderly citizens. According to the statistics of the Japanese Health, Labor, and Welfare Ministry, the proportion of the elderly (65 years or older) reached 20.8% in the fiscal year 2006, and is estimated to increase to 39.6% in 2050. This has induced various health issues among caregivers in nursing homes. The occupational condition is related to the requirement for the caregivers to repeatedly perform activities such as lifting the patients from and to anomalous postures. Patient transfer has been found to be associated with most low back injuries suffered by caregivers(Russell *et al*. 2007; Schibye *et al*. 2003; Skotte *et al*. 2002). Additionally, nurses and caregivers exhibit high rates of low back pain (LBP) and worker compensation claims for back injuries(Daynard *et al*. 2001). In the year 2011, the total annual medical cost of work-related LBP was estimated to be 82.14 billion yen(Itoh, Kitamura, and Yokoyama 2013). It is thus reasonable to suppress an increase of this medical cost by suppressing the occurrence of work-related LBP in the country. A recent systematic review particularly reiterated the prevalence and high risk of work-related LBP in patient-handling and nursing occupations(Yassi and Lockhart 2013).

Although knowledge has been gained about the possible causes of work-related LBP, little progress has apparently been made in preventing this critical work-related complaint. Identification and preventive procedures related to musculoskeletal disorders (MSDs) have been the major focus of the 12th Occupational Safety and Health Program (Ministry of Health, Labour and Welfare, Japan, 2013).

Near-infrared spectroscopy (NIRS) affords a noninvasive and continuous means of monitoring the relative concentration changes of the oxygenated and deoxygenated forms of hemoglobin (Oxy-Hb and Deoxy-Hb, respectively) in muscles of interest(Ryan *et al*. 2012). Studies have shown correlations among recovery time, work load, and lactic acidosis(Chance *et al*. 1992b; Ding *et al*. 2001a; Masuda *et al*. 2005). Low back muscle oxygenation has also been measured by NIRS using different methods and loads(Dupeyron *et al*. 2009; Masuda, Miyamoto, and Shimizu 2006; Shin and Kim 2007). NIRS measures during isometric ESM activities have exhibited a moderate to strong intraclass correlation coefficient (ICC) of 0.69–0.84 (Kell, Farag, and Bhambhani 2004). It is, however, not known how the intensity of a patient-handling movement might affect the oxygenation measures. Nevertheless, knowledge of the reliability level of such measures is critical to interpreting the differences among their magnitudes for different types of movements and possible training-induced changes to prevent muscle fatigue.

Another approach that has been explored for the determination of joint contact forces involves numerical calculation using free body segments and inverse dynamics (Figure 4-1). However, the hemodynamics approach to investigating muscle activity(Katsuhira *et al*. 2008) is yet to be applied to the study of patient transfer tasks. Many of the modelling methods that have been used to estimate low back load and establish guidelines for the maximum allowable loads in the healthcare industry have been reasonably successful for demonstrating the effects of the body posture on overall spine load indexes such as low back compression. However, while such methods may be useful for addressing the most overt violations of biomechanical principles to reduce the risk of injury in the healthcare industry, they do not elucidate how the spine functions, do not identify individual differences that cause certain people to be predisposed to injury, and do not address the many subtle mechanical characteristics of the spine that are important to the consideration of injuries (Stuart M. McGill, 2007).

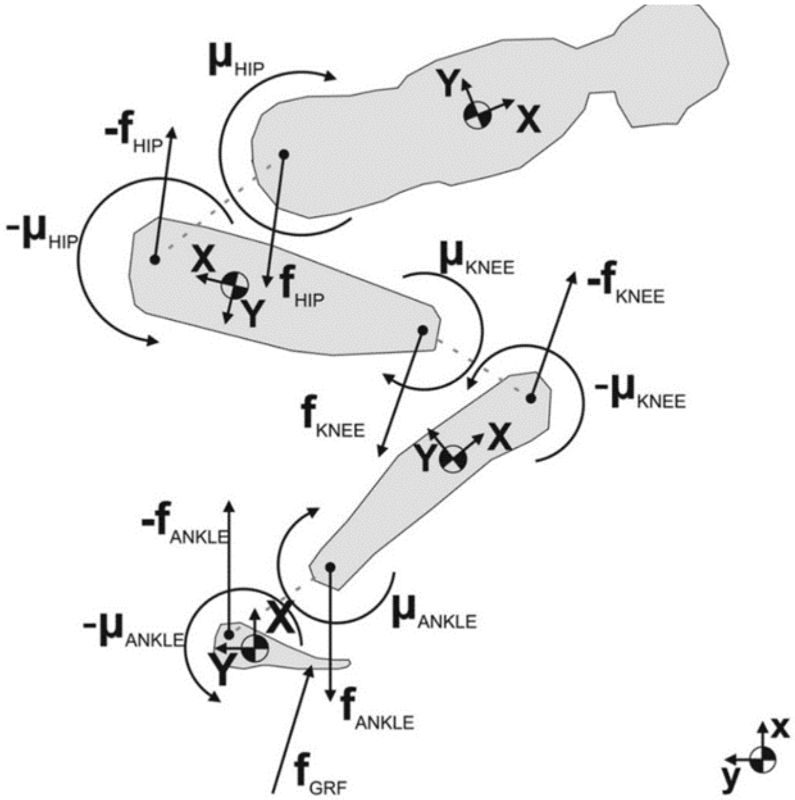


Figure 4-1: Complete free-body diagram (ankle, knee, hip and trunk), showing reaction force (f), net moment of force (μ), and all linear and angular accelerations.

Biomechanical modelling techniques for determining tissue loads from the structural architecture of the human body are effective for analyzing injury mechanisms, assessing injury risks, and developing injury avoidance strategies (Stuart M McGill, 2007). Hence, the mechanisms that are used to understand the overuse of the back muscle can be employed in evaluating physical performance through estimation of the joint moments and monitoring of the oxygenation level and subsequent recovery time.

NIRS and 3D Movement Analysis System

When moving patients during care activities, caregivers frequently adopt postures asymmetrical to the median sagittal plane, including lateral bending and turning the trunk, and laterally positioned arms including sideward force exertion. Furthermore, they exert lifting, pulling, and pushing forces varying over time respect to amplitude and direction (Koppelaar *et al.* 2012). Therefore, a three-dimensional (3D) determination and replication of both, the posture and the action forces in high temporal resolution, are needed for and adequate approach for quantifying biomechanical indicators of load on the lumbar spine (Clemes, Haslam, and Haslam 2010; Daynard *et al.* 2001; Theilmeier *et al.* 2010). In addition, repetitive lifting during manual handling task has been associated with muscle fatigue. However, the biomechanical mechanism linking muscle fatigue and back injury development has not been fully investigated.

Although there is evidence of the reliability use of 3D motion capture and NIRS, until this date no research has assessed whether objective measurements of both methods when using together.

The aim of the current research is to understand the physiological and biomechanical changes associate with patient-handling task. Specially, consecutive movement is hypothesized to: (1) decrease tissue oxygenation; (2) increase L3/L4 joint moment; (3) increase biomechanical loading of the spine; (4) increase time of reoxygenation level.

4.2. Methods

4.2.1 Participants

Informed written consent to the purpose of the study and its potential risk and benefits was obtained from each of the 11 healthy female participants, who were college students. The ages of the participants ranged between 18 and 20 years. None of them experienced LBP or any metabolic, cardiovascular, pulmonary, or orthopedic disorder at the time of the study. The BMIs of the participants were all below 25. In addition, the skinfold thickness lateral to the L3 spinous process of each participant was less than 18 mm. A mannequin (Sakamoto Model Co, Japan) (weight = 16 kg, height = 160 cm) was used as the patient. A mannequin was used to avoid the interference of a human simulated patient; hence, only the movement of the caregiver needed to be measured (Westhoff, 2004). The experimental protocol was approved by the Prefectural University of Hiroshima Ethical Committee, and complied with the 1975 Helsinki Declaration regarding ethical principles for medical research involving human subjects.

4.2.2. Experimental Protocol

The study subjects were required to perform two distinct transfer tasks: 1) Elevation of the patient from a supine position in bed to a sitting position (SS), and 2) Transferring of the patient from sitting on the bed to sitting in a wheelchair (SW). An additional third task, namely, continuous performance of SS and SW (SS+SW) was also performed (Figure 4-2). No instructions were given to the subjects prior to performing the tasks, but they were told to handle the mannequin with care and use a normal pace (Figure 4-3 to 4-5).

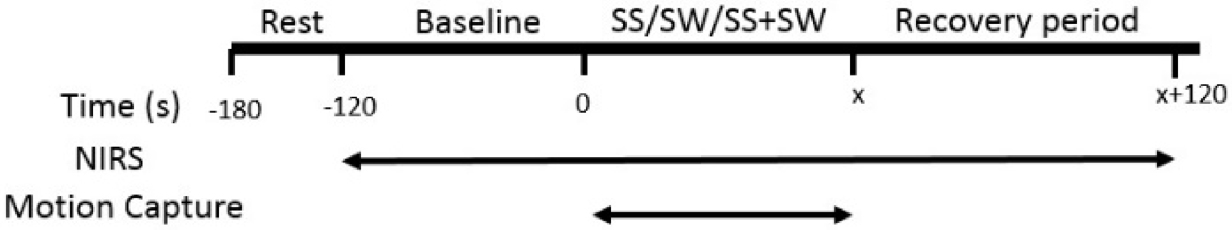


Figure 4-2: Schematic representation of the experimental design. After a 1-min rest and 2 min of baseline, the subjects performed the transfer assistance task, and this was followed by a recovery period of 2 min. Another 15 min of rest was allowed between trials. The motion capture data were only extracted during the performance of the tasks. The near-infrared spectroscopy (NIRS) parameters were obtained from the beginning of the baseline period to the end of the recovery period.

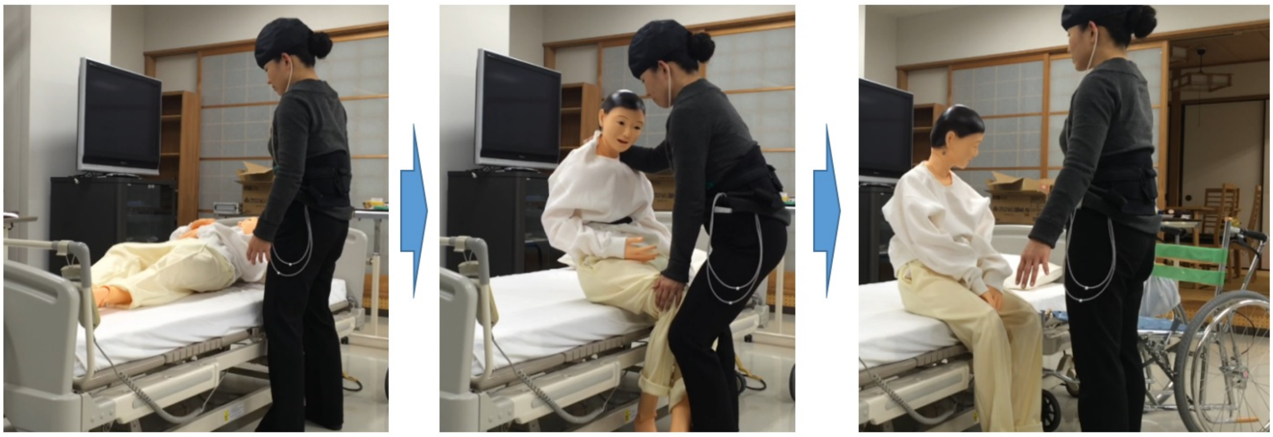


Figure 4-3: A patient handling task in which the subject is elevating the mannequin from supine position in bed to a sitting position (SS).

Figure 4-4: A patient handling task in which the subject transfer the mannequin from sitting on the bed to wheelchair (SW).

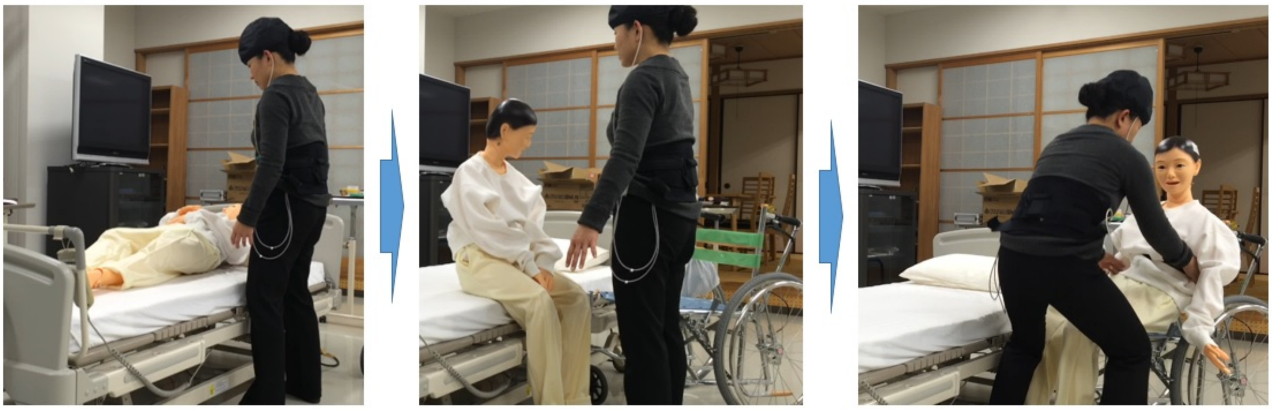


Figure 4-5: A patient handling task in which the subject elevate the mannequin from a supine position on the bed to sitting in a wheelchair (SS+SW).

4.2.3. Experimental Setup

A 3D motion analysis system that included 12 infrared cameras (VICON MX: Vicon Motion System; Oxford, UK) and two force plates (AMTI; Watertown, MA, USA) were used to record the kinematic and kinetic data at a sample frequency of 100 Hz (Figure 4.6). The recorded data were low-pass-filtered by a fourth order recursive Butterworth filter with a cut-off frequency of 6 Hz. A total of 29 reflective makers were attached to the following landmarks on the subjects: front and back of the mid-temporal points, bilateral of the shoulder, lateral epicondyle, ulnar styloid process, acetabulum, anterior-superior iliac spine, iliac crest, knee, ankle, and fifth metatarsal. Additional markers were placed at the L3/L4 lumbar level and both sides of the trochanter. The transfer tasks were performed using a bed and wheelchair seat of the same height of 40 cm from the floor. The angle between the bed and wheelchair during the SW and SS+SW was 45°.

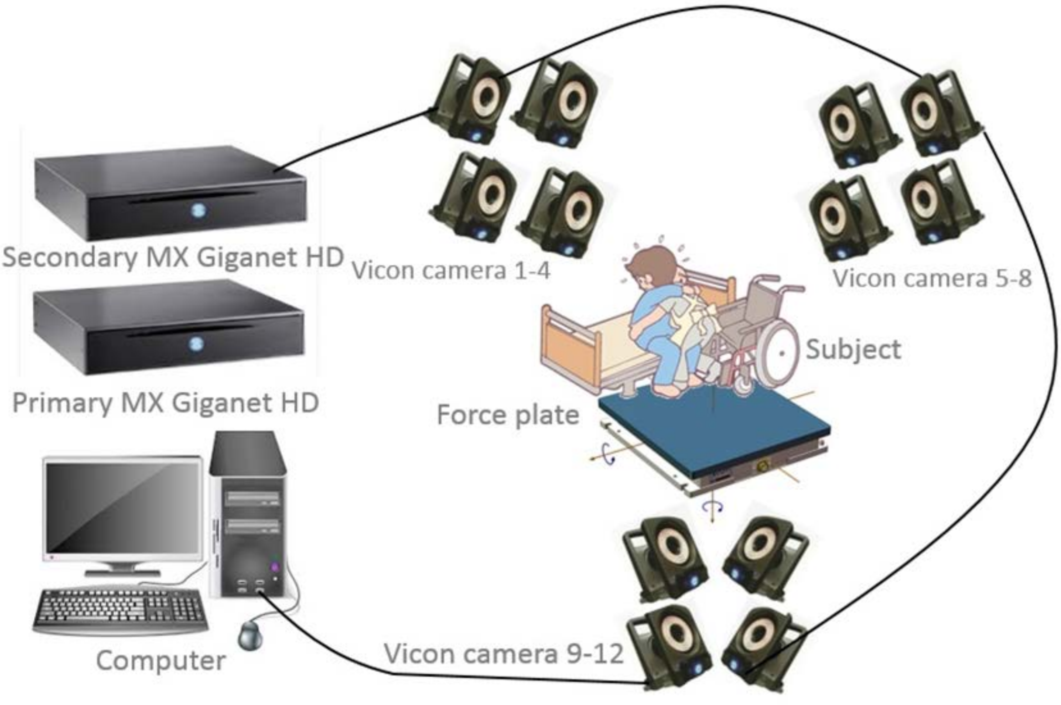


Figure 4-6: A schematic example of typical motion capture setup (Vicon cameras, MX Ultranet Hd, PC and force plate)

4.2.4. Calculation of L3/L4 Joint Moment

Downward 3D inverse dynamics was used to determine the L3/L4 net joint moments. The computational details are available in a previous publication(Winter 2005). An expanded equation of motion was used to calculate the joint moment, starting from the ankle joints, and then the knee and hip joints. The forces and moments of the L3/L4 joint, hip joints, knee joints, and ankle joints were estimated using the kinematic and inertial properties of the body, together with the process of inverse dynamics and the developed free body diagram (FBD) for motion analysis, based on the kinetics of the lower limb muscles and bone joints.

The entire trunk was modeled as a single rigid segment connected to the pelvic segment through the L3/L4 joint. Data on the masses, centers of mass, and moments of inertia of the segments were obtained from Winter (2005)(Winter 2005). The peak joint moment at the L3/L4 joint during the central part of each task was used as the characteristic variable(Skotte *et al.* 2002). The point between the third and fourth lumbar vertebrae was defined as the center of rotation of the low back joint in this study. The position of the actual marker was interpolated to the center point of the vertebral body, using the length between the surface of the skin and the center of the vertebral body determined by MRI imaging, as described by Katsuhira *et al.* (2007). Five selected subjects were used for this purpose (mean age = 19.57±0.49 years, mean height = 1.56±0.03 m, mean weight = 46.95±2.45 kg. The determined mean length, 85.14±2.33 mm, was used for the interpolation.

4.2.5. Near-infrared Spectroscopy (NIRS)

Two spatially resolved NIRS probes (NIRO-200NX, Hamamatsu Photonics, Japan) were attached to a subject using a double-adhesive tape and the manufacturer's custom-designed optically dense black holder, at the level of the third lumbar vertebra over the right and left erector spinae muscle, 3 cm from the spinous process(Albert *et al.* 2004; Kell and Bhambhani 2006). The intereptode spacing between the emitter and the detector was 4 cm. The NIRO-200NX probes were used to determine the tissue oxygenation index (TOI) (percentage) and the relative changes in the oxyhemoglobin and deoxyhemoglobin (ΔμM). To improve intersubject comparability, the TOI values were determined relative to the baseline. The NIRS signals during all the processes were acquired at a sampling frequency of 20 Hz, and the data were storage on an SD card before analysis by a PC. MATLAB Savitzky-Golay filtering (Mathworks, Massachusetts, USA) was implemented on the data before analysis using a customized Microsoft Excel software program (Microsoft Corporation, Redmond, Washington).

4.2.6. Half Time to Recovery Measured by NIRS

The half-time to recovery (hTR) was calculated by monoexponential curve fitting as the time taken to reach 50% of the post-exercise maximal value(Allart *et al.* 2012; Buchheit and Ufland 2011; Chance *et al.* 1992a; Ding *et al.* 2001b; Motobe *et al.* 2004; Olivier *et al.* 2013).

4.3. Data Analysis

All the recorded VICON data, after filtration, were analyzed in the Windows Excel environment. The motion phase was extracted and scaled to 100% of the relative time. Data for three trials of each task by each subject were collected. The median peak value for the three trials and the closest value were averaged to obtain the representative value of a particular data type for the analysis. The peak L3/L4 joint moment was normalized by the height and weight of the subject, as described by Kerrigan (1998)(Kerrigan *et al.* 1998). The reproducibility of the L3/L4 joint moment about three axes was analyzed to compute the ICC using a two-factor mixed effect model and the type consistency. After testing the normality of the distribution of the residuals through a Shapiro-Wilk test and visual inspection of their histograms, a repeated measures analysis of variance (ANOVA) was performed using the three tasks as the fixed factors. A Tukey post-hoc test was also performed when significant differences were observed. Values of $p < 0.05$ were considered to be statistically significant. The data on the task duration and lift height were also analyzed. The lift height was calculated as the difference between the maximum heights of the marker placed on the head of the mannequin. The analysis was done using the statistical software SPSS Version 20.0 for Windows (IBM Corp., Armonk, NY, USA).

4.4. Results

The physical characteristics of the subjects are summarized in Table 4-1.

Table 4-1. Physical characteristics of the subjects.

Variable	Subjects (*n* = 11)	*p* value
Age (years)	18.8(0.71)	.938
Left skinfold (mm)	15.7(1.85)	.952
Right skinfold (mm)	17.9(1.57)	.652
Height (m)	1.59(0.01)	.899
Body mass (kg)	50.8(4.63)	.961
BMI (kg/m²)	20.1(1.83)	.995
Right side dominant	11	

Values are mean (±SD)

4.4.1. Test of Reliability and Normality

A moderate-to-low degree of reliability was observed in the L3/L4 joint moment measurements on the torsional plane during SS+SW. The single-measure ICC was 0.68 with a 95% confidence interval of 0.16–0.90. The mean trial variation was 0.01±0.01. Conversely, a high degree of reliability was observed along the lateral axis with an ICC of 0.94 and a 95% confidence interval of 0.81–0.99. The mean trial variation was 0.01±0.02 (Table 4-2). Through normality testing and visual histogram inspection, the normal Q-Q plots of the box plots showed that the TOI were approximately normally distributed for the two separate tasks. The following were determined: a skewness of -0.195 (SE = 0.427) and kurtosis of -0.942 (SE = 0.833) for the SS; a skewness of -0.283 (SE = 0.427) and kurtosis of -0.943 (SE = 0.833) for the SW; and a skewness of -0.586

(SE = 0.464 and kurtosis of -0.702 (SE = 0.902) for the SS+SW. With regard to the peak moment of the L3/L4 joint, approximately normal distributions were observed for only SW and SS+SW.

Table 4-2. Lateral, torsional and extension intra-class correlation coefficient (ICCs) for subsequent tasks.

Axis	Tasks	ICC	95% Confidence interval		Mean variance
			Lower bound	Upper bound	
A) Lateral	1. SS	0.88*	0.6	0.96	0.05 ± 0.13
	2. SW	0.92*	0.74	0.97	0.03 ± 0.1
	3. SS + SW	0.86*	0.58	0.96	0.00 ± 0.12
B) Torsional	1. SS	0.82*	0.48	0.95	0.00 ± 0.02
	2. SW	0.86*	0.58	0.96	0.00 ± 0.01
	3. SS + SW	0.68*	0.16	0.9	0.01 ± 0.01
C) Sagittal	1. SS	0.70*	0.22	0.91	0.01 ± 0.02
	2. SW	0.84*	0.5	0.95	0.00 ± 0.02
	3. SS + SW	0.94*	0.81	0.99	0.01 ± 0.02

The peak extension moment for each of the three tasks was determined, with that for SS observed to be slightly smaller than those for SW and SS+SW. The mean peak L3/L4 joint moments in the three directions during the different tasks are presented in Table 4-3.

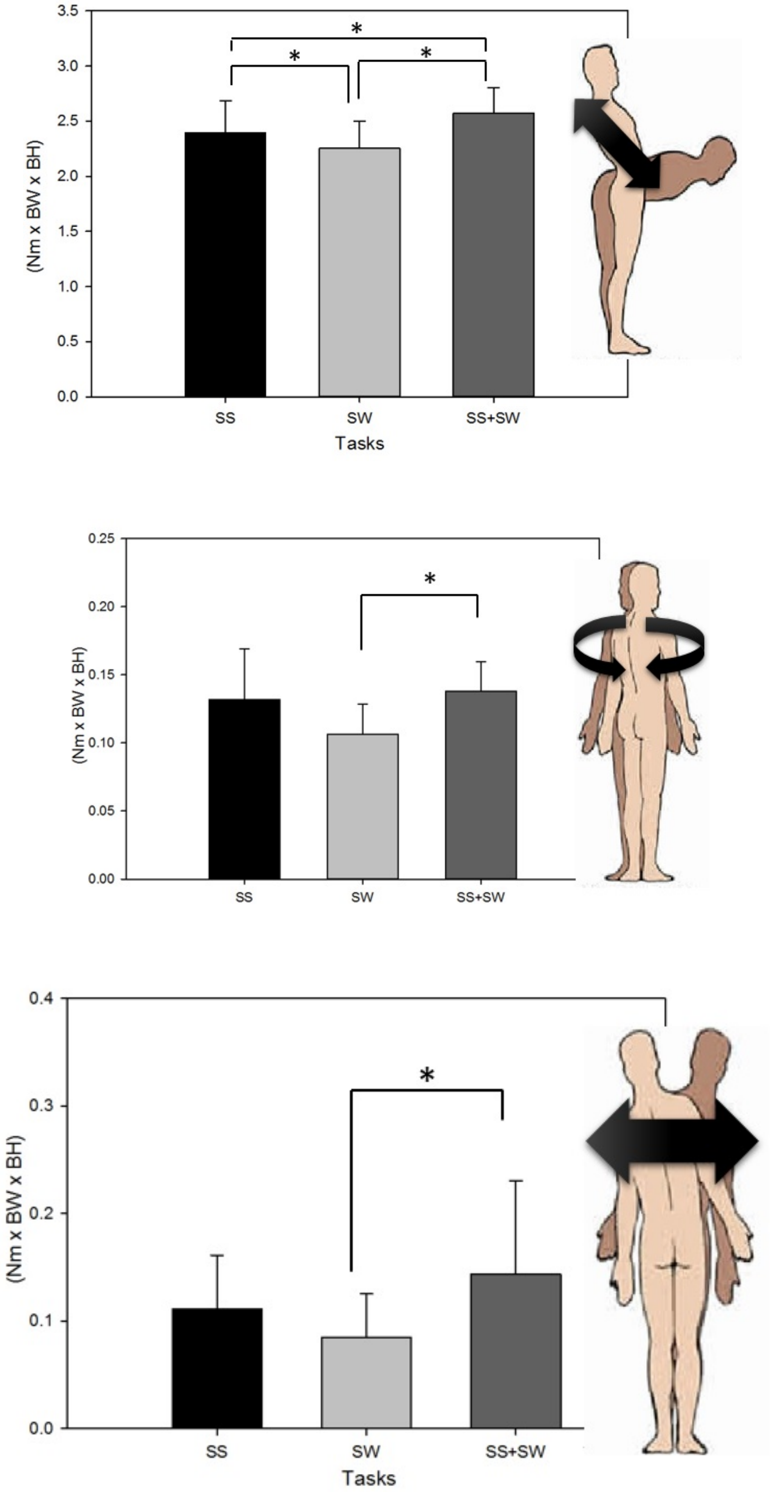


Figure 4-7. Difference between Peak L3/L4 joint moments (Nm x BW x BH) and standard deviations during patient-handling tasks (SS: supine-to-sitting; SW: sitting-to-wheelchair; SS+SW: supine-to-wheelchair) calculated in three directions of force (Sagittal, Torsional and Lateral).

Table 4-3. Peak L3/L4 joint moments and standard deviations for the different patient-handling tasks

	Extension moment (Nm / BW x BH)	Lateral moment (Nm / BW x BH)	Torsion moment (Nm / BW x BH)
1. Supine to sitting (SS)	2.40 ± 0.27*	0.11 ± 0.04	0.13 ± 0.03
2. Sitting to wheelchair (SW)	2.25 ± 0.23*	0.08 ± 0.03*	0.10 ± 0.02*
3. Supine to wheelchair SS + SW	2.57 ± 0.22*	0.14 ± 0.08*	0.14 ± 0.02*

* Significantly difference between tasks ($p<0.05$).

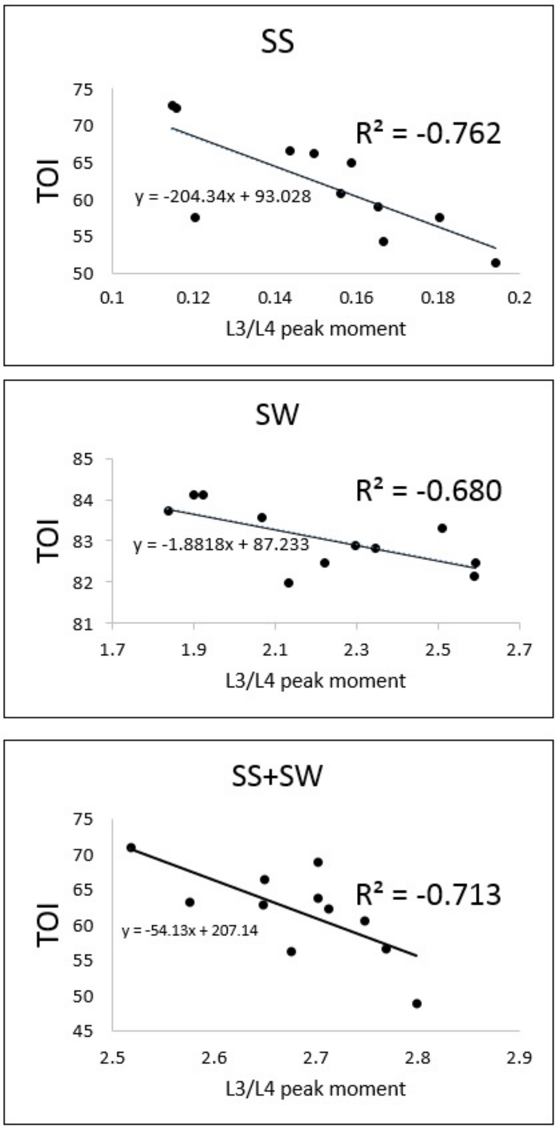
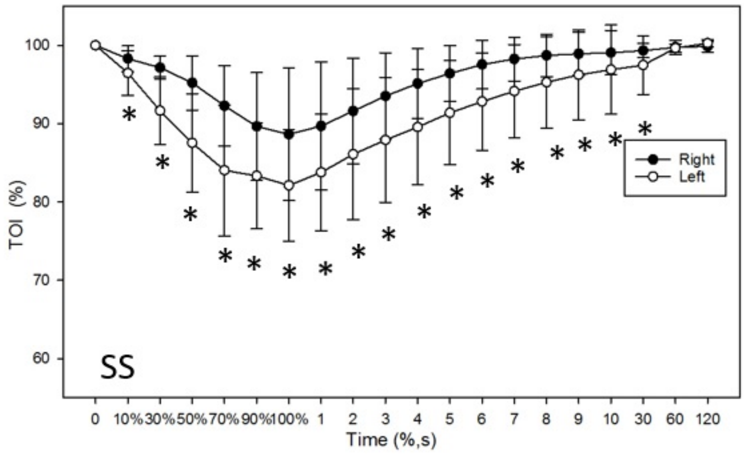
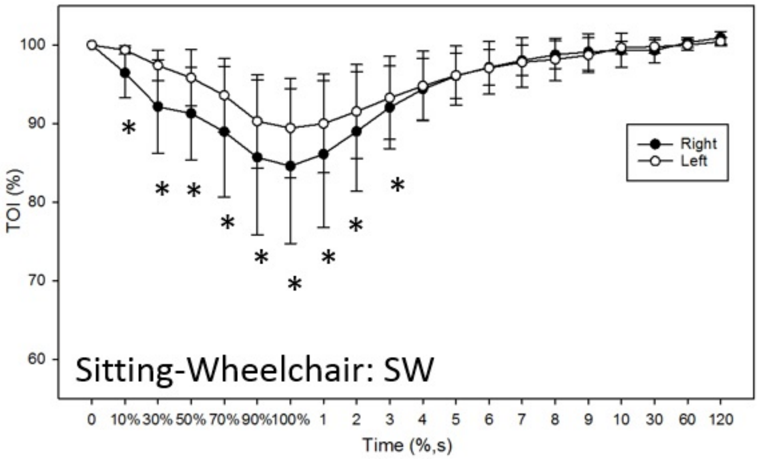


Figure 4-8: Pearson's correlation coefficient between TOI and L3/L4 peak moment during SS: supine-to-sitting; SW: sitting-to-wheelchair; SS+SW: supine-to-wheelchair.





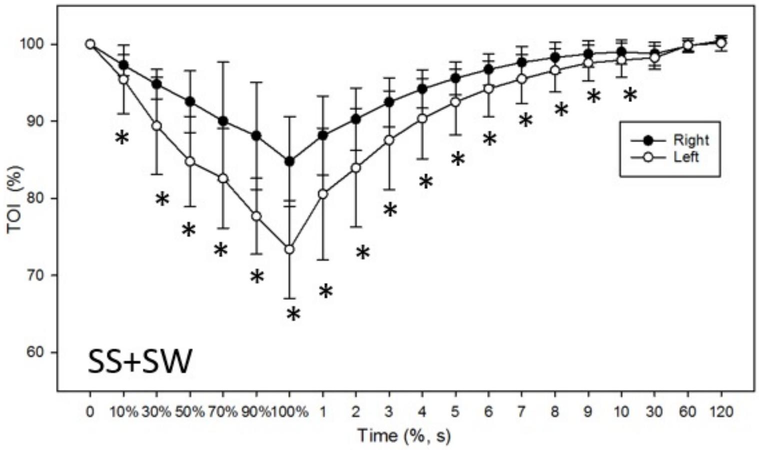


Figure 4-9: Single representative data for lumbar Tissue Oxygenation Index (TOI) of a caregiver during and after each task. SS: supine-to-sitting; SW: sitting-to-wheelchair; SS+SW: supine-to-wheelchair.

The bending angle of the trunk increased when the subject moved close to the patient, and further increased when the patient was lowered after being lifted (Table 4-4). There were statistically significant differences among the tasks with regard to this parameter as determined by a one-way ANOVA (*F*(2,96) = 19.312, p < 0.01). The Tukey *post-hoc* test revealed that the average angles in degrees for SS (44.07±8.40°, p < 0.01) and SS+SW (44.51±6.76°, p < 0.01) were statistically significantly higher than that for SW (34.51±6.88°). There was no statistically significant difference with regard to this parameter between SW and SS+SW (*p* = 0.968).

Table 4-4. Overview of the averaged maximum trunk forward-bend angle (degrees), maximum mannequin lift height (m), and average time length (s) for the different patient-handling tasks.

Tasks	Δ Trunk forward bend angle (°)	Mannequin lift height (m)	Time length (s)
1. Supine to sitting (SS)	44.08 ± 14.31*	0.68 ± 0.03	34.19 ± 13.97
2. Sitting to wheelchair (SW)	34.51 ± 6.22	0.36 ± 0.05	25.62 ± 7.37
3. SS + SW	44.52 ± 5.92*	0.90 ± 0.05	47.43 ± 14.97

* Significantly difference between tasks (p<0.05).

Single representative data for lumbar Tissue Oxygenation Index (TOI) of a caregiver during and after tasks are shown on Fig. 4.8. Pearson's correlation coefficient between TOI and L3/L4 peak moment during SS, SW, SS+SW patient handling tasks (Figure 4.7). A two-way ANOVA was conducted to examine the effects of the hTR and the three different tasks. No statistically significant interaction was observed (*F*(2,192) = 0.525, p = 0.59). However, a simple main effect analysis showed that the hTR for

SS+SW was significantly higher than those for SS and SW ($p < 0.05$), but there were no differences between the right and left lumbar during SS and SW (Figure 4-9).

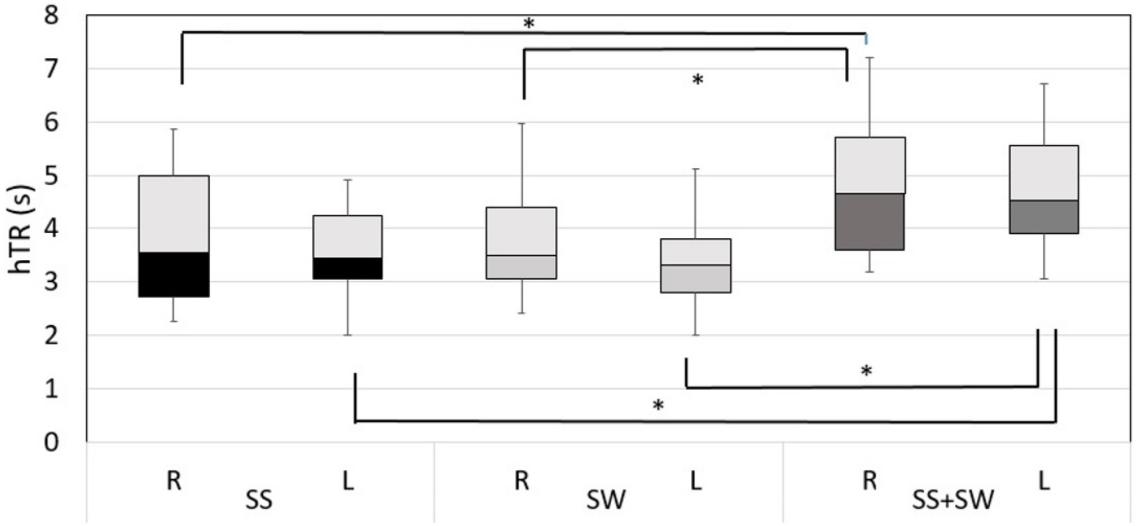


Figure 4.10: Box plot of half-time to recovery (hTR) ordered by medians of R (right) and L (left) lumbar and three different tasks (SS: Supine-to-sitting; SW: Sitting-to-wheelchair, SS+SW: Supine-to-wheelchair). Whiskers indicating lower and higher measurements.

4.5. Discussion

The objective has not been consider the effectiveness of the technical aids for disabled use. The present study main purpose was to estimate the L3/L4 joint moments and the hemodynamic effects of the ESMs during the simulation of patient-handling. For use as references, the moments were measured using data obtained by motion capture and force plates. The tissue oxygenation indexes were also determined by NIRS. Because the net forces of the L3/L4 joint moments could not be directly measured, the forces and moments at the hip joints, knee joints, and ankle joints were estimated based on the kinematics and inertial properties using the inverse dynamic process and a developed free body diagram for motion analysis. Although the forces acting at the distal end of a segment, the weight of the segment, and the kinematics of the segment can be typically determined by direct measurement, the forces and moments at the proximal end must be calculated using the equations of motion and the known quantities.

To determine the unknown forces at the ankle, knee, and hip joints, the lower extremity was sectioned into three parts (the thighs, legs, and feet) to determine their interactions. The L3/L4 joint moment was finally calculated. In agreement with the finding of Skotte *et al*. (2002), the present data indicated that the low back joint extension moment was larger than the lateral and torsional moments. However, the peak mean value of 1.73±0.44 Nm/kg in the previous study is smaller than the present value of 3.77±0.56 Nm/kg. The reason for the difference may be the differing levels of the joints and differing moments of arm assessed. The L3/L4 joint was considered in the present study, compared to the L4/L5 joint in the previous study. The present results indicated significant differences among the three tasks, with the extension moment for

SS+SW being larger than those for SS and SW. This may be due to the differing time lengths of the different tasks and the angular accelerations of the subjects. It is unsurprising that the moments were affected by the weight of the trunk when the external load was relatively small.

Although the biomechanical parameters of the present study indicated task dependency, it must be noted that the situations of the patient-handling tasks differed. The individual characteristics of the subjects are also crucial to understanding the differences and achieving more consisted results.

Skotte *et al*. (2002) reported that the low back extension moment was largest among the rotations about all the axes during the lifting of a patient from sitting on a bed to standing on the floor. This is in good agreement with the present finding. However, the mean peak value of 184±42 Nm observed in this previous study is slightly higher than the 179.6±26.6 Nm of the present study.

A simulated stroke patient was used in the previous study, whereas a mannequin of weight 16 kg was employed in the present one. The discrepancies between the study results were thus likely caused by the differing subjects and methods. The maximum trunk flexion angle of 47.7±13.8° determined for SW in the present study was different from a previously published value of 34.5±6.2°. This may be attributed to the differing heights and angles of and between the bed and the wheelchair, respectively, in the two studies(Katsuhira *et al*. 2008).

The lift height for SS+SW was higher than those for the other tasks. Varady *et al*. (2015) observed a steady decrease in the maximum lift height with increasing load. However, in the present study, the mannequin load was constant at 16 kg. There is widespread concern about the recognized tissue damage that results from repeatedly handling heavy loads.

The important questions remains whether the reduction in mechanical load during patient handling activities will be sufficient to prevent the occurrence of low back pain. It has to be considered that the occurrence of low back pain is not always work-related. The etiology of back complaints is multifactorial and epidemiological surveys have identified various individual, psychosocial, and physical risk factors. The occurrence of low back pain can, therefore, not entirely be prevented by the appropriated time to rest. Given the fact that consecutive task in this study was associated to higher time to recovery, a lower recovery time may be certainly be expected to lead to a substantial reduction in the occurrence of low back.

4.5.1. Factors Affecting Recovery Time

According to Chance (1992), the recovery time is determined by the balance between oxygen supply and oxygen demand during the recovery changes after an exercise, when the bioenergetic resources are restored. It is the time required for the resynthesis of phosphocreatine (PCr), and in some cases, adenosine triphosphate (ATP)(Hamaoka *et al*. 2011).

The TOI hTR of the bilateral ESMs was measured for the three tasks of the present study. No statistical difference was found between the hTRs of the left and right sides of the ESMs. It was, however, observed that the hTR after SS+SW was significantly longer than those after SS and SW. This was because SS+SW involved the consecutive performance of SS and SW. Masuda *et al*. (2006)(Masuda, Miyamoto, and Shimizu 2006) found that the oxygenation level was significantly decreased during forward bending, especially when handling loads. This explains why the trunk flexion angles for SS and SS+SW were higher than that for SW. Additionally, the lowest TOI corresponded to SS+SW. However, a lower TOI may not only be due to the type of task, but also to the efficiency of performing the task.

Further investigation is required to better understand the mechanism of the change in the oxygenation level and the relationship between the efficiency and the training and expertise of the handler. In occupations such as those involving the transfer of patients, the posture of the worker has been implicated in the cause of health complaints (Freiberg *et al.* 2015). In our previous study, static movement of the ESM tend to produce fatigue according to the time of exposed.

The findings of the present study reiterate the importance of maintaining muscle oxygenation between tasks after static contraction of the erector spinae muscle. (Gerr *et al.* 2002) also demonstrated a link between musculoskeletal symptoms/disorders and occupational ergonomic exposures such as sustained static muscle contraction, highly repetitive movements, and insufficient recovery time. Decreased muscle oxygenation may be attributed to increased oxygen demand and metabolic rate of a contracting muscle and increased intramuscular pressure, which may restrict oxygen supply via blood flow.

Masuda *et al* (2005), reported tissue blood volume and its oxygenation were decreased significantly during forward bending, lateral bending, and loading tasks. In the other hand, stretched muscles had less blood volume and oxygenation, and they decreased with increasing load. Their results showed that these postures and conditions might lead to fatigue of ESM muscles. Therefore, proper patient-handling techniques must thus be accurately used to prevent both caregivers and patients from being fatigue and injured. Some studies related to patient-handling techniques have recommended that caregivers should plan in advance the activities for performing their tasks. In the present study, we found that the hTR for SS+SW was longer than those for SS and SW. SS+SW thus required a longer time for the hemodynamic recovery of the muscle. To achieve quick recovery, the task should be planned in such a manner that the patient is handled through subroutines rather than through the execution of an entire technique in one continuous process.

4.5.2. Limitations

The model described in this paper and the study as a whole have some limitations that need to be addressed. Firstly, the model is based on the assumption of general and frictionless joints, fixed segment lengths, and fixed centers of mass. The effects of friction and joint structures were thus not considered in the analysis of the reaction forces between the subject and the mannequin. Secondly, the number of participants of the study is questionable. Because specific procedures for sample-size calculations for NIRS investigations are yet to be established, the present calculations were performed based on the availability and similarities of the participants.

The question therefore arises as to whether the findings based on a university population are globally applicable. The generalization of laboratory findings to the real world is a challenging issue, especially considering the considerable adaptability of experienced workers in physical tasks. In this context, because the present study only assessed the physiological responses of the selected age group of women participants during simulated patient-handling tasks, only approximate guidelines can be developed from the observations for actual performance of the tasks with varying intensity levels, loads, and time durations.

The replication of the present findings for different activities, both in the laboratory and on the field, is also important to enhancing their practical relevance. Future work to address the above issues would require the adoption of numerous factors and considerations. It is noteworthy that the present model also neglected the compression reducing effects of intra-abdominal pressure, upper limb joint moments, and extensor ligamentous structures. This had an effect on the obtained results. Nevertheless, the L3/L4 joint moment data are comparable or slightly lower than those of most previous studies that employed similar tasks. In addition, as in many previous studies, a mannequin was used instead of a real patient or a healthy person.

The mannequin was used in the present study to ensure constancy of the load borne by the subjects (caregivers) only, during all tasks movements. Furthermore, although the markers were attached to the bodies of the subjects to best represent the joint center, anatomical constraints inevitably caused small errors. For example, the markers of the ankle joints were placed on the lateral malleolus. However, the articulation of the tibial/talus surfaces is such that the distal end of the tibia (and the fibula) moves in a small arc over the talus. The true axis of rotation is actually a few centimeters distal of the lateral malleolus. The feet of a subject were also not arbitrarily fixed on the force plate to measure the reaction force during the tasks. This might have decreased the rotation (lateral and torsional moment) of the lumbar region to compensate for the restricted movement ranges while executing the tasks. No single intervention can be used to consider the above issues; instead, each patient-handling task would have to be separately analyzed to determine how to maximize the reduction of both the peak and cumulative lumbar forces during a manoeuver. However, no published literature was found for a comparison or basis that attempted to quantify the correlation and possible association between NIRS and motion capture system related do human musculoskeletal system.

Since, to our knowledge, no data were available on the variability of ESM hemodynamic activity during patient-handling task, generalizability of the present findings is unknown.

4.6. Conclusion

This study shows that the ESM tissue oxygenation index decreased in all subjects during patient-handling task. Along with the increased in peak L3/L4 joint moment. These finding suggest that the longer hTR is, a higher risk of muscle injury might be developed.

We encourage the conduction of further study towards developing new guidelines that consider the effects of dynamic loads and hemodynamics for preventing LBP on workers. This would contribute to reducing incidences of worker illness and injury, thereby improving the overall well-being of workers. The results of the present study showed that the quantitative estimation of individual low back joint moments and oxygenation level provide information for the design of proper work/rest schedules for caregivers that perform patient-handling tasks.

Chapter 5

General Conclusions

5.1. Conclusions

Three conclusions relative to future research of this type can be drawn from this study. The first part of conclusion dealt with an experimental approach of the isometric contraction of ESM measuring with EMG and NIRS. Combining NIRS and EMG it was shown that NIRS-derived oxygenation responses to varied of period contractions it has correlated with EMG myoelectric responses. For a sustained contraction, responses were of a reasonable physiological nature was done assessing the myoelectric manifestations. For a 30-40% MVC contraction sustained for 2-3 minutes (or until fatigue), subjects had a longer hTR, but oxygenation responses during the contraction were different between them. By knowing the hTR it is possible somehow evaluate the proper time to rest and prevent muscle to fatigue. The responses for oxygenation and myoelectric activity were time and specific. Based on this findings, NIRS demonstrated to be a suitable technique for assessing physiological measurement of the ESM, including the assess of hTR.

The second part of conclusion is related to the mechanisms of fatigue after isometric contractions of EMS. A reduction in the strength (i.e., EMG), endurance, and oxygenation levels (i.e., NIRS) of the low back muscles has been implicated as a contributory factor to fatigue. Adequate blood supply is obviously the most essential component to withstand fatigue and prevent the loss of lumbar muscle function. However, it was observed that after 40% of time to exhaustion, the TOI trend remained fairly consistent and showed a plateau until the end of the exercise. Necessary hTR of 20 to 38 s (right) and 22 to 32 (left) with 155 ± 33 s was shown. Furthermore, prolonged static posture might diminish oxygenation level and MF, increasing susceptibility to fatigue.

The third conclusion, based on the results of the caregiver's ESM contraction during transfer movement, it was thought that allowing breaks or recess between work schedules would be more effective in reducing fatigue rather than using short and frequent recovery time during working cycle.

In summary, the general conclusions from this research address several aspects of the erector spinae muscle contraction in NIRS based on the oxygenation and reoxygenation level. The feasibility of building a recovery time model with few representative samples has been demonstrated.

5.2. Recommend for the Future Work

A concern in the thesis is the characteristics of the subjects (college students) in being different form the reality of caregivers. Although, the aim of this thesis was to examine the movement itself. Thus, for future directions applying NIRS for studying caregiver /nurses in their labor places is important to robust the data.

Chapter 2: On first conclusion, it was shown that MF decrease as the oxygenation level declines during all tasks (isometric contraction), which should taken into account in future studies to understand the mechanisms of fatigue. The NIRS proved to be a valid tool to measure the hTR after exercise. NIRS data might help comprehend the mechanisms to prevent injury.

Chapter 3: The findings of this study have implications for future investigations on the mechanism of fatigue from low back muscle. A reduction in the strength (i.e., EMG), endurance, and oxygenation levels (i.e., NIRS) of the low back muscles has been implicated as a contributory factor to fatigue. Adequate blood supply is obviously the most essential component to withstand fatigue and prevent the loss of lumbar muscle function. Necessary hTR of 20 to 38 s (right) and 22 to 32 (left) with 155 ± 33 s was shown. Furthermore, prolonged static posture might diminish oxygenation level and MF, increasing susceptibility to fatigue.

Chapter 4: We encourage the conduction of further study towards developing new guidelines that consider the effects of dynamic loads and hemodynamics for preventing LBP on workers. This would contribute to reducing incidences of worker illness and injury, thereby improving the overall well-being of workers. The results of the present study showed that the quantitative estimation of individual low back joint moments and oxygenation level provide information for the design of proper work/rest schedules for caregivers that perform patient-handling tasks.

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