Alteration in Neck Neuromuscular Responses and Upper Limb Proprioception in Response to Neck Muscle Fatigue

By

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TITLE

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ABSTRACT

Neck and upper limb disorders constitute two of the most frequent musculoskeletal problems that place a huge burden on the healthcare system. Neck muscles have a very high density of muscle sensory input to the central nervous system (CNS) and are known to play an important role in sensory motor integration of upper limb movements. The CNS uses the position of the head and neck in interpretation of upper limb joint position sense (JPS). Therefore, any altered neuromuscular function of the cervical extensors has the potential to impair the awareness of upper limb joint position which is critical for carrying out smooth, purposeful movements. Despite this, only a small amount of basic science research has attempted to explore the relationship between altered afferent input from the neck on both neck and upper limb neuromuscular control. Additionally, the cervical flexion relaxation ratio (FRR) is a reliable and reproducible neuromuscular marker, which has been shown to differentiate between neck pain patients and healthy controls, and presents an objective way to measure changes in neuromuscular function. Induction of fatigue provides an experimental method for altering afferent input from the neck muscles to the CNS, enabling the effects of both neck muscle function and upper limb JPS to be investigated in an experimental setting. Studies in this thesis sought to investigate whether the elbow JPS and neck FRR can be altered by fatigue of the cervical extensor muscles (CEM). This study revealed that CEM fatigue decreased the cervical FRR, by increasing the EMG activity in relaxation phase, and reduced the accuracy of elbow joint position matching in healthy individuals. Whereas, slightly expanded the FRR in subclinical neck pain patients, by increasing the EMG activity in re-extension phase. This work has important implications for our understanding of the mechanisms that the

CNS uses to stabilize the neck in the face of altered afferent input, and the implications that this may have for upper limb proprioception and associated motor performance.

KEYWORDS

Proprioception, Fatigue, Elbow Joint Position Sense (JPS), Cervical Extensor Muscles (CEM), Upper Extremity, Absolute Error, Constant Error, Variable Error, Flexion Relaxation Phenomenon (FRP), Flexion Relaxation Ratio (FRR).

DECLARATION OF ORIGINALITY

I hereby certify that the thesis submitted entitled:

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is the best of my knowledge and it does not infringe upon anyone's copyright and any ideas, techniques, quotations, or any other material from the previous works are fully acknowledged in my thesis in accordance with the standard referencing.

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I lovingly dedicate this thesis to my parents, brother, sisters

and my dearest loves, Ali and Sara,

without their support and sympathy none of this would have been possible.

TABLE OF CONTENTS

TITLE II

ABSTRACT III

KEYWORDS IV

DECLARATION OF ORIGINALITY V

ACKNOWELEGEMNT VI

TABLE OF CONTENTS VIII

LIST OF FIGURES X

LIST OF TABLES XI

LIST OF APPENDICES XII

LIST OF ABBREVIATIONS USED XIII

SECTION 1 1

Introduction to the Thesis 2
Objective of the Thesis 6
Hypotheses of the Thesis 6

SECTION 2 7

LITERATURE REVIEW 7
Introduction to the Literature Review 8
Brief Overview of Movement Neuroanatomy 8
Proprioception 10
Muscle Spindles and Golgi Tendon Organs 14
Joint Position Sense (JPS) 17
Muscular and Neuromuscular Fatigue 18
Absolute, Constant, and Variable Errors 26
Effect of Muscle Fatigue on Accuracy of Limb Proprioception 27
Elbow and Forearm Joint Position Sense 27
Cervical Joint Position Sense 40
Shoulder Joint Position Sense 41
Knee Joint Position Sense 44
Flexion Relaxation Phenomenon 45
Phases of Flexion Relaxation Phenomenon 47
Reliability and Reproductively of the Flexion Relaxation Ratio 48
Spinal Stabilization and Theoretical Models 49
Body Position and Flexion Relaxation Phenomenon 52
Changes in FRP and FRR in the Lumbar Spine 54
The FRP and FRR in the Cervical Spine 65
Conclusion of the Literature Review 73

SECTION 3 76

MANUSCRIPTS 76
MANUSCRIPT 1 77

NECK MUSCLE FATIGUE ALTERS UPPER LIMB PROPRIOCEPTION 77
Abstract 78
Keywords 78
Introduction 79
Methods 82
Data Analysis 91
Statistical Analysis 93
Results 93
Discussion 99
Strengths of study 103
Limitations of the Study 104
Conclusion 104
MANUSCRIPT 2 105
NECK MUSCLE FATIGUE ALTERS THE CERVICAL FLEXION RELAXATION RATIO (FRR) .. 105
Abstract 106
Key words 107
Introduction 108
Methods 112
Data analysis 123
Statistical Analysis: 126
Results 127
Discussion 134
Strength of study: 142
Limitations of the Study 143
Conclusion: 143

SECTION 4 145

THESIS SUMMARY 146
REFERENCES 148

SECTION 5 154

APPENDICES 154

LIST OF FIGURES

Figure 1: Sequence of Fibers in the Dorsal Column Pathway 12
Figure 2: Location of the Surface EMG Electrodes 83
Figure 3: Rigid Body Marker Setup 85
Figure 4: Fatigue Protocol 87
Figure 5: Experimental Procedure 90
Figure 6 (A, B, C): Absolute, Variable, Constant Errors 96
Figure 7 (A, B): Average of MNF and RMS 98
Figure 8: EMG Kinematic Marker Setup 116
Figure 9: Fatigue Protocol 118
Figure 10: EMG Activities of the Right and Left CEM and Force Template during the Fatigue Protocol 120
Figure 11: Typical EMG Data during the Cervical Flexion Relaxation Phenomenon. 122
Figure 12: Experimental Procedure 123
Figure 13: Euler Angles 126
Figure 14: Average of MNF and RMS of Fatiguing CEM 129
Figure 15: Flexion Relaxation Ratio (FRR) 131
Figure 16 (A,B): Onset and Offset Angles of the Silent Period 133

LIST OF TABLES

Table 1: Demographics and Self-Report Measures 113

LIST OF APPENDICES

APPENDIX 1: Neck Disability Index (NDI) 156
APPENDIX 2: Edinburgh Handedness Inventory (EHI) 157

LIST OF ABBREVIATIONS USED

AE	Absolute Error
CE	Constant Error
CEM	Cervical Extensor Muscles
CLBP	Chronic Low Back Pain
CNS	Central Nervous System
CRNP	Chronic or Recurrent Neck Pain
EMG	Electromyography
ER-Ratio	Extension Relaxation Ratio
ES	Erector Spinae
FRP	Flexion Relaxation Phenomenon
FRR	Flexion Relaxation Ratio
JPE	Joint Position Error
JPS	Joint Position Sense
LBP	Low Back Pain
MNF	Mean Power Frequency
MVC	Maximum Voluntary Contraction
NP	Neck Pain
PSD	Power Spectrum Density
RMS	Root Mean Square
ROM	Range of Motion
sEMG	Surface Electromyography
TDPM	Threshold to Detection of a Passive Movement
VAS	Visual Analog Scale
VE	Variable Error
WAD	Whiplash Associated Disorders

SECTION 1

Introduction to the Thesis

Advances in technology within many industries have led to an increased risk of musculoskeletal disorders in the general population (Falla 2004). Neck pain (NP) is a common and significant problem, which affects about 30-50% of Canadians every year and can place a large burden on the healthcare system (Hogg-Johnson et al. 2008). In many cases, NP is initiated in the workplace due to prolonged, abnormal flexion in sitting or standing postures (Yoo et al. 2011) (Ming et al. 2004), or from a sedentary life style. Additionally, our dependence on technology such as computers, laptops, tablets and cell phones have substantiated the issue (Ming et al. 2004). The prevalence of repetitive strain injuries (RSI) and occupational overuse injuries (OOI) affecting mainly the upper limb, has increased dramatically over the past ten years with the Canadian Community Health Survey indicating that one in ten Canadian adults have RSI or OOI severe enough to limit normal daily activities (Statistics Canada 2000). Upper-extremity disorders increased 3-fold in the United States between 1986 and 1993 and large increases have also been reported in the UK, Australia, Norway, Sweden and Japan (Yassi 1997).

Interestingly, despite this parallel increase, the link between awkward neck postures, neck muscle fatigue and the effects on motor control of the neck and upper limb are underexplored. This thesis attempts to address this with two basic science studies. The first investigates the effect of neck muscle fatigue on awareness of elbow joint position in healthy subjects, and the second investigates the effect of fatigue on neuromuscular responses of the neck in both healthy participants and those with neck pain.

A study found that alterations in head and neck position alter upper limb proprioception, namely elbow joint position sense (JPS) (Knox and Hodges 2005), and a number of studies have shown altered JPS subsequent to fatigue of the muscle crossing that joint (Skinner et al. 1986, Brockett et al. 1997, Jull et al. 2007); however, to date, no studies have investigated how neck muscle fatigue might influence upper limb proprioception.

Neck muscles are fundamental for maintaining body balance, and for providing an appropriate reference point for the position of the head and body, with respect to their movement organization (Strimpakos et al. 2006). Neck muscles have numerous sensory receptors that are responsible for central and reflex connections to the vestibular, visual, and postural control systems (Jull et al. 2007). During limb movement, the kinaesthetic and visual inputs are constantly matched against the brain's internal map or "schema" of the body, to predict the future position of the limb. In the absence of visual feedback, muscle spindles are responsible for limb proprioception (Proske and Gandevia 2009). Muscle spindles signal both static and dynamic changes in muscle length through changes in firing rate (Proske and Gandevia 2009). Limb proprioception refers to an awareness by the central nervous system (CNS) of a limb's location in 3D space (Enoka and Duchateau 2008).

Section 1: Introduction

During fatigue of the cervical extensor muscles (CEM), the neural control structures cause a transfer of load from active structures to the passive of the neck to balance destabilizing physical forces (Letafatkar et al. 2009). Therefore, altered input from neck muscles (Letafatkar et al. 2009) and fatigue (Barker 2011) would affect the sensory feedback to the CNS and consequently could impair accuracy of limb movement in space (Letafatkar et al. 2009). Neck muscles have a large number of sensory receptors that are used by the CNS for upper limb proprioception (Jull et al. 2007, Letafatkar et al. 2009). The first manuscript of this thesis attempts to extend our understanding of the effects of neck muscle fatigue, with a submaximal voluntary contraction until failure, on the accuracy of the elbow JPS in healthy participants.

The strength and endurance of the cervical flexor muscles is reduced in NP patients (Falla et al. 2004) and neck muscle recruitment patterns are known to be altered in those suffering from neck complaints (Murphy et al. 2010). Electromyographic (EMG) activity of the Erector Spinae (ES) muscles, which contract to control vertebral movements, during trunk flexion and neck flexion are known to stop or "switch off" once full flexion is reached (Floyd and Silver 1955). This pattern is known as the Flexion Relaxation Phenomenon (FRP), which is the reduction in myoelectric activity in the lumbar or cervical ES muscles when an individual goes from an upright position to full forward flexion. However, this phenomenon does not occur in back (Othman et al. 2008) or neck pain (NP) patients (Marshall and Murphy 2006), as previous work has shown higher myoelectric activity in NP or back pain patients than healthy control participants during full forward cervical or lumbar flexion (Marshall and Murphy 2006, Othman et al. 2008).

Spinal disorders play a significant role in poor stabilization of the spine (Murphy et al. 2010). NP patients are unable to fully relax their CEM and have increased muscle activity during full forward cervical flexion (Maroufi et al. 2013). In addition, it has been stated that fatiguing the lumbar ES modulates both onset and offset angles of the flexion relaxation phenomenon (FRP) (Descarreaux et al. 2008). It is possible that in the case of pain or insufficient spinal stability, previously-injured structures might be at risk of further injury during fatiguing activities. Little is known about the implications of CEM fatigue on parameters of the FRP particularly in neck pain participants. Previous studies investigated the influence of CEM fatigue, on parameters of the FRP only in healthy participants (Nimbarte et al. 2014). Therefore, the effect of fatigue on the cervical FRP and FRR needs to be further explored in neck pain patients. The second manuscript of this thesis investigates the influence of CEM fatigue on the FRP parameters in a group of participants with ongoing low level neck pain and stiffness in comparison to healthy participants and evaluates the differences between pre- and post-fatigue conditions.

Objective of the Thesis

1- To explore the effect of cervical extensor muscle fatigue on elbow joint position sense in healthy participants.

2- To explore the effect of cervical extensor muscle fatigue on parameters of the cervical flexion relaxation phenomenon in both subclinical neck pain patients and a control group.

Hypotheses of the Thesis

1- Fatigue of the cervical extensor musculature with 70% of maximal voluntary contraction will negatively impact the ability to reproduce a previously presented angle at the elbow.

2- Fatigue of the cervical extensor musculature with 70% of maximal voluntary contraction in subclinical neck pain patients will increase activity of the neck extensor muscles in full forward cervical flexion and/or extension phases, leading to altered parameters of the cervical flexion relaxation kinematics.

SECTION 2

LITERATURE REVIEW

Introduction to the Literature Review

This section reviews current literature relevant to the proposed objectives of this thesis. It begins with an overview of proprioception focusing on how accuracy of joint position sense is altered with muscular fatigue. It then provides an overview of previous literature relevant to the effect of muscular fatigue on limb proprioception. Finally, factors known to affect the FRP in both the cervical and lumbar spine are discussed with a focus on how changes in afferent input from the spine due to pain or fatigue can modify the EMG activity of that area.

Brief Overview of Movement Neuroanatomy

The nervous system is divided into two sections: the central nervous system (CNS) and the peripheral nervous system (PNS). The CNS is the major managing and controlling center thorough the nervous system. The CNS is responsible to receive reports from the PNS, then decode them and answer back to the PNS again. The PNS consisted of the somatic and autonomic nervous system. The somatic nervous system (SNS) consciously regulates and processes sensory information and voluntary muscle contractions and the autonomic nervous system (ANS) un-consciously control the automatic actions of the internal organs. The SNS contains the afferent (sensory neurons or dendrites) and efferent (motor neurons or axons) structures. The afferent structures carry impulses from sensory organs to the CNS and then they get transferred from the CNS to the muscles by efferent structures (Rose and Christina 1997, Heidelberger et al. 2009). The CNS is consisted of two reference frame types: egocentric and allocentric. The egocentric is associated with the body and the allocentric with the external world. The CNS interprets the signals within these two reference frames to generate proper kinaesthetic sensation (Paulus and Brumagne 2008), perception of body position, movement, and muscular tension (Allen and Proske 2006), which refers to the awareness of location of the body parts in relation to each other in 3D space.

Sensory feedback regarding the interaction between antagonistic muscles and load provides the cortex information to enable the perception of a joint's angle and its stability. In guiding body movements and creating awareness of JPS, the cerebellum has a fundamental role. Information about muscle activity is delivered to the somatosensory cortex through afferent feedback from muscles and joints, evaluated in the cerebellum, and then efferent (outgoing) motor commands to the limbs are adjusted accordingly (Feldman and Latash 1982). The anterior horn of the spinal cord contains the cell bodies of the motor neurons that control the final output neurons in direct limb and body movements. The size of motor neuron is variable. Fast-twitch muscle fibres, which contract quickly and get fatigued rapidly, have larger motor neurons; while slow-twitch muscle fibers, which contract slowly and are more fatigue resistant, have smaller motor neurons (Purves et al. 2001). Proprioceptors refer to sensory receptors located in the skin, joints, and skeletal muscles (Grigg 1994). They convey information about a joint's position including joint angle, muscle length, and tension, and transfer this information to the cortex trough the direct and indirect pathways. The direct pathways do not synapse in the cerebellum and transfer the inputs from the upper and lower limbs to the somatosensory cortex. The indirect pathways have synapses within the medulla that can then be traced to the anterior and posterior lobes of the cerebellar cortex (Strominger et al. 2012).

The motor system, which consists of the motor cortex, spinal cord, brain stem, and association cortex, is responsible for generating desired joint movements. The smooth expected movements are calculated by the various regions of the brain and transferred to the muscle by the lower motor neurones. The motor system estimates the joint position by the perception of the length and forces required to generate proper levels of muscle activation (Purves et al. 2001).

Proprioception

Body movement and sensations are consciously and unconsciously signalled by muscle receptors. Signals about muscle length which contribute to awareness of joint position are signalled by muscle receptors (muscle Spindles and Golgi tendon organs) (Allen and Proske 2006). Conscious information about external items can be provided by all four types of discriminative sensation: touch, proprioception, pain, and temperature (Lundy-Ekman 2013). This information is conveyed via the dorsal column pathway (medial lemniscus and spinothalamic pathways) to the cuneate and gracile nuclei in the medulla, and transmittied via the thalamus to the primary somatosensory cerebral cortex. This conscious information contributes to our understanding of the physical word and to control of fine movements (Lundy-Ekman 2013) (Figure 1). The conscious role of muscle receptors are identified as proprioception (Allen and Proske 2006, Hogg-Johnson et al. 2008) which is the awareness of body position, balance and movements that is required for each daily activities (Juul-Kristensen et al. 2007).

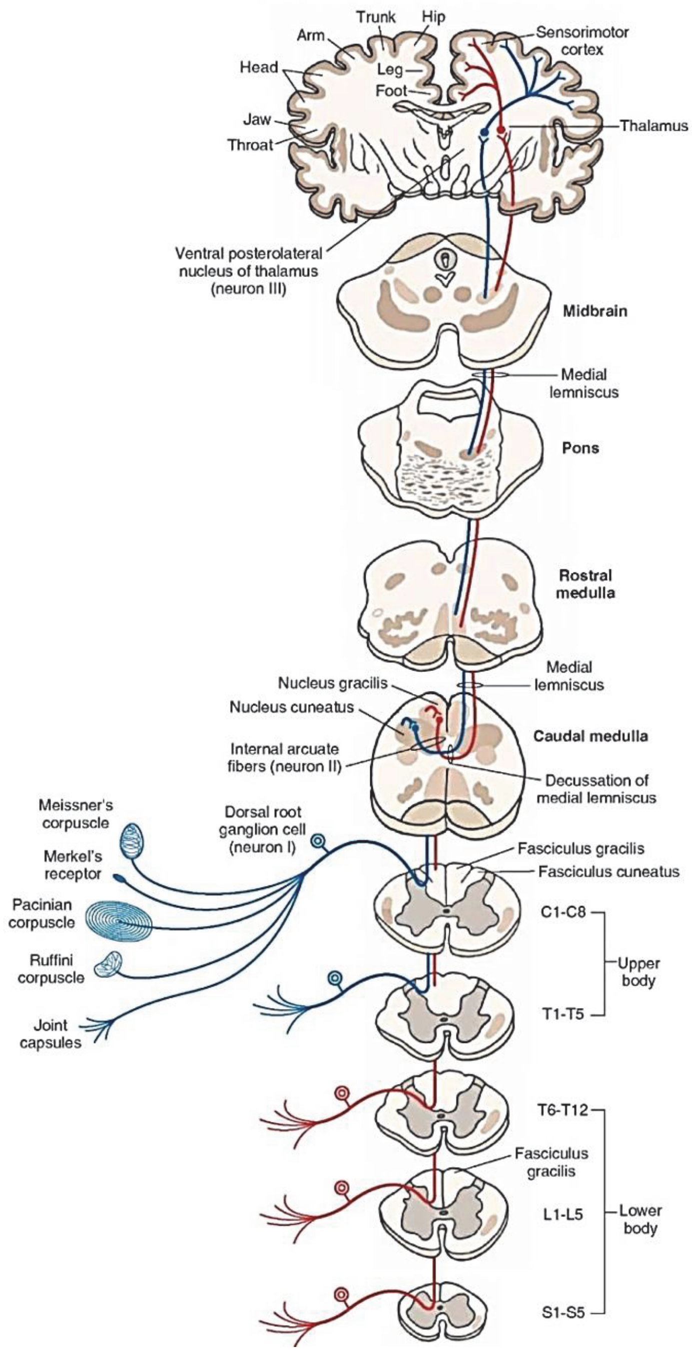

Figure 1: Sequence of Fibers in the Dorsal Column Pathway
Principal cutaneous receptors for position sense: Meissner's Corpuscles (respond to delicate tactile stimuli and are rapidly adapting), Merkel Disks (response to sustained pressure and are slowly adapting), Pacinian corpuscles (particularly sensitive to vibration and are very rapidly adapting), Ruffini endings (respond to shearing stress and detect steady pressure and are slowly adapting) (Elizabeth O. Johnson 2014). Figure reproduced from (Spinal 2014)

Proprioception is divided into two forms: static and dynamic proprioception. Static proprioception or JPS is the perception of the position of body segments conveyed via sensory receptors (Ruffini endings, Pacinian corpuscles, free nerve ending, and etc.) in connective tissue surrounding joints, and type II muscle spindle receptors in muscles. Dynamic proprioception is known as kinesthetic sense, and is correlated with direction of movements and tension detection and these receptors are found more in joints and cutaneous tissues (Grigg 1994, Brockett et al. 1997, Proske 2005, Juul-Kristensen et al. 2007). Proprioception is a composite function of many parts of the afferent system (Juul-Kristensen et al. 2007). Afferent signals from muscles and joints, as well as the visual, vestibular , and auditory systems provide information to the CNS (Hiemstra et al. 2001, Strimpakos et al. 2006). This sensory information is integrated in the brain in relation to the brain's internal representation of the body, referred to as body schema for awareness of body position (Johnson 2001, Knox and Hodges 2005, Paulus and Brumagne 2008).

Mechanoreceptors consciously and unconsciously receive and transfer mechanical information about joint position, movement, and body's periphery to the CNS (Dover and Powers 2003, Allen and Proske 2006, Juul-Kristensen et al. 2007) and they respond to pressure and to stretch (Lundy-Ekman 2013). Proprioception is associated with a specific sensory receptors that are located in joint, muscles and surrounding tissues(Jami 1992) and Kinesthesis sense is associated with those receptors that are found in joints and cutaneous tissue (Burgess et al. 1982). Position sense is first detected by mechanoreceptors and then signalled by changing the activity of the receptors or the number of activated receptors (Hogg-Johnson et al. 2008). Muscle receptors are important for signalling the mid-range of joint range of motion, whereas ligamentous receptors are activated near the end range of joint motion (Gear 2011).

Signals from visual, tactile, and proprioceptive system are integrated in the CNS. Visual inputs play a very important role in limb proprioception because the visual signal is evaluated by the brain to be matched with kinaesthetic inputs. The sensory information from visual and kinaesthetic inputs is integrated in the cerebellum to predict the limb's future position (Proske and Gandevia 2009). However, in a dark room we are capable to put our index finger on the tip of the nose (Walsh et al. 2006). This is because in the absence of visual input, the primary endings of muscle spindles are able to provide a sense of limb position in space and in association to the other limbs (Winter et al. 2005, Walsh et al. 2006, Proske and Gandevia 2009). The kinesthesic sensations is detected by Ruffini endings, muscle spindles, and Pacinian corpuscles and proprioception is detected by the Golgi tendon organs and Flower Spray endings of muscle spindles (Kandel et al. 2000). In the absence of visual feedback the sensory signals from muscle stretch, contraction, and tension are sent integrated in the CNS to generate awareness of limb proprioception (Brockett et al. 1997, Kandel et al. 2000, Dover and Powers 2003).

Muscle Spindles and Golgi Tendon Organs

The two peripheral receptors that provide the kinaesthetic sense are located in muscle spindles and skin (Proske and Gandevia 2009). Muscle spindles are those type of mechanoreceptors that are sensitive to the muscle length and with any change in length, they transmit afferent signals to the CNS enabling interruption of muscle contraction for response to the limb and joint proprioception (Kandel et al. 2000). Muscle spindles are sensitive to the muscle stretch (Hiemstra et al. 2001) and signals from the muscle spindles initiate the sense of the limb's position sense and movement. The primary and secondary endings of muscle spindles are responsible for limb proprioception. The primary endings contribute to signalling limb position and movement and the secondary endings contribute to signalling the length of the muscle, and position sense (Brockett et al. 1997, Proske and Gandevia 2009).

Muscle spindles contain a number of intrafusal muscle fibers, afferent and efferent motor fibre endings. The intrafusal muscle fibers are arranged in parallel with the extrafusal muscle fibres (typical muscle fibers) and any changes in length of extrafusal muscle fibres change the length of the intrafusal fibres. In the case of muscle stretch, the sensory endings of muscle spindles are more activated in compare to passive tissues and in muscle shortening their activity decreases due to the lack of load on the spindles (Kandel et al. 2000). Within a muscle stretch, the length of muscle changes on two levels. The first level is known as dynamic and second level is static phase. The dynamic phase is a rate of length changing, and the static phase is the muscle stabilizing at a new length. Depending on the movement type the numbers of muscle spindles that are activated changes. To perform smooth movements, muscles with more spindles get activated and for coarse movements there is less need for muscles with a high density of spindles (Kandel et al. 2000).

Slow progressive limb motion changes the spindle firing rates, which changes the limb movement perception. Occasionally, signals about the sense of position and the sense of movement arrive at the cortex by contribution of their receptors' inputs; but they are processed separately in the CNS. When muscle is in its resting position without any contraction, connections develop between actin and myosin. This connection between actin and myosin shortens the muscle length because it increases the stiffness of both the extrafusal and intrafusal muscle fibres. When examining limb proprioception, any previous changes in muscle history prior to the testing can affect the volume and direction of the errors. Therefore, muscle conditioning with contracting the muscle by 20% MVC is the most applicable method to remove slack form intrafusal fibres and increase the spindle resting activity (Proske and Gandevia 2009) prior to testing JPS. The Golgi tendon organ is located at both the origin and insertion of skeletal muscle fibers embedded in the tendons of skeletal muscle where the tendon fibers connect to the muscle fibers. These organs are very sensitive to changes in muscle tension and have many collagen fibre bundles and are in line with the extrafusal muscle fibers. In intensive muscle contractions, the Golgi tendon organs relax the muscle contraction and protect it from injury. Signals regarding length changes are transferred to the spinal cord by the muscle spindles to trigger stretch reflexes and shorten the muscle when it is unexpectedly stretched. In the opposite way, the Golgi tendon organs work to stop the stretch or strong contraction for a longer duration (Zelená and Soukup 1977).

Decreases in proprioceptive sense have been related to pain, injury, and muscle fatigue. Muscle fatigue has been shown to impair kinesthetic and proprioceptive sense of joints by raising the level of muscle spindle discharge, disrupting afferent feedback, and changing awareness of JPS (Strimpakos et al. 2006).

Joint Position Sense (JPS)

JPS is one aspect of proprioception (Dover and Powers 2003). JPS is the ability to recognize where the position of a body segment is in relation to space or other body parts. JPS is associated with joint angle proprioception and is measured by the ability to actively or passively replicate a previously presented joint angle (Carpenter et al. 1998, Dover and Powers 2003).

Pain, injury, and musculature fatigue are all known to lead to proprioceptive deficits (Strimpakos et al. 2006). Fatigue or muscle weakness defined as an inability to sustain a force during an action (Gear 2011) decreases the accuracy of JPS (Carpenter et al. 1998). Fatigue also decreases the sensitivity of capsular receptors (Carpenter et al. 1998) although it does not influence the sensitivity of muscle receptors (Allen and Proske 2006). It changes the effort required to produce a given force needed and disturbs the sense of limb position (Allen and Proske 2006).

Muscle fatigue alters both joint perception and stabilization (Allen and Proske 2006). In fatiguing contractions, the muscle tissues can be affected more than joint tissues (Hiemstra et al. 2001). Fatiguing interval exercises affects the efficiency of muscle spindles and decreases the ability to actively reproduce a joint angle (Gear 2011). Activity of the Golgi tendon organs and muscles decreases in hypoxia, muscle acidosis, ischemia, and electrically stimulated fatigue (Hiemstra et al. 2001) . Therefore, in experimental procedures it is essential to determine what type of fatiguing exercises (concentric or eccentric, maximal or submaximal, and power or endurance contractions) are needed, because different types of muscle contractions might cause different mechanisms of fatigue (Hiemstra et al. 2001). Muscle fatigue impacts the upper level of motor functioning and it can be improved by performing endurance training activities (Carpenter et al. 1998). It has also been suggested that proprioception might be decreased even with low intensity muscle contractions (Gear 2011).

Muscular and Neuromuscular Fatigue

Muscular fatigue is defined as a decline in an individual's ability to generate force to create a performance. It can occur with the repetitive intensive maximal activities or using a motor task for a long duration of time with some submaximal contractions (De Luca 1984, Enoka and Duchateau 2008). Constant contractions of skeletal muscles can lead to failure in muscle function and result in fatigue progression (Westerblad and Allen 2002, Taylor et al. 2005, Letafatkar et al. 2009). Frequently after performing submaximal muscle contractions with lower stimulation frequencies, muscles experience a long-lasting decline in force production with slower recovery from fatigue (Enoka and Duchateau 2008).

Muscle contraction is initiated in the motor cortex and the pathway ends on one muscle or muscle group to produce movement and force. Therefore, any alterations in processing the information along this pathway from motor cortex to spinal cord to peripheral nerve to muscle fiber might be a cause of muscular fatigue (Gandevia et al. 1996, Taylor et al. 2005, Letafatkar et al. 2009). In general, muscular fatigue is categorized into two groups: central and peripheral fatigue. Any sub-optimal output from the CNS can cause some decline in MVC, which is termed central fatigue (Westerblad and Allen 2002, Taylor et al. 2005). Peripheral fatigue is caused by alteration in the muscle cells, nerves and/or neuromuscular junction. In another type of categorization fatigue has been classified into two forms: experienced and physiological fatigue. Experienced fatigue is a problem initiating or maintaining voluntary activities, whereas physiological fatigue is a decrease in ability of neuromuscular structures to complete their performance within a single muscle or muscle group (Gandevia et al. 1996).

In a state of fatigue, the body is unable to provide adequate energy and/or the metabolic chemical conditions that are needed for increased energy demands (Westerblad and Allen 2002, Letafatkar et al. 2009). Proteins control intracellular calcium to stimulate actin and myosin in muscle contraction. Constant contraction and musculature fatigue impairs the structure of proteins and results in actin-myosin interaction and combination of excitation-contraction of the intracellular structures which cause delay or difficultly in recovery from fatigue (Westerblad and Allen 2002).

In experimental muscular fatigue it is common to perform activity with the MVC or submaximal voluntary contraction against a load and monitor change in performance (Taylor et al. 2005). Physiological fatigue can be occur with failures both centrally (at the CNS) and peripherally (at the muscles). Therefore, in performing a MVC, fatigue decreases the motor unit firing rates due to central fatigue and maximal voluntary power of human motor-neuron and muscle fibers due to peripheral fatigue (Gandevia 2001). Voluntary muscle contraction with short-term MVCs has shown are different among individuals, days, trials, and muscles (Enoka and Duchateau 2008).

The sense of movement generated by muscle spindles can be disturbed by the fatigue. Severe fatiguing activities affect both force- and position-matching tasks (Allen and Proske 2006). It changes the amount of force needed to maintain limb position. Therefore, even though the fatigued limb tries to create a movement, the altered position sense means that the individual is unable to produce the desired motion (Allen and Proske 2006). Neuromuscular fatigue can be generated by any failure in the CNS, the pathway from CNS to muscles, or muscle fibers (Bigland-Ritchie and Woods 1984). If participants are not prepared or motivated enough to sustain a contraction, force production also declines. Encouraging participants to focus on task performance, increases the force generation and EMG activity during an MVC and delays the onset of fatigue. However, sometimes even well- trained or extremely motivated participants have been shown to be unable to generate an MVC and recruit all their motor units (Davis and Bailey 1997). One school of thought argues that during voluntary contraction, neuromuscular block is the main reason for fatigue (Bigland-Ritchie and

Woods 1984). In fatigued and sometimes in non-fatigued conditions, the CNS is unable to voluntarily employ and activate all motor units. With constant stimulation, the range of action potentials decreases along motor axons. Therefore, while the motor activity of the CNS is still enough to keep the force, impairment in transforming the nerve impulse to muscle contraction force decreases the contraction of all motor units (Bigland-Ritchie and Woods 1984).

In order to identify whether fatigue is created by the influence of central or peripheral factors, the maximal voluntary force that a subject can produce is compared to supra-maximal electrical stimulations. During both maximal voluntary contractions and imposed electrical contractions, the CNS commands to the motor neuron are decreased. Any changes in efferent or afferent signals might be the result of metabolic changes during the activity (Davis and Bailey 1997). Alterations in neurotransmitter function in the brain can generate fatigue during the contractions. The most important neurotransmitters which are involved in fatigue are serotonin, acetylcholine, and dopamine. During exercise, serotonin increases in the brain, which is related to the development of fatigue and loss of the motor drive. Dopamine is one neurotransmitter involved in control of movement and its metabolism is enhanced during endurance physical activities. Acetylcholine is necessity for force generation and in the CNS it is associated with memory, awareness, and temperature regulation (Davis and Bailey 1997).

Neuromuscular fatigue is described as a failure of a single muscle or muscle group to maintain a required or desired force (Bigland-Ritchie and Woods 1984). The onset of fatigue can be delayed after performing the activity for a long time. The percentage of maximum isometric force production and the time that force is held, are contributors in the creation of fatigue. Therefore, in maximal contractions the onset of force declines immediately after performing a task, and in submaximal endurance contractions it has a gradual decline. Therefore, in fatigue development, there is a linear relationship between ratio of MVC to time (Bigland-Ritchie and Woods 1984).

In addition, muscular fatigue can be determined by quantifying changes in body metabolites, assessing the EMG power spectrum, and velocity of the muscle contraction. A decline in the level of Adenosine Triphosphate (ATP) and phosphocreatine supply due to build-up of lactate and hydrogen ions as a by-product of increased muscle metabolism has been shown to decrease force generation (Bigland-Ritchie and Woods 1984). One way to evaluate fatigue is by measuring changes in EMG activities in relation to the force (Taylor et al. 2005, Enoka and Duchateau 2008). EMG signals are known to change during sustained voluntary contraction with an alteration in the frequency spectrum of the myoelectric signal (De Luca 1984). Depending on the level of voluntary contraction, the effect of fatigue is found as a decrease in myoelectric signal spectral frequencies, both mean and median, and an increase in myoelectric signal amplitudes (Merletti et al. 1990, Enoka and Duchateau 2008).

It is has been stated that all motor units of the muscle need to be employed to produce an MVC, and supra maximal motor nerve stimulation can be used to activate any motor units not recruited voluntarily. By recruiting all motor units to fatigue the muscle, the power spectrum of the EMG, shifts to lower frequencies. There are several explanations for this alteration. First, it might be due to a longer duration of action potential from muscle fibres. Second, synchronization of firing at lower frequencies or an overall drop in firing frequency may affect the power spectrum of EMG. The final explanation is related to the action potential of slow and fast motor units. Through the overall spectrum, the fast units have higher frequency contents and the slower units have lower frequency components. It has been reported that, muscle function recovery after fatiguing performance occur in different times. For example: action potential amplitude recovers between 30 to 60 seconds, and maximum voluntary contraction over 5 to 10 minutes (Mills 1982).

The influence of ES muscle fatigue on myoelectric signals in lumbar flexion relaxation performance was investigated under four conditions: no fatigue/no load, no fatigue/load, fatigue/no load, and fatigue/load. Load was holding 12-kg barbell with the hands and lumbar musculature fatigue was induced by lying prone with the iliac crest aligned with the edge of the table and lower body fixed to the table and fatigue task was to maintain the horizontal, unsupported position of the trunk until failure. Fatiguing the ES muscles modifies the FRP and after fatigue there was an earlier onset during flexion and later offset of EMG during extension. In addition, the myoelectric silence period was observed in presence and absence of extra load and ES muscle fatigue shifted the load sharing to the passive stabilizing tissues. It has therefore been suggested that inadequate muscle contribution and improper neuromuscular activation may compromise spinal stability following a fatiguing task (Descarreaux et al. 2008).

During submaximal voluntary contractions, the elderly are less likely to fatigue than young adults. In a comparison between old men and young men (71.3±3 years), (21.5±4.4 years), performing contraction of the elbow flexors with a 20% MVC until to failure, older men performed the contraction longer than younger men and their fatigue development rate was more gradual. In contrast, in maximal voluntary contraction of dorsiflexor muscles, old men (77.2±1.4 years) are more fatigable than the young men (30.5±2.5 years) (Baudry et al. 2007). In spite of these results, other research has found an equal degree of fatigue between elderly and young adults during intermittent submaximal voluntary contractions (Enoka and Duchateau 2008). In addition, in submaximal contraction at 20 to 25% MVC, women performed a hold up contraction of the elbow flexors for a longer duration than men, but in maximal contractions men were more successful than women (Enoka and Duchateau 2008). In addition with a target of 50% MVC contraction for the elbow flexors for women and men with matched strength, women were able to perform contractions longer than men. This gender differentiation in submaximal uneven contractions might be due to different type of muscle mass recruitment (Enoka and Duchateau 2008). Men have stronger muscles and bigger body mass than women. Therefore, to create similar force and perform the same activity, men have to activate a larger muscle mass than women (de Ruiter et al. 2007). Therefore, women activate a smaller degree of glycolytic metabolism to supply ATP during fatiguing contraction in comparison to men, and their intramuscular pressures and occlusion of blood flow is likely to be greater. As a result, women are less fatigable in submaximal contraction than men (Enoka and Duchateau 2008).

During a muscle contraction a larger muscle mass creates larger absolute force, conversely it might increase intramuscular pressure and decrease blood flow to the active muscles and affect the amount of energy available to the working muscle generating the force (Bigland-Ritchie and Woods 1984, Thompson et al. 2007). In comparing between men and women, it has been shown that women normally have less muscle mass to generate the total muscle force and their endurance time is greater than men (Thompson et al. 2007). In a study by the correlation between increased muscle tension and blood flow in forearm muscles was compared between men and women. Both genders accomplished isometric handgrip training with either 20% or 50% MVC to task failure. Based on the result, women generated less maximum voluntary force and longer overall performance time for 20% MVC than men. However, there were not any differences between the genders in their force production and time for 50% MVC. Therefore, in muscular fatigue activities, muscle mass might be a factor in fatigue progression rather than gender (Thompson et al. 2007).

Some studies have examined the influence of the muscular fatigue on the neuromuscular control between proprioceptive afferents to the CNS and efferent responses to the muscles to maintain dynamic muscular stability. Adverse changes in the proprioception and the sensations of joint movement and positioning have been reported to result from muscular fatigue (Letafatkar et al. 2009). The next section of the review discusses the effect of fatigue on joint proprioception.

Absolute, Constant, and Variable Errors

The standard way to determine awareness of joint position is to ask participants to either reproduce or match a previously presented joint angle. In determination of joint position sense three variables, absolute error (AE), constant error (CE) and variable error (VE) are frequently calculated (Juul-Kristensen et al. 2007).

The AE is the uncertainty in a measurement and has been described as difference in degrees between the presented and reproduced target angle. The AE is the overall difference between trials and direction of error is not considered. The CE is a measurement between the presented and reproduced angle, and it is a source of error that causes measurements to deviate consistently from their true value. Because there is no exact zero for their start point, this error can be either higher or lower than its true value. Constant errors are difficult to identify because they remain unchanged regardless of how many times an experiment is repeated. The result of this error might be negative or positive, which shows the direction of the error. Therefore, to report CE value without considering the direction uses are the terminology absolute constant error. The VE is defined as a standard deviation of a set of trials. It is a measurement of the variation of responses produced by a participant who is struggling to have accurate results and each response has a measurable dimension.

Effect of Muscle Fatigue on Accuracy of Limb Proprioception

Some of the reliability studies of proprioception concentrated on measuring JPS. Every joint has a specific number of muscle spindles and mechanoreceptors that physiologically and anatomically are different than other joints (Juul-Kristensen et al. 2007). In this part of literature review the effect of muscle fatigue on the accuracy of joint proprioception in elbow, forearm, and shoulder, neck, and knee joints is explored.

Elbow and Forearm Joint Position Sense

Neck muscle proprioception is known to play an significant role in body balance, appropriate body reference, and movement organization (Strimpakos et al. 2006). Neck muscles have numerous receptors that are important for vestibular, visual, and postural control. Inaccuracy of cervical joint proprioception may include deficits in range of motion, a decrease proper muscular performance, and impairments in controlling the body posture. Head position is one of the main factors in organization of the central sensory information for upper limb joint position (Paulus and Brumagne 2008). It is hypothesized that the CNS uses the position of the neck and head to compute the position of the upper limb segments. Therefore, with alteration in their position, contribution of internal and external sensory inputs might misdirect the movement. In addition, it has been hypothesised that the accuracy of the upper limb movements decline with the change in gaze direction. Further, proprioceptive information might be disrupted with severe changes in the neck and head near the end of joint range of motion and it rise the inaccuracy of the elbow JPS (Knox and Hodges 2005).

Knox and Hodges (2005) in a study of healthy individuals investigated the accuracy of elbow JPS by altering the head and neck in four positions: neutral, flexion, rotation and combined flexion/rotation. They measured error as the difference in degrees between the offered and duplicated target elbow angle. They reported that the AE and VE were larger in those performances that target elbow angle was duplicated with the head and neck in flexion, rotation, and combined flexion/rotation than when they were in neutral anatomical position. These findings are relevant to the theory that the position of the head and neck is uses by the CNS to estimate the position of the upper limb segments (Knox and Hodges 2005). However, this study did not consider the effect of possible biomechanical changes in muscle activity that are attached to the cervical spine or alteration in trunk or shoulder posture that is associated with any head and neck changes (Knox et al. 2006). In another study, Knox et al. (2006) in order to eliminate any effects of biomechanical changes in accuracy of the upper limb proprioception investigated the elbow joint position sense with unnatural alteration in neck and head positions. The awareness of head position was stimulated by galvanic vestibular stimulation (GVS). GVS involves the application of low intensity electrical current between the mastoid processes, and this leads to altered firing of vestibular afferents. GVS induced a sensation of head tilt towards the side on the performance of elbow JPS task. Result showed that, in mid-way of elbow movement, an illusory change in head position with GVS stimulation produced changes in the error of elbow proprioception. These findings verify that in both real and illusory changes, the head is a reference for upper limb movement Knox et al. (2006).

In a study of 11 healthy participants, the effect of neck muscle fatigue on accuracy of elbow joint reposition was investigated. The fatigue protocol required participants to maintain a 100% isometric maximum voluntary contraction (MVC) cervical extension resistance against a strap placed around the forehead, for a duration of 30 seconds. This study reported no significant changes in CE, VE, and AE between pre and post- fatigue trials in elbow joint angle repositioning (Barker 2011).

In NP participants, the effects of two types of activities (conventional proprioceptive and cranio-cervical flexion training) on cervical JPE were investigated. Both types of training improved the JPE as well as decreasing neck pain, but the proprioceptive exercise was more effective in reducing neck pain. These pain relief exercises lead to an improved ability to correct the JPE following a period of 6-weeks of training along with the development of improved ability to contract the superficial and deep cervical flexor muscles, known to be important for protecting the cervical segments and lordosis (Jull et al. 2007).

Another study investigated the accuracy of elbow JPS in both healthy and subclinical neck pain (SCNP) participants (Haavik and Murphy 2011). Subclinical neck pain was defined as ongoing low level neck pain and/or stiffness for which the participants had not yet sought treatment. The study also investigated the accuracy of an elbow joint repositioning task in a SCNP group after manipulating dysfunctional cervical segments as compared to no intervention (Haavik and Murphy 2011). The results demonstrated that the accuracy of JPS in SCNP participants was lower when compared to healthy individuals. Moreover, upper limb joint proprioception was improved by chiropractic manipulation of the cervical segments in subjects with SCNP. This improvement in elbow JPS in the SCNP subjects might be due to addressing the spinal dysfunction that is treated by cervical manipulation. These results support the theory that altered afferent input due to neck joint dysfunction can impair upper limb JPS which can then be improved following treatment of the neck joint dysfunction (Haavik and Murphy 2011).

Individuals with whiplash-associated disorders (WAD) have been reported to have a lack of upper limb movement. (Knox et al. 2006), in two groups of healthy participants and people with WAD, investigated the influence of head position alteration on elbow JPE. Head position was included of positioning the head in 30° and midline. In addition, for WAD group to determine the effect of pain in final results, pain was monitored during the test. As this study, in neutral head position the AE between two groups was not different. However, in WAD participants even with small movements in head and neck, the elbow JPE was affected more than in healthy individuals (Knox et al. 2006).

Near the lateral or medial epicondyle of elbow joint, there is a set of sensory nerve endings which are responsible for joint proprioception and signalling angle changes during movement (Juul-Kristensen et al. 2007). It is known that concentric exercise increases muscle damage, specifically muscle spindles that are responsible for joint repositioning after exercise (Allen and Proske 2006). The effect of elbow flexor fatigue in forearm repositioning was investigated by Allen and Proske (2006). For this study, the elbow flexors were exercised with 30% of MVC with the mean of 330 concentric contractions. As a result, the fatigued arm had to work harder against the force of gravity to maintain a given arm position after consecutive exercises and it led to forearm position-matching errors (Allen and Proske 2006).

In a study the test-retest reliability of the elbow joint proprioception, threshold to detection of a passive movement (TDPM) was investigated in healthy individuals with a 30 minute interval between test and retest trials. JPS was assessed by actively repositioning the forearm in relation to the upper arm. TDPM was measured by the ability of subjects to very quickly recognize a passive movement. The detection between test and retest demonstrated that both JPS and TDPM measurements can be highly recommended as a test device for AE. However, they can only be recommended with a very small degree for CE or VE (Juul-Kristensen et al. 2007).

Brockett et al. (1997) investigated the influences of concentric and eccentric exercises of elbow flexor muscles on forearm position sense. At the same time, the elbow flexors of one arm performed concentric and other arm eccentric contraction by 20% MVC for a minimum of 120 contractions. The results state that following exercise there were some changes in forearm position sense. Eccentric exercise damages muscle fibres, and also affects muscle spindles, tendon organs, and muscle receptors such as muscle spindles. Therefore, because of muscle fibre damage after performing eccentric exercises, the ability of muscle spindles to signal muscle length for accurate JPS was impaired (Brockett et al. 1997).

Sharpe and Miles (1993) in a study of 13 healthy right-handed participants who were involved in two different experiments, investigated elbow position sense after fatiguing contractions. The left arm of the blindfolded participants was randomly and passively moved to the target angle (between 60° and 135°) and this angle had to be matched with their right arm. The difference between perceived angle with right arm and target angle on the left arm was recorded. Afterward, they performed the fatigue protocol which was five 20 second MVCs of right elbow flexion. In experiment one, immediately after the fatigue task; the elbow position-matching was performed again using exactly the same protocol as pre-fatigue. In experiment two, at a minimum of 1 week later, the right arm was fatigued and the left arm was placed in the target angle and participants were asked to match the position of the fatigued (right) arm with the non-fatigued (left) arm. The results demonstrated that following the fatigue protocol, the MVC of the right elbow flexors was decreased up to 30-60%. In addition, there were some increases in variable errors between pre and post-fatigue trials between participants, however in both experiments the effect of fatigue was not significant (Sharpe and Miles 1993).

In another study, limb proprioception with four different experiments on 15 blindfolded participants was investigated. In experiment one, the reference arm being supported versus unsupported was tested. In the reference arm supported trials, the reference arm was moved passively by the experimenter to 45° flexion and placed on a support, but in reference arm unsupported trials, the participants were trained to move their reference arm from the horizontal to 45° flexion. Then, in both trials they were asked to match this angle by their indicator arm. In experiment two, muscle conditioning in the supported arm was assessed. The conditioning consisted of triceps brachii contraction in the direction of arm extension, and biceps contraction in the flexion position. In experiment three, the position matching error was compared between the unsupported reference arm with and without the reference arm weighted with a 2 kg weight, which was affixed to the paddle of the reference arm. In experiment four, the matching position of the unsupported reference arm after muscle conditioning was compared to the reference arm weighted with a 2 kg weight. As a total conclusion about the results of these experiments, if subjects placed and held their forearm in a target position themselves unsupported, their results were more accurate. This is because in unsupported arm trials, the CNS is more active to hold the arm against the force of gravity than in supported arm trials. Furthermore, increasing the weight on the reference arm, decreases available spindles and as a result the position errors in the direction of extension will be increased. Also, conditioning in the supported and unsupported arm cannot increase the accuracy of position matching. However, it has been shown that after flexion conditioning, the indicator arm matched the joint angle toward more extended position (Winter et al. 2005).

In the absence of visual feedback, the muscle spindle's primary endings are the main source of information for limb proprioception and movement. In order to maintain an unsupported arm position, larger spindle gain is activated by the fusimotor system, and because muscle spindles are stretch receptors, when the muscle is lengthened they can provide a position signal. Therefore, the CNS uses the link between muscle length and sustained spindle firing rate in limb position matching (Winter et al. 2005). The ability of forearm position matching before and after eccentric exercise was tested using a three-pronged approach. Eccentric exercise was used to produce a constant decrease in muscle force. Both forearms of blindfolded participants were strapped. In the first experiment, their reference arm was passively moved to the target angles (30° or 60°) in the horizontal plane. Then with their matching arm, participants were asked to match the reference position. The experiments found that the matching angles were more toward an extended position. In the second experiment, in order to reduce any clues from gravitational torques, both arms were counterweighted. That means that each hinge was attached by a rigid 1 kg steel shaft directed backward. The result showed that the subjects were less sure of the placement of their arm and the directions of matching errors were more toward the flexion direction. In the third experiment, to minimize the effects of gravitational clues, the forearm position matching was tested in a horizontal frictionless surface plane. The forearms and upper arms were supported by a cradle at the level of elbow joint. The outcomes between matching trials showed that the errors with the wider range were more towards extension. After pre-fatigue trials, the fatigue protocol was performed with 30% of MVC eccentric flexion and extension contractions. Position matching was then re measured 24 hours post exercise. The eccentric exercises led to fall in MVC and the elbow flexor muscles were damaged by these exercises. The reduced voluntary torque after exercise altered the connection between effort and force and that consequently increases matching errors. Therefore, for all three kinds of experiments (unsupported arm, counterweighted, and horizontal matching), the mean errors were smaller before performing the exercises in comparison to immediate post-fatigue measures (Walsh et al. 2006).

In eccentric exercises, the active muscles are lengthened and following performing a set of contractions, Golgi tendon organs have an unchanged response to both passive and active change in muscle tensions (Weerakkody et al. 2003, Gregory et al. 2004). The intrafusal and extrafusal of spindles fibres and Golgi tendon organs are damaged, and limb proprioception is disturbed after intensive eccentric contractions. For this reason after a cycle of eccentric exercises, pain and difficulty in performing skilled movement is experienced. The effect of eccentric contraction on limb proprioception has been investigated in various studies. Decrease in force matching with elbow flexors after a sequence of eccentric contractions of the elbow has been reported, and eccentric contractions of the reference forearm increase the arm position error toward the flexed position than the unexercised reference arm (Weerakkody et al. 2003, Gregory et al. 2004).

Position sense at the elbow arises from peripheral signals generated from muscle spindles and cutaneous receptors. Eccentric exercise damages the intrafusal fibers of muscle spindles and affects the ability of the muscle spindles to accurately signal joint position (Walsh et al. 2006).

In a study with a total of 25 healthy participants, elbow flexor matching force was evaluated following eccentric exercises. This study consisted of three experimental procedures. In the first experiment, matching tension after eccentric exercise was evaluated. The forearm was secured to the vertical boards (90°) of the apparatus. The reference arm was maintained at five different target torque levels. The participants were able to see the MVCs of their designated reference arms, but they tried to match it with their indicator arm without any visual feedback from that arm. For each torque, ten trials were accomplished with both left and right arms that in turn were acting as reference. In the exercise part, five sets of ten eccentric elbow flexor contractions were performed against a biodex isokinetic dynamometer. Then, the matching tension at the forearms was repeated again. In the second experiment, EMG activity was recorded after eccentric exercises. Only one arm was used for this experiment. The subject's forearm was secured and with the help of visual feedback, they were asked to develop levels of target torques. EMG data was collected for the biceps brachii. In the exercise part, the subjects completed five sets of ten eccentric and concentric elbow flexion contractions. Then, instantaneously following the exercise and at 2, 24, 48, and 96 hours later, measurements of EMG were conducted with various torque levels. For the third experiment, matching torques was measured at different elbow angles. The indicator arm was locked in the vertical (90°) position, while the reference arm could be locked in place at various degrees of flexion. Then participants performed an MVC with their reference arm with visual feedback. Once they attained the reference torque for 2 s, this torque was matched with their indicator arm that was flexed at 90° (without visual feedback). Results demonstrated that after eccentric exercise the effort–torques were disturbed, because of damage and fatigue in muscle fibres. The maximum voluntary torque was lower after eccentric exercise. After fatiguing the indicator arm, the torque-matching was less than the reference level and once the reference arm was fatigued, matching errors shifted in the reverse direction. The authors suggested that the inability to match torque following fatigue could be due to a change in central moto-neuronal excitability, a change in the muscle length–tension relationship, or motor unit synchronisation (Weerakkody et al. 2003).

The effect of agonist and antagonist arm fatigue in alteration of JPS was investigated by Jaric et al. (1999). The dominant arm of the subjects was in 90° abduction and their forearm in a frictionless manipulandum in a neutral position. At the angles of 75° and 115° of elbow flexion, two rigid arrows were fixed to the end of the manipulandum. Participants performed 24 of the fastest possible movements (12 flexion and 12 extensions) from one target to another. The elbow joint angles were measured using a goniometer for each trial. In the fatigue protocol, they held 60% of their MVC against a strain-gauge dynamometer until failure (defined as a reduction in force below 30% of MVC). Immediately after muscle contractions, participants performed their post-fatigue trials. They found that elbow extensor musculature fatigue did not affect the elbow flexion movements, but it altered the final position of elbow extension movements. Changes in peripheral or central mechanisms of muscle performance during the fatigue can disturb the final joint position sense. Therefore, fatiguing the agonist elbow muscles reduced the ability of muscle shortening to apply force in elbow extension. Whereas, fatiguing the antagonist elbow muscle is involved with various reflex and central mechanisms operating around the stretched muscle, which help the limbs assess the final movement position (Jaric et al. 1999).

The effect of arm musculature fatigue on limb proprioception and movement was examined in a study by Allen and Proske (2006). Both arms of the blindfolded participants were fastened to an apparatus, while their upper arm was at 45 degree to the horizontal plane. In the position-matching test, the reference forearm was moved passively to one of the three target angles (15°, 30° or 45°) and was held unsupported; then these target angles were matched with the indicator arm. The position errors were the difference in angle between the target and perceived forearm angles. At the next step the reference arm was exercised by lifting a weight (30% of MVC) in ten repetitions and performing three MVCs on each arm at the end of exercise. Then, immediately and 1 hour after fatiguing exercises, five repetitions of position-matching tasks were performed using exactly the same protocol as pre-fatigue trials. Based on the results, in pre-exercised trials an accuracy of 2°–3° was achieved. However, after the fatiguing procedure, participants had a significant increase in matching error of 1.7° in the direction of extension when the reference arm was fatigued, and 1.9° in the direction of flexion when the indicator arm was fatigued. Fatigued muscles produce less force; therefore, more effort was required to maintain the exercised arm against the force of gravity. Consequently, the fatigued arm by shifting to the vertical position, matched the effort to hold the un-fatigued arm in target position, thus increasing the degree of matching error for the actual joint position(Allen and Proske 2006).

The effect of paralysis on wrist position-matching was measured in a study by (Gandevia et al. 2006). The right forearm was strapped to the table and the hand held in a manipulandum that let the wrist move in the direction of the flexion and extension plane and the fingers were held in full extension. The right forearm, hand and apparatus were covered, so participants were unable to see them. Surface electrodes were attached to the flexor carpi radialis and extensor carpi radialis to record EMG activity. The right wrist was passively moved into flexion or extension and then fixed at one of six positions (-30, -20, -10, 0, +10 and +20 degrees). Then, the subjects were asked to move the pointer with the left wrist to match the perceived position with the right wrist. Each position was matched three times. For the first set, the subject had visual feedback and for the second set the subject was blindfolded. In the final set, wrist and hand muscles were completely paralysed and almost all their sensations were stopped. To generate a phantom hand and eliminate all voluntary movements of their wrist and hand, a wide cuff was positioned on the right arm that could be blow up in less than a second. Then, a large amount of lignocaine was injected under the cuff into the muscle to ensure that all sensation was lost below the cuff. Again, the matching trials were repeated in randomised angles between (-20, 0 and +20 degree). The results indicate that there is a linear relationship between target and perceived position before paralysing the hand and wrist. However, 20 degrees of error toward flexion and extension in the perceived position was reported after the paralysed performances. It might be because of block below the cuff, the fusimotor axons and small-diameter afferents become inactive, and it had negative effect in wrist and hand movement, which due to the additional effort required to match the position, the perception of the hand moved back to the neutral position (Gandevia et al. 2006).

Cervical Joint Position Sense

Muscle weakness appears very early in the beginning of neck complaints and even after recovery from NP it does not automatically disappear (Medical 2014) (Haavik and Murphy 2011). It is known that symptomatic patients have some deficiencies in their neck muscles and somatosensory function. Neck muscles have numerous sensory receptors and particularly deep segments of the sub-occipital muscles have the maximum cervical receptor density that are responsible for central and reflex connections to the vestibular, visual, and postural control systems (Jull et al. 2007). Individuals with NP have been reported to have less accurate position sense of their head and upper limbs. Neck pain alters upper limb proprioception, decreases cervical range of motion, alters postural activity of neck muscles, and can lead to balance instabilities, and altered eye movement control (Jull et al. 2007, Paulus and Brumagne 2008). It was assumed that pain and injury of the neck impaired the CNS signals (Paulus and Brumagne 2008). Patients with neck whiplash injuries are unable to copy a particular target head position and even maintaining an upright head position is hard for them (Strimpakos et al. 2006).

Cervical interventions in NP patients, especially those that focus on reflex connections and performance of sub-occipital muscles can improve the cervical JPS performance and decrease NP (Jull et al. 2007). In a study changes of conventional proprioceptive and craniocervical flexion exercise (particularly the deep cervical flexor muscles) on cervical JPE were investigated in chronic NP patients. All participants exercised for 10–20 min per day, over 6-weeks. For the cervical proprioception acuity, participants performed right and left cervical rotation and extension up to the end of their range of motion and then returned to the starting position as precisely as possible. The difference between their initial position and repositioning following six weeks of exercise was calculated. Results showed that in NP patients both exercises lead to improved JPE. Also, proprioceptive training had a greater effect in JPE reduction in individuals who completed this type of exercises. Cervical afferent inputs or direct training of relocation sense improve with proprioceptive exercises. Therefore, it was concluded that for NP patients the proprioceptive exercise had more advantages and provided more benefits than the craniocervical flexion exercise (Jull et al. 2007).

Shoulder Joint Position Sense

Joint proprioception has an important role in limb performance. Afferent signals transfer to the CNS from mechanoreceptors that are located in joints and soft tissues. Available mechanoreceptors in the shoulder are located in the joint capsule, extra capsular ligaments, tendons, rotator cuff muscles and free nerve endings in the glenoid labrum. Proprioceptive nerve endings that are located in the glenohumeral joint capsular ligaments and free nerve endings that are found in the glenoid labrum are responsible for signalling, joint proprioception, and muscle tension (Carpenter et al. 1998, Lee et al. 2003).

Active and passive shoulder joint proprioception can be altered by shoulder joint dysfunction and instability. Shoulder instability significantly increases with muscle fatigue. Therefore, the high range of motor performance relying on accurate shoulder joint position, perception may be decreased by a decrease in sensitivity of capsular receptors. However, it is possible that exercise, especially endurance training, improves joint proprioception sensitivity (Carpenter et al. 1998). The influence of muscle fatigue on active and passive shoulder joint repositioning, has shown that there are significant differences between pre and post fatigue results in active relocation in shoulder external rotation (Voight et al. 1996). However, in a study that investigated the effects of active and passive shoulder repositioning; muscle fatigue did not influence shoulder proprioception (Voight et al. 1996, Lee et al. 2003).

Lee et al. (2003) studied the effect of musculature exhaustion on shoulder proprioception during active and passive repositioning. The fatigue protocol consisted of exercise of the same arm by isokinetic shoulder internal and external rotations. All results were the same for internal rotation pre and post fatigue trials for both passive and active performance. Whereas, in shoulder external rotation there was a large difference from pre fatigue to post fatigue trials in active repositioning (Lee et al. 2003). Fatigue decreased the sensitivity of the muscle mechanical receptors in rotator cuff tendons, and when performing isokinetic muscle exercise, shoulder external rotator muscles are more fatigable than internal rotator muscles (Lee et al. 2003). External rotation stimulated the rotator cuff tendons and capsular ligaments to become more contracted and indirectly deceased shoulder proprioceptive sense, while in internal rotation these ligaments and tendons are more relaxed (Carpenter et al. 1998).

Dover and Powers (2003) on two consecutive days investigated the reliability of JPS and force reproduction in shoulder internal external rotation. The result proved that the JPS and force reproduction (FR) measurements were highly reliable, and no discrepancy was detected between the trials of JPS and FR error scores. Also, target forces were much higher for internal rotation than external rotation target positions. In shoulder internal rotation, the external rotators and in external rotation the internal rotators of the shoulder are lengthened and with shoulder they might affect the force production. However, JPS was not affected by the lengthening of the external versus the internal rotators (Dover and Powers 2003).

In healthy individuals the effects of muscular fatigue on shoulder JPS has been investigated. The shoulder was internally or externally rotated without any previous warning and participants recorded their first detected motion of the shoulder as soon as they felt the movement. Then the same arm fatigued with performance of maximal effort until internal rotation peak torque decreased consistently by 50% of MVC. Afterward, the shoulder was immediately retested again for JPS measurement. In post fatigue trials, the mean onset of movement detection for both shoulder internal and external rotation was increased (Dover and Powers 2003).

In a study of healthy participants, the effect of shoulder muscular fatigue on active and passive proprioception of the glenohumeral joint has been investigated. The pace for passive and active repositioning was at 0.5 and 2 deg/s. The shoulder was internally or externally rotated through the axis of the joint, and once participants sensed if it was at the reference angle (45° internal or 75° external rotation), they pushed the stop button. After pre- fatigue measurement, the same arm with the internal and external rotation was exercised at the pace of 180 deg/s (with 50% MVC until this peak torque dropped consistently by 50% three times), then three minutes after fatiguing exercises the same evaluation was performed again. All results were same before and after muscle fatigue except differences in pre and post fatigue trials in active repositioning of shoulder external rotation (Lee et al. 2003). In shoulder external rotation, capsular ligaments and rotator cuff tendons are more contracted. Thus, decline in shoulder proprioception is more significant in external rotation (Carpenter et al. 1998, Lee et al. 2003).

Knee Joint Position Sense

Knee joint proprioception is dependent on both joint and muscle receptors. These receptors can modify each other and both of them provide stability and stiffness to the knee (Hiemstra et al. 2001). However, during fatigue neuromuscular control is unable to dynamically stabilize the knee (Hiemstra et al. 2001) (Carpenter et al. 1998). The knee is the most frequently injured joint, and severe damage to its ligaments is very common (Hiemstra et al. 2001). The effect of exercise and fatigue can increase knee joint laxity and it may contribute to alterations in knee proprioception (Hiemstra et al. 2001).

The role of three levels of quadriceps and hamstring muscle fatigue on knee JPS has been investigated (Gear 2011). The knee was exercised in the direction of flexion and extension with isokinetic exercises until torque output was 50%, 70%, or 90% of the peak hamstring torque. There were significant differences between the before and after 90% and 50% of peak of hamstring torque (Gear 2011). Fatiguing the hamstring muscles decreased sensory output of the muscle spindles in posterior section of the thigh. Therefore, knee JPS was decreased with movements into extension. In addition, the thigh has faster twitch muscle fibers than slow twitch muscle fibers. Its fast twitch fibers are more fatigable and they have more afferent receptors. Therefore, fatigue in quadriceps and hamstrings are hypothesised to affect afferent responses with decline in knee joint proprioception (Gear 2011).

Flexion Relaxation Phenomenon

The FRP is a marker of altered neural control of the trunk and neck and provides a potential "window" into the effects of fatigue on muscles and ligaments of these regions. Trunk flexion from straight position is a combination of working the vertebral column and pelvis. During full forward trunk flexion, the ES muscle contracts to control vertebral movements, while hamstring and hip extensors muscles are responsible for the pelvic actions. In maximum full trunk flexion and some time before it, electrical activity of the ES stops (Gupta 2001). The myoelectric silence in ES was first observed in the lumbar region (Pialasse et al. 2009). Allen (1948) stated it to be a decline of electrical activity in the ES following a certain amount of trunk flexion from the straight position. In 1955, Floyd and Silver introduced this phenomenon as the flexion relaxation phenomenon (FRP). The FRP is a reduced or sudden onset of myoelectric silence that occurs in the ES muscles of the back when moving from upright standing to a full forward flexion of the trunk with a slow and controlled movement (Gupta 2001, Murphy et al. 2010). With the knees in a straight position, the FRP occurred at 40° to 70° of trunk flexion (Floyd and Silver 1955, Othman et al. 2008).

The mechanism of the FRP is defined as transferring the extension moment force from active superficial paraspinal muscles to passive structures of the spine (e.g. viscoelastic structures) or from superficial muscles to deeper muscles (Pialasse et al. 2010, Maroufi et al. 2013). In deep flexion, tension in the stretched passive tissues is enough to protect the trunk opposed to gravity (Pialasse et al. 2010). In another definition, the mechanism of the FRP was described as a load sharing between muscles and various viscoelastic tissues such as ligaments, dorso-lumbar fascia, or discs (Burnett et al. 2009, Hashemirad et al. 2009). In forward trunk flexion, the posterior muscles start to work harder to prevent the trunk from uncontrolled forward bending. At the same time, the passive forces that come from viscoelastic tissues stretch increase to reflexly silence the muscle forces (Burnett et al. 2009). In order to maintain fully forward trunk flexion, afferent feedback from passive structures such as the lumbo-dorsal fascia and other ligaments leads to a reduction or silence of the active muscular tension due to stretch reflex inhibition (Olson et al. 2004).

The FRP and flexion relaxation ratio (FRR) are quantitative measurements that can be used to distinguish neck and back pain patients from asymptomatic individuals (Holleran et al. 1995). It has been well documented as a silence of myoelectric activity in the back extensor muscles in LBP patients (Murphy et al. 2010). Several factors have been shown to influence the FRP in the low back, such as the magnitude of external spine loading, the speed of trunk flexion and extension, body posture, low back muscle fatigue, repetition of movement, and previous lumbar disorder (Pialasse et al. 2010, Ning et al. 2011).

Phases of Flexion Relaxation Phenomenon

The movement of the neck and head in the sagittal plane with four phases of the cervical flexion-extension movement are well documented in the literature. It starts with a straight anatomical position (Phase 1), flexion or bending from upright to full forward cervical flexion where the chin rests on the chest (Phase 2), relaxation or sustaining cervical full flexion (Phase 3) and re-extension or returning to the starting position (Phase 4). Phase 3 is where the FRP takes place (Marshall and Murphy 2006, Yoo et al. 2011, Maroufi et al. 2013).

Several different suggestions have been reported in the literature for the duration of each phase. This duration is varied from 3, 4, and 5 seconds for each phase. Participants were asked to bend the head slowly and gradually, approximately chin to the manubrium, and hold that until informed to back to the neutral position. The rate and duration of each phase was controlled by a sound signal generated from a metronome (Marshall and Murphy 2006, Yoo et al. 2011, Maroufi et al. 2013). The flexion relaxation ratio (FRR) is defined as the ratio of myoelectric activity during re extension of the trunk compared to full flexion (Marshall and Murphy 2006, Murphy et al. 2010, Ning et al. 2011).

Changes in the FRR are seen as an effort by the CNS to maintain spinal stability in the face of ongoing spinal dysfunction (Maroufi et al. 2013). Decreases in the FRR can be due either to increased EMG activity in relaxation phase compared to the re-extension phases or decreased EMG activity in the re-extension phases compared to the relaxation phase(Othman et al. 2008).

The ES muscles become electrically silent in full forward flexion and transfer the extensor moment to passive paraspinal structures or deep muscles. However, due to either increased stretch sensitivity and possibly fear avoidance, this does not happen in Low back pain patients (Marshall and Murphy 2006). The FRR is represented as a numerical ratio and is reported as lack of silence or lower ratio values in a cervical spine disorder population than in control groups (Marshall and Murphy 2006, Ning et al. 2011). Therefore, it is a consistent marker of neuromuscular impairment and function and can be employed to distinguish the healthy individual from NP populations (Murphy et al. 2010, Maroufi et al. 2013).

Reliability and Reproductively of the Flexion Relaxation Ratio

The FRR has been used as a reliable measurement to discriminate between chronic neck and LBP patients from control group. In full forward trunk flexion (relaxation phase), chronic LBP participants demonstrated a higher myoelectric activity than healthy control group (Othman et al. 2008). In addition, in full forward cervical flexion chronic neck pain participants have shown a lack of myoelectric silence compare to healthy individuals (Barker 2011). Previous investigations have found that treatment in low back (Othman et al. 2008) and cervical region (Murphy et al. 2010), such as spinal manipulation and exercise interventions could improve the neuromuscular function in painful area and normalize altered patterns of muscle recruitment to improve the pain and electrical relaxation (Othman et al. 2008, Murphy et al. 2010).

Spinal Stabilization and Theoretical Models

Most daily living physical activities include both full trunk and neck flexion (Hashemirad et al. 2009). Performing prolonged sedentary works with high level of static postures of the spine is one of the main factors in development of neck, shoulder, and back musculoskeletal disorders and pain (Yoo et al. 2011). Therefore, it is critical to understand the biomechanics and clinical implications of cervical and trunk spine movements and changes that are risk factors in the initiation of chronic pain (Hashemirad et al. 2009). Pain can lead to altered motor control and load transferring between tissues (Maroufi et al. 2013). Altered neuromuscular activity in patients, specifically the chronic NP population, is associated with increased excitation in activity of superficial and inhibition of deep neck muscles (Maroufi et al. 2013).

According to biomechanical models of the spine, highly-coordinated activation of active elements (muscles and tendons) interacts with passive elements (vertebral bones, intervertebral discs, ligaments and fascia) and neuromuscular structures to stabilize the spinal (Hashemirad et al. 2009, Yoo et al. 2011). The spinal movements, containing flexion and extension, are controlled by a very complicated neuromuscular system. The neural control unit is responsible for evaluating information about the static and dynamic mechanical status of the spine and for generating appropriate commands in recruitment of active or passive components. Altered neuromuscular function is a marker for impaired FRP (Hashemirad et al. 2009).

Two theoretical models in clarification of this phenomenon are the “Pain Adaptation Model” (Lund et al. 1991) and “Panjabi’s Model of Spinal Stability” (Panjabi 1992, Panjabi 1992). The Pain Adaptation Model states that muscle dysfunction may simply be part of the normal adaptation that the body uses to protect against pain and potential muscle damage (Lund et al. 1991). For example, during full trunk flexion in LBP participants, silence in ES muscles has been seen along with a stretch inhibition reflex. It allows the passive structures to have the required extension moment and inhibit the ES activity (Lund et al. 1991). The “Panjabi’s Model of Spinal Stability” developed in 1992 theorizes the interactions between the active muscle components, passive articular structures and the neuromuscular systems that are required to maintain spinal stability (Panjabi 1992, Panjabi 1992, Descarreaux et al. 2008). In order to have a mechanical spinal stability these three subsystems work together and dysfunction or adaptation in one of them might affect the other two systems. The neural unit discriminates positional and force feedback, which comes from active and passive components, and integrates them to balance destabilizing forces with appropriate levels of muscle activation (Panjabi 1992, Panjabi 1992, Descarreaux et al. 2008, Hashemirad et al. 2009).

The mechanisms underlying the FRP during progressive full trunk and cervical flexion are due to transfer of load-sharing from active elements of the extensor musculature to the passive ligamentous and articular structures (Maroufi et al. 2013). This phenomenon continues until the active extension moment of the posterior spinal muscles is needed. The required tension is provided by sensory feedback from passive viscoelastic structures with increasing mechanical load in the posterior disks, ligaments, and zygapophyseal joints (Descarreaux et al. 2008). Spinal stability is the result of coordinated working of the anterior and posterior active and passive elements that can be influenced by the spinal load, posture and task requirements (Descarreaux et al. 2008).

The onset and offset of myoelectric silence can be affected by the speed of movements, the direction of the trunk and hip movements or the overall laxity of the joints. In addition, it has been reported that body position (standing and supine) influence the FRP. The FRP was more obvious in full trunk flexion in standing position in comparison to the supine position. It highlighted the effect of the gravity that act as a modulator of the FRP for the lumbar spine (Descarreaux et al. 2008). During full forward trunk flexion hip extensor muscles (hamstring and gluteus) and ES interact with each other to provide adequate lower back stabilization (Descarreaux et al. 2008). Additional trunk flexion decreases the anterior rotation of pelvis and increases the tension in the hamstring and thoracolumbar muscles and fascia. More flexion decreases the ratio of active to passive extensor moments to the point of full flexion-relaxation of the ES (Descarreaux et al. 2008). Having knowledge about the shift of tissue loads from active to passive structure in spinal (trunk and neck) flexion means it is important to consider recording, normalization, and interpretation techniques, and biomechanical models of normal trunk and cervical flexion, when assessing and interpreting the FRR.

Body Position and Flexion Relaxation Phenomenon

Prolonged low level of muscles contraction impairs oxygen transportation that might be associated with muscle pain and injury (Callaghan and Dunk 2002). Prolonged sitting in many working environments causes a flexed curvature of the lumbar spine that often results the back pain (Callaghan and Dunk 2002). In addition, in comparison between healthy and neck pain participants during performing the computer tasks, head tilt and neck flexion have been observed in NP population (Caneiro et al. 2010).

In the standing position, when performing full trunk forward flexion, the lumbar ES exhibited a larger decrease in muscle activation than the thoracic ES (Callaghan and Dunk 2002). However, changes in thoraco-lumbar sitting postures such as slump, thoracic upright and lumbo-pelvic sitting significantly change the levels of trunk muscle activities (Caneiro et al. 2010). In addition, various lumbar sitting positions (comfortable, slouched, erect, forward inclined) can alter cervical spine posture (Burnett et al. 2009). The type of lumbo- pelvic posture has a significant effect on investigating the kinematics of the cervical spine and motor activity of the neck muscles (Burnett et al. 2009). In upright sitting posture, the activation of cervico-thoracic muscles (cervical

ES and upper trapezius) is decreased. Therefore, there is a kinematic contribution between lumbo-pelvic sitting and cervical spine posture. It indicated the necessity to standardize posture when measuring the cervical FRR (Caneiro et al. 2010).

The impact of three standardized thoraco-lumbar sitting postures (lumbo-pelvic, thoracic upright and slump) on cervico-thoracic muscle activity and head/neck posture in NP participants were investigated by Caneiro et al. (2010). The participants were in a lumbo-pelvic sitting posture to keep the head/ neck in neutral position and a specific chair was used with some support at the level of lumbar and lower thoracic spine to decrease the activity of the superficial extensor muscles in the cervico-thoracic spine. During the performance of cervical full forward flexion tasks this position eliminates possible variability of onset and offset angles (Caneiro et al. 2010). It has been demonstrated that sitting posture affects both activity of the cervico-thoracic muscles and head and neck posture. The curvatures of the lumbar and thoracic were different and activation of the upper trapezius was not significantly difference in all three sitting postures. In comparison between postures, slumped sitting shows bigger flexion of the head and neck, increased anterior changes of the head and increased muscular activity of cervical ES (Caneiro et al. 2010).

Thoracic upright sitting was associated with larger thoracic extension and smaller head/neck flexion. In this posture reduced cervical ES and increased thoracic ES muscle activity has been reported (Caneiro et al. 2010). In this posture reduced activity of the cervical ES is reported as a lack of flexion moment on the head and increased activity of the superficial anterior neck muscles. Also, there was no flexion moment on the head which increase the necessity of the CEM activation. In the lumbo-pelvic posture the head/neck has neutral position with reduced activity of superficial extensor muscle of the cervico-thoracic region. Prolonged none neutral spinal postures increase muscular activity of the neck and shoulder and over load the cervical spine. Consequently , the chronic NP patients have shown are unable to hold an upright sitting posture for a period of time (Caneiro et al. 2010).

Changes in FRP and FRR in the Lumbar Spine

Many daily routine activities are a combination of both full trunk and cervical flexion. Low back pain (LBP) is a common disorder (Lalanne et al. 2009), which affects 80% of the world's population (Rheumatology 2014). Work related activities such as long lasting static or dynamic trunk motions can increase the risk of LBP in the working population. Repeated trunk flexion and lifting movements are accompanying by muscular fatigue and large flexion moments in passive spinal tissues, which cause intervertebral disc and ligaments injuries and increases the risk of developing low-back complains (Dickey et al. 2003).

Some risk factors for low back pain are spinal instability, excessive spinal load, and ligament/ disc strain. Prolonged static or cyclic strain in the spinal ligaments and discs disturb the effect of neuromuscular activity to stabilize the spine and surrounding structures in the low back region. The result of these dysfunctional activities is limitation in stabilizing control and increase risk of low back injury and pain (Granata et al. 2005). Therefore, during active muscular recruitment such as prolonged lumbar ES activation, LBP patients utilize both spinal and ligamentous components to stabilize the spinal structures and protect them from further injury and pain (Granata et al. 2005).

Impaired neuromuscular activities are hypothesised as one origin of nonspecific low back pain (Marshall and Murphy 2006). Muscle pain disturbs proprioception, stiffness, and motor control activities. Altering stretch sensitivity and altered neural discharge could amplify muscle stiffness and myoelectric activities in order to compensate for the effect of the structural deficit in an effort to maintain spinal stability (Murphy et al. 2010). Trunk flexion is the combined activity of eccentric contraction of the lumbar ES with the hip extensors and hamstrings muscles and passive stretching of posterior ligaments and capsules in the spine (Lalanne et al. 2009). At full trunk flexion, the stretch inhibition reflex relaxes the action of the ES and passive elements provide the necessary extension moment (Marshall and Murphy 2006, Murphy et al. 2010). The best lumbar stability is achieved by co-activation of the active and passive stabilizing components, which can be altered by loading, fatigue and pain (Lalanne et al. 2009). In full forward trunk flexion the EMG activity of lumbar ES muscles declines in healthy individuals; whereas, constant activity of the lumbar ES muscles and increased FRP has been found in LBP patients. The elevated myoelectric activity in LBP patients has been attributed to an adaptation to pain, absence of neuromuscular harmonization between trunk and hip activities, altered motor control strategies, or an immobilizing response in an attempt to increase lumbar stabilization (Watson et al. 1997, Marshall and Murphy 2006, Lalanne et al. 2009, Murphy et al. 2010).

It has been hypothesized that the FRR can be used as a reliable marker to discriminate between back pain patients and control groups (Watson et al. 1997, Murphy et al. 2010). This ratio can be changed in response to therapeutic interventions. Some improvements were reported in relaxation phase (decreases in myoelectric activity) following an exercise intervention for LBP patients (Marshall and Murphy 2006, Murphy et al. 2010). Research on fifteen LBP patients evaluated the effect of long-term changes for the feed-forward activation of the deep abdominals following 12-week exercise intervention and manipulation. Interestingly, they found significant improvement in FR Ratio due to approximately a 67% decline in relaxation EMG and almost no changes in the active components during the active movement phases. They suggests it takes time for the nervous system to regulate the effect of treatment (Marshall and Murphy 2006).

Neblett et al. (2003) investigated the effect of spinal rehabilitation on 54 work-related spinal disorder patients. They found before treatment less than 30% of participants had ability to achieve FRP during full trunk flexion. However, after 7 week rehabilitation programs, 94% of participants had ability to achieve FRP. They reported that the FRP in chronic LBP patients can be improved under rehabilitation treatment (Neblett et al. 2003). In another study by Lalanne et al. (2009) the effects of spinal manipulation on the FRR in individuals with chronic LBP was investigated. 13 CLBP and 14 asymptomatic individuals participated in this study. Both groups accomplished a set of 5 complete trunk flexion-extensions. Then CLBP subjects received a lumbar spinal manipulation, applied to the middle lumbar sections, while the control group was placed in a side-lying control position for 10 seconds. Afterward, both groups completed a second set of 5 full trunk flexion-extensions. The LBP patients demonstrated a significant decrease of EMG activity during full forward trunk flexion compared to the control group. The onset and offset angle of the FRP did not change within groups or conditions. This study concluded that lumbar spine manipulation in the LBP patients can control stabilizing neuromuscular reactions of the lumbar spine to the FRP even for a brief period (Lalanne et al. 2009).

Previous literature on the low back has stated that muscular fatigue impairs the amount of adequate force needed for spinal stability. In addition, it has shown that participants with a greater level of myoelectric fatigue in the low back musculature had a reduced flexion relaxation ratio. In order to stabilize the vertebral units in trunk flexion, load from muscles transfers to passive structures and causes an increase in the duration of myoelectric silence in a flexion relaxation task. Therefore in case of low back disorders this load transferring places previously-injured structures at risk of further injuries because of in adequate muscle force production and improper neuromuscular activation (Lalanne et al. 2009).

Descarreaux et al. (2008) investigated the effect of spine loading and ES muscle fatigue on onset and offset of EMG silence during a full forward trunk flexion-relaxation task. Twenty healthy participants performed 3 blocks of complete trunk flexion under 4 different experimental conditions: no fatigue/no load (1), no fatigue/load (2), fatigue/no load (3), and fatigue/load (4). The non-fatigue conditions were always completed prior to the fatigue conditions. The load consisted of holding 12

Kg barbell with the elbow in 90° flexion and upper arms hanging along the trunk. Lumbar musculature fatigue was induced according to the Sorenson fatigue protocol, which was fixing the lower limbs at the edge of table in laying position and maintaining the horizontal, unsupported position of the trunk as long as possible. This study found a significant effect of muscular fatigue on both onset and offset of myoelectric silence for all muscle. In healthy participants, myoelectric silence increased following the fatigue performances with an earlier onset and later offset of myoelectric silence. Additionally the major effect of load was a resistance of myoelectric activity of the ES in flexion in load conditions. They concluded that ES muscles fatigue modifies the FRP and load has significant effect on spinal stability from active to passive structures on post fatigue trials (Descarreaux et al. 2008).

Descarreaux et al. (2010) in another study explored the effect of hip and back extensor muscle fatigue on FRP parameters. They recruited 27 healthy individuals and same as their previous study the flexion relaxation tasks completed with four experimental settings with the same loads and different fatiguing protocol. In this study they fatigued the hip and back extensor muscle by the constant sub maximal isometric contractions. Participants lay prone with the iliac crest aligned with the edge of the table and trunk was fixed to the table. Then they were asked to push with 60% MVC force on the dynamometer plate with both feet as long as they were able to hold the contraction. Results showed that hip extensor and ES musculature fatigue reduced hip flexion angle and decreased FRP onset angle. It highlights the role of the hip extensor, hamstring and gluteus muscles in lower back stabilization and in lumbo-pelvic rhythm (Descarreaux et al. 2010).

Holleran et al. (1995), in 10 healthy subjects examined the effect of loading on EMG activity during 4 postures of standing, and at 45°, 90°, and full trunk flexion. The EMG activities of the ES were recorded bilaterally during the 0-50% of MVC trials at the level of L3. The results showed that the ES muscles did not activate in full flexion positions for loading as high as 50% of their MVC. In full trunk flexion, alternative muscles might be activated to protect the passive tissues. Full forward trunk flexion is combination of lumbar spine and pelvis activity. The first 50 degree of flexion performs by lumbar spine and the rest of that accomplish by rotation of the pelvis (Holleran et al. 1995).

Dickey et al. (2003) examined the effect of repeated trunk flexion on the mechanics of the flexion–relaxation phenomenon on thirty healthy participants. They completed 100 consecutive trunk flexion cycles and returned to an upright standing position with the pace of 11 seconds per each trunk flexion-extension set. Each set was divided into three phases with the tone of trunk flexion (4.5 s), relaxation (2 s) and re-extension (4.5 s). The loads (10 kg for male and 5 kg for female participants) were held in the hands with a specific defined repetition throughout 100 trunk flexion-extension movements. Result showed that the FRP was increased after performing repeated trunk flexion, which might be a result of some alteration in the neuromuscular control system. Following repeated spinal flexion, the silence of the erector muscles occurs at a greater spinal flexion angle that it might increase the risk injury associated with repeated flexion as there is less active spinal control (Dickey et al. 2003).

Olson et al. (2004) investigated the effect of sustained cyclic lumbar flexion on the lumbar FRP. Twelve healthy individuals participated in this study and performed full forward lumbar flexion with duration of 5s for each phase of flexion, relaxation, and re-extension. In order to normalize the same angle, full trunk flexion was completed when they touched the toes with their fingertips during each cycle. A significant increase of myoelectric silence and enhanced FRP with earlier cessation of EMG during flexion and delayed activation of trunk extensors during extension was reported. These results verify that constant cyclic lumbar flexion reduces lumbar stability and damages the viscoelastic tissues (Olson et al. 2004).

Othman et al. (2008) compared the FRP of back muscles between LBP patients and healthy individuals. Fifteen participants consisting of five healthy women, five LBP women with FRP, and five LBP women without FRP performed full forward trunk flexion that was 90° trunk flexion by placing the hands on the knees. The results showed four parameters were statistically significant. Those parameters were average Root Mean Square (RMS) in full flexion, flexion relaxation ratio (FR Ratio), extension relaxation ratio (ER Ratio), and ratio between average RMS during full forward flexion and standing. It has been concluded that these parameters can be used as an indicator to distinguish the healthy individuals from the LBP patients without FRP (Othman et al. 2008).

"Creep is a continuous, time-dependent deformation observed in viscoelastic structures under a constant load" (Lakes 1998). When the passive structures of lumbar spine are exposed to a constant load over time, it results on creep development in the viscoelastic structures (Solomonow et al. 1999). Due to this creep phenomenon the laxity and tension-relaxation generates and it results in desensitization of the mechanoreceptors in the viscoelastic structures (Solomonow et al. 1999, Williams et al. 2000). Theses increase the risk of more intervertebral movements and possibility of injuries and pain(Hides et al. 2001). What is the appropriate rest time for the posterior viscoelastic tissues of the spine to recover from the creep phenomenon? Usually, a suggested resting period for workers with repeated or sustained spinal flexion is a10-minute rest following each 50 minutes of work (Solomonow et al. 1999). However, in a human vivo study, after 20 minutes of deep lumbar flexion, a 50-minutes rest period was required to reach 70% recovery from the resulting creep (McGill and Brown 1992). Also, it was suggested if the lumbar spine is exposed to a static load, even overnight rest would not be sufficient to recover from the micro-damages and for complete recovery from the neuromuscular disorder at least two days needed (LaBry et al. 2004).

In an investigation, Solomonow et al. (2003) studied whether the creep developed in the lumbar viscoelastic tissues during static lumbar flexion caused alteration in the muscular responses of the FRP. Twenty-four healthy participants accomplished three sets of lumbar flexion-extension prior and following exercise activities that was 10 minutes static lumbar flexion. After lumbar exercises, the ES muscles were more active in flexion, and there was earlier onset of myoelectric silence in FRP. Also, over 50% of the participants had some spasms through the static lumbar flexion. It has been concluded, despite some viscoelastic micro-damage in the lumbar muscles, the CNS attempts to compensate the damage created by generating muscle spasms (Solomonow et al. 2003).

Ning et al. (2011) examined the effect of asymmetry on low back FRR. Twelve healthy participants performed 15 full trunk flexion and extensions cycles in the direction of three asymmetric postures: 0° in sagittal plan and 15° and 30° in the transverse plane. They reported the presence of the FRP in the sagittal symmetric posture (0°) and significant reduction in the FRP in both asymmetric (15° and 30°) conditions. From 0° to 30° the maximum lumbar flexion showed a 10% decrease (Ning et al. 2011). It was reported that lumbar muscles on the same side as the asymmetric posture often did not show the flexion relaxation while muscles on the contralateral side were affected by the asymmetry, decreasing on the trunk flexion angles at which the flexion relaxation occurred (Caneiro et al. 2010).

Hashemirad et al. (2009) in a study of trunk flexion and extensions examined the influence of flexibility of the lumbar spine in EMG activity of the ES. Flexibility was measured by the modified Schober and toe-touch tests. The EMG activities from the lumbar ES were recorded along with the angles of the hip and trunk during all movements of trunk flexion-extension. It was shown that in participants with greater toe-touch scores, the onset of ES relaxation was at bigger angles of trunk, hip, and the lumbar spine with earlier reactivation in extension movements. Participants with higher modified Schober scores demonstrated later ES muscle relaxation and earlier reactivation according to lumbar angle and curvature. These results are in parallel with previous research that general flexibility affects the trunk and hip angle and lumbar spine flexibility affects the lumbar angle and curvature. This confirms that the stabilizing system of more flexible individuals are more dependent on the active components than passive elements (Hashemirad et al. 2009).

Gupta (2001) investigated the myoelectric activity of the ES in trunk flexion and extension movements in 25 healthy participants. All three involved flexion angles (vertebral, hip, and trunk) in trunk bending measured during flexion from an upright anatomical position to full forward trunk flexion and back to the straight position again. This study was performed under three conditions: (1) trunk flexion from upright standing with and without holding the pelvis against the wall, (2) fastening the weights posteriorly around the iliac crest and bending forward, and (3) bending forward while holding the weight with the hands. In the first condition, the pelvis was against the wall to limit the movement of the pelvis in trunk flexion. In the second and third conditions, the influence of the weights employed anteriorly or posteriorly on axis of the hip was explored. The research found that the average maximum flexion was 68.8° for the hip and 57.1° for the vertebrae and without leaning on the wall, the FRP occurred at 57% of the maximum hip flexion and at 84% of the maximum vertebral flexion. By holding the pelvis against the wall there was an earlier onset of electrical activity at 75% of full flexion of the vertebral column and reactivation of ES happened sooner once the extension began. In the two last experiments, by holding the weight anteriorly or posteriorly the myoelectric silence occurred at larger vertebral flexion angles. The authors stated that flexion and extension torques of stretched posterior vertebral ligaments rather than stretch receptors are responsible for the FRP (Gupta 2001).

Previous studies have investigated the incidence of the FRP on static trunk flexion postures during lifting, lateral bending, and sitting (Dickey et al. 2003). In forward trunk flexion from an upright position, the activities of the paraspinal muscles decreases and passive tissues support the trunk against the gravity. In deep trunk flexion, the EMG activity changes from a high level in early flexion to myoelectric silence from mid to the complete forward trunk flexion angles (Olson et al. 2006). Olson et al. (2006) examined the effect of the gravity on both anterior and posterior trunk muscles during forward trunk flexion and extension. Thirteen healthy individuals performed trunk flexion- extension tasks under the two testing conditions: standing (gravity parallel to the body axis) and supine (gravity perpendicular to the body axis). In the standing position, trunk flexion was demonstrated by abdominal muscles activity and myoelectric silence of the lumbar posterior and hamstring muscles. In the supine position, trunk flexion followed posterior musculature activities and myoelectric silence in the abdominal and quadriceps muscles. These findings demonstrated that a 90° change in the lumbar flexion altered the gravity vector leading to a disappearance of the myoelectric silence in paraspinal muscles (Olson et al. 2006).

The FRP and FRR in the Cervical Spine

The cervical FRP has been defined as a myoelectric silence in neck extensor muscles during cervical full forward flexion (Pialasse et al. 2009). Chronic or recurrent neck pain (CRNP) individuals have been shown are unable to fully relax their CEM during the neck full forward flexion (Murphy et al. 2010). The CRNP patients are along with joint instability and dysfunction and altered patterns of muscle recruitment. The FRP can be an indicator for altered neuromuscular performance and a reliable measurement to distinguish the NP patients from the asymptomatic individuals (Murphy et al. 2010). Chiropractic treatment including spinal manipulation and exercise can alter the neuromuscular patterns in a CRNP population. In addition, it can improve the FRR in the lumbar (Marshall and Murphy 2006, Marshall and Murphy 2006, Marshall and Murphy 2008) and cervical (Barker 2011) spine.

Murphy et al. (2010) explored the reliability of the cervical FRR at baseline and after 4 weeks in a study of 14 chronic NP patients and 14 asymptomatic individuals. They suggested that FRR might be a valuable marker of altered neuromuscular performance, because in both groups the FRP was highly reproducible when evaluated at baseline and 4 weeks apart. In addition, the FRR was significantly higher in the asymptomatic group than the NP patients. They concluded that in the cervical spine, the FRR can be used as a reliable measurement to distinguish between NP patients and healthy controls (Murphy et al. 2010). In another study, Murphy et al. (2010) investigated whether a 4-week period of chiropractic treatment improved the ability of chronic non-specific neck pain patients to respond to an 8-week period of exercise intervention. Twenty chronic NP patients participated in this study and they randomly were divided into two groups. Group 1 received chiropractic treatment while group 2 did not receive any care or treatments for a duration of 4 weeks. Then all participants performed a series of exercise activities for a period of 8 weeks. Results demonstrated that with no significant variance between the two groups, all participants had significant decreases in their neck disability index and visual analogue scale. They concluded these two techniques are effective to reduce functional disability and pain in chronic NP population (Murphy et al. 2010).

Barker (2011) by studying 11 chronic or recurrent NP participants explored the effect of 12 weeks of cervical and upper thoracic chiropractic treatments in cervical pain improvement and in cervical FRR. Twelve weeks of spinal manipulation improved the FRR of the CEM between baseline to 12 weeks and 6 weeks to 12 weeks. This proves the theory of improvement in neuromuscular performances after treatment. In comparison between the results of this study and a previous study of 4 week chiropractic care in chronic NP patients (Murphy et al. 2010), it has been concluded that when pain changes to become chronic a longer duration of treatments in required for patients to get relief from the pain and reverse the effects of altered neuromuscular activities from their painful area (Barker 2011). Both studies have shown some level of improvement in the cervical FRR in NP participants subjects from baseline to 4 weeks (Murphy et al. 2010), baseline to 6 weeks, 6 to 12 weeks, and baseline to 12 weeks. These results draw the attention to the fact that 4 to 6 weeks of cervical spine treatment may not be enough for improvement of dysfunction of the neuromuscular patterns in NP population. Therefore, 12 weeks or even more care might be needed to see the proper results of treatment. It provides both clinicians and patients with a possible proper timeframe to know when treatment has a significant effect on FRR (Barker 2011).

Pialasse et al. (2009) in a study of 19 young healthy adults explored the presence of cervical FRP in two different experimental conditions, from a neutral erect seated and 45° forward leaning seated position. The kinematics and EMG activities of the neck region were measured to evaluate onset and offset angle of cervical myoelectric silence. Results demonstrated that for the kinematic parameters there were no significant differences between the two experimental conditions. The FRP was observed bilaterally in 67.4% of the tasks with neutral trunk position, and 79.0% with 45° forward trunk flexion (Pialasse et al. 2009).

Meyer et al. (1993) expressed that when neck flexion is limited to the cervical and upper thoracic regions movement without any thoracolumbar flexion, the cervical paraspinal muscles exhibited a consistent FRR similar to that documented for the low back muscles (Meyer et al. 1993). However, in a study by Murphy et al. (2010) in an asymptomatic population, the FR ratio for the neck was lower (4 – 4.5) than the low back (12–15). The cross sectional area of the cervical extensor musculature is lower than the lumbar extensors muscles. Therefore, with flexion in both the cervical and lumbar regions, the low back recruits a greater number of motor units and creates a bigger EMG signals with a higher ratio of muscular activation than the cervical region (Murphy et al. 2010).

Maroufi et al. (2013) compared the characteristics of cervical FRP in 22 chronic NP patients with 21 healthy individuals. In order to analyze the onset and offset angle of the cervical FRP, the EMG activity of cervical ES and upper trapezius muscles were compared between the two groups. They found the FRP to occur in the cervical ES muscles in 85.7 % of healthy and in 36.3 % of chronic NP patients and no FRP in the upper trapezius. In addition, the onset and offset of FRP parameters started later in flexion and ended sooner in extension. It indicated that this phenomenon was shorter and lower in chronic NP patients than the control group, which confirms the concept that NP patients have some difficulty in relaxing their CEM in full forward flexion. This phenomenon might be the result of increased muscular activity in the full flexion phase or a decreased muscular activity in the re-extension phase. Other results showed that the surface EMG activity of the CES in CNP patients was higher than the control group. This represents an altered pattern of motor control to modify neurological reflexes that enhance the activity of the cervical ES muscles to protect the spine from further injury in neck full forward flexion (Maroufi et al. 2013).

Lee et al. (2011) examined the effects of various backpack loads on the cervical FR ratio in 14 healthy male participants. They analyzed the cervical FRR in three different back loads, unloaded, 10% of body mass (BM), and 20% BM. They found that the FRR is influenced by the amount of load, with heavier backpacks significantly decreasing the FRR. The biomechanical effects of a heavy backpack is a forward shift in the neutral centre of body mass that modifies the position of the head and upper and lower cervical vertebrae. The prolonged uses of heavy back packs hold the head in erect position and decrease the cervical curve, which is commonly seen in neck pain patients. They concluded that heavier backpacks increases the risk of being affected by neck pain (Lee et al. 2011).

The active cervical range of motion (ROM) is often used to discriminate between symptomatic and asymptomatic neck pain individuals. Reduced active cervical movement, which can be seen in most sedentary work, might disturb the functional activity of the neck area and it has been associated with development of cervical discomfort (Yoo et al. 2011). In one study, Yoo et al. (2011) examined the relationship between the active cervical ROM and the FRR in 20 healthy participants of visual display terminal workers. They found that the cervical FRR had a positive correlation with cervical movements. Alteration in cervical ES activation is associated with decrease cervical ROM including flexion and lateral flexion (Yoo et al. 2011).

Burnett et al. (2009) studied the occurrence of the cervical FRP during neck forward flexion in a lumbo-pelvic siting posture. Twenty pain free individuals participated in this study. The lumbo-pelvic siting posture or anterior rotation of the pelvis consisted of sitting on a stool with hip and knees at 90°, feet positioned shoulder width apart, and arms relaxed by their side and viewing a point at eye level. In this posture, the thorax is relaxed, head is upright, and lumbar is in neutral lordosis. They reported that no FRP was seen in upper trapezius or thoracic ES. These findings might be the result of different methodological approach such as standardized sitting posture or speed of neck flexion movements (five seconds duration for each phase) (Burnett et al. 2009). In addition, they reported highest EMG activity during re-extension. This is predictable because the CEM have to work harder in the opposite way to return the head to neutral from a flexed position and work against the force of gravity (Burnett et al. 2009).

Pialasse et al. (2010), by recruiting 18 healthy participants, investigated the effect of load and velocity of neck movements on EMG activities for each phase, and kinematic parameter, and cervical FRP. Two different rhythm conditions slow and fast, were applied to assess the effect of the speed. Flexion, relaxation, and extension were performed for the slow pace with 5, 3, and 5 seconds and in fast pace with 2, 3, and 2 seconds, respectively. In addition, three various loadings were performed, loaded by 700 grams, non-loaded, and counterweight of -300 grams. Results have shown that increased load amplified the FRP onset and offset angles and RMS values in cervical flexion-extension cycle; while, increased speed enhanced RMS values in the extension phase and onset angle in percentages with no effect on angles in degrees. Performing the neck movements with faster rhythm and heavier loads activates more muscles and it increases their stiffness. In addition, reliability of RMS for the kinematics parameters in flexion and relaxation phases was moderate, and for extension phase there was excellent reliability (Pialasse et al. 2010).

Airaksinen et al. (2005) studied neck muscle activity using wireless on-line surface EMG electrodes and evaluated its usability in dynamic exercises. Two subjects, one healthy and one NP patient participated in this study. The electrodes were placed at the level of C4 and C5 of the cervical spine and cervical angle changes were measured with inclinometer. All three phases were performed with open eyes and slow speed. Result showed that the quality of the EMG signal was good for both participants during contraction. The EMG during flexion–relaxation rhythm in the healthy participant was clear and in neck pain patient it was unclear. Generally, the wireless EMG technology appeared to be a valuable method to collect good data in a practical test. The EMG activity was higher and neck muscle flexibility and tension were decreased in neck pain patients compared to the healthy participant (Airaksinen et al. 2005).

Barker (2011) in a study investigated the effect of CEM fatigue on the FRR and on timing of the flexion-extension phases. For the purpose of this study 9 healthy participants with no previous chronic or recurrent neck pain were recruited. The three cervical FRR phases (Flexion, relaxation, and re-extension) were performed by neutral head position in pre and post CEM fatigue conditions. Fatigue was induced by holding the head strap against a wall force transducer for duration of 30s MVC. The cervical flexion angle related to the onset and offset of myoelectrical silence was examined throughout the FRR tasks. CEM fatigue increased duration of the myoelectric silence in flexion and extension performance but it did not have a significant effect on the FRR by itself. These results are in harmony with the Panjabi's theoretical model of spinal stability that predicts that dysfunction in one of the 3 stabilizing systems (active, passive, neural) is compensated by the other two systems. Therefore, maximum fatigue in neck extensor muscle transfers the loads sharing to the passive structure of the neck and the neural control system. Information from active and passive structures is integrated by neural system to recruit appropriate level of muscle activation for spinal stability, which is early onset and delayed offset of muscular silence during neck flexion- extension movements (Barker 2011).

In a study of thirteen healthy individuals, the effect of CEM fatigue on FRR and onset and offset of myoelectric silence in FRR with two shoulder postures (neutral and shrugged) was investigated by Nimbarte et al. (2014). The Sorensen protocol was used to monitor the neck muscle fatigue. The participants were asked to hold their head and neck against of gravity by lying prone on a table while their head was positioned off its surface. Their finding demonstrated that cervical FRP for both pre and post fatigue trials was only observed when shoulders were in neutral position. In addition, in neutral shoulder posture the FRR significantly declined following the fatigue protocol, while it did not change in shrugged shoulder posture. In post fatigue performances the average onset angle significantly reduced and a smaller decrease was observed in the offset angle. It has been concluded that CEM fatigue altered the cervical FRP and a shoulder shrugged posture can modulate the neck cervical extensor demands by more myoelectric activities and absence of the FRP in full forward cervical flexion (Nimbarte et al. 2014).

The cervical FRP was measured on fifteen young male workers, which were healthy or suffered from some mild back or neck pain, before and after performing below-knee assembly workout. This workout consisted of 10 minutes using the same work station at the height of 32 centimeter above the floor. To monitor the neck/back pain a visual analog scale (VAS) was used. The FRR was significantly decreased following the post workout trials. In addition the VAS score was significantly increased for those participants who had mild neck or back pain prior to performing the task. It has been suggested that the below-knee work is a risk factor for musculoskeletal disorders (Shin and Yoo 2014).

Conclusion of the Literature Review

Joint position sense is a reliable measure of proprioception testing. Many authors have used joint position tests for detecting proprioceptive deficits. However, the role of muscular fatigue on proprioception is still not completely clear and there is not enough available information regarding how it is altered or decreased as a result of fatigue. It has been well established that proprioceptive sense is mediated through joint and muscle receptors. Position of the head and neck are very important for upper limb proprioception because they act as a body reference and any alteration in sensory feedback from the neck muscles might affect upper limb proprioception.

Neck extensor musculature fatigue has a negative effect on cervical joint stabilization. Afferent signals from limbs to the CNS and efferent signals from the CNS to the limbs are disrupted by muscle fatigue. It has been reported that cervical CEM fatigue with 100% of MVC with duration of 30 seconds did not have any impact in AE, CE, and VE in elbow joint repositioning in condition of fatigue and none fatigue trials. However, fatigue can disturb the spinal stability and altered the CNS outputs, therefore, the effect of neck muscle fatigue on elbow JPS need to be explored with various levels of fatigue protocols and with larger population and the first study of this thesis address this.

Advances in technology means that people have increased the risk of having abnormal postures for a longer duration. Nowadays, performance of prolonged static contractions during work is a major cause of musculoskeletal disorders in general population, and neck, shoulder and back pain have become the most common complaints in western society. In the back and neck a very complex collection of muscles and ligaments are responsible for controlling the lumbar and neck movements. These muscles are more involved in cervical spine stability, which their abnormal recruitment increases the risk of some disorders. Between back and neck muscles, the lumbar and cervical ES muscles are frequently damaged due to performing activities with abnormal postures.

In back and neck pain patients strength and endurance of the spine muscles are reduced, which is associated with pain during performing dynamic movements. EMG is an appropriate instrument to explore changes in muscle activation. It can be used in cervical and lumbar region to evaluate the FRP and FRR to demonstrate neuromuscular function and differentiate between pain patients and healthy individuals. In full forward back or neck flexion, chronic LBP patients demonstrated a higher myoelectric activity than healthy control and chronic NP patients were unable to silence their CEM compared to healthy individuals. There is some literature for the low back and neck pain populations, which indicates that some chiropractic treatments or exercise interventions can improve pain and normalize the EMG activities.

The myoelectric silence in ES first observed in lumbar region. Some factors might affect the FRP such as spine loading, the speed of trunk flexion and extension, body posture; low back muscle fatigue, and previous lumbar disorder. Healthy individuals with the state of fatigue on their low back musculature are unable to properly stabilize their spine and have altered FRR Therefore in case of low back disorders due to inadequate muscle force and improper neuromuscular activities the previously-injured structures might at risk of further injuries.

After reviewing the available literature for the cervical region, it is evident that the major focus is either comparison on the EMG activities between healthy and neck pain population or investigation of the effect of the effects of treatment in neck pain patients. This is interesting because fatigue has been shown to be a potent moderator of the lumbar FRR. Only one study investigated the effect of CEM fatigue in FRR and onset and offset of myoelectric silence in healthy individuals. There are no studies that investigate the effect of CEM fatigue in neck pain patients on FRR parameters and compare the effects with asymptomatic participants. Both spinal disorders and muscle fatigue have a big role in the deficient stabilization of the spine, therefore CEM fatigue in a neck pain population might have a significant effect on the FRP parameters.

This is a gap that the second thesis study explores.

SECTION 3

MANUSCRIPTS

MANUSCRIPT 1

NECK MUSCLE FATIGUE ALTERS UPPER LIMB PROPRIOCEPTION

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Abstract

Limb proprioception is the awareness by the central nervous system (CNS) of the location of a limb in three-dimensional space (Sherrington 1947, McCloskey 1978) and is essential for movement and postural control. The CNS uses the position of the head and neck when interpreting the position of the upper limb and altered input from neck muscles may affect the sensory inputs to the CNS, and consequently may impair the awareness of upper limb joint position.

The purpose of this study was to determine if fatigue of the CEM using a submaximal fatigue protocol alters the ability to recreate a previously presented elbow angle with the head in a neutral position. Twelve healthy individuals participated. Cervical extensor muscle activity was examined bilaterally using surface electromyography (EMG) and kinematics of the elbow joint was measured. An isometric neck extension task at 70% of maximum until failure was used to elicit fatigue.

Joint Position Error increased following fatigue, demonstrating a significant main effect of time ($F_{2, 22}$=27.02, p≤0.0001) for absolute error. No significant differences were found for variable error ($F_{2, 22}$ =0.65 of time, ns) or constant error ($F_{2, 22}$ =1.37 of time, ns). This study confirms that fatigue of the CEM can reduce the accuracy of elbow joint position matching. This suggests that altered afferent input from the neck subsequent to fatigue may impair upper limb proprioception.

Keywords

Proprioception, Fatigue, Elbow Joint Angle, Joint Position Sense, Cervical Extensor Muscles, Upper Limb, Absolute Error, Constant Error, Variable Error

Introduction

Neck muscles have numerous sensory receptors that are responsible for central and reflex connections to the vestibular, visual, and postural control systems (Bolton 1998). The role of visual and muscle afferent inputs is imperative for limb proprioception, because during limb movement, the brain constantly matches visual and kinaesthetic inputs to predict future limb position (Proske and Gandevia 2009). Joint position sense (JPS) is the awareness of the position of different body segments for both passive and active movements. Head position is one of the main factors in the organization of sensory information for upper limb JPS (Paulus and Brumagne 2008). Knox and Hodges (2005) demonstrated that changes in the position of the head and neck, in the absence of visual cues, affects the processing of incoming sensory inputs and can alter awareness of elbow JPS (Knox and Hodges 2005). They demonstrated that the position of the head and neck are used by the CNS to help determine the spatial position and orientation of the upper limb segments.

JPS awareness is conveyed by specific sensory receptors that are located in muscles, deep tissues, and joints (Grigg 1994, Hiemstra et al. 2001, Dover and Powers 2003, Proske 2005, Gear 2011, Strominger et al. 2012). JPS measures an individual's ability to actively or passively reproduce a previously presented joint angle in either an open or closed chain environment (Carpenter et al. 1998, Dover and Powers 2003). It has been suggested that JPS is significantly reduced by fatiguing activities of the muscles around the joint being tested (Rudroff et al. 2008). Muscle fatigue alters afferent feedback, and may impair consciousness of joint position by changing the amount of effort needed to produce a movement, thus affecting joint proprioception (Bilodeau et al. 2001). The fatigued limb attempts to produce a movement, but fatigue alters the sense of position and the ability to re-create the desired joint position (Allen and Proske 2006).

The effect of eccentric, concentric, and isometric muscular contractions on forearm and elbow JPS has been explored in previous studies. Walsh et al. (2006) tested the ability to match forearm position before and after a repetitive elbow extension movement at 30% of maximum voluntary contraction (MVC). Participants lowered the weight at a controlled pace until the arm was completely extended and completed four to five sets of 10 eccentric contractions. The reference arm was passively moved to the target angle and these angles were reproduced by the fatigued arm. The eccentric exercises led to a decrease in MVC and the reproduced angles were more toward the extended elbow position. Allen and Proske (2006) explored the effect of a fatiguing elbow flexion task on forearm repositioning, also at 30% MVC. They found that the fatigued arm resulted in forearm position-matching errors. Finally, Jaric et al. (1999) investigated the effect of agonist and antagonist muscle fatigue on changes in forearm position. The fatigue protocol consisted of holding an isometric contraction with 60% MVC until the external force fell below 30% MVC. They found that fatigue did not affect elbow flexion movements, but it did alter the final elbow extension position.

From previous studies it is evident that forearm position sense can be altered by fatiguing activities. However, although it is understood that the CNS uses the position of the head and neck in interpretation of upper limb JPS (Paulus and Brumagne 2008), to our knowledge there are no investigations that focus on how fatigue of the neck musculature impacts upper limb proprioception. Previous work has demonstrated that altered input from the neck can affect upper limb proprioception and it is important to understand how fatigue, which may occur in a myriad of ergonomic neck muscle and recreational settings, might impact upper limb proprioception. Past work by Haavik and Murphy (2011) examined the accuracy of elbow JPS comparing participants with subclinical neck pain (SCNP) (defined as low grade neck pain which the participant has not yet sought treatment for), to healthy controls. They demonstrated that the accuracy of JPS in SCNP participants was lower compared to healthy individuals. In another study, Knox and Hodges (2005) tested the precision of elbow JPS after altering head and neck positions. They reported that the absolute and variable elbow joint position errors were higher when the head was in flexion, rotation, and combined flexion/rotation than when it was in a neutral position.

If neck pain and posture can impact upper limb position sense, it is highly likely that neck muscle fatigue might also impact upper limb JPS. The purpose of this study was to determine whether a sub-maximal fatigue protocol targeting the CEM could alter the ability to recreate a previously presented elbow joint angle while the head remains in a neutral position. This study included an isometric sub-maximal fatigue protocol at 70% MVC until failure.

Methods

Participants

Twelve healthy right handed volunteers (six males and six females) aged 19 years and older (mean age, 21.66 ± 3.55 years) participated in this study. Handedness was confirmed by the Edinburgh Handedness Inventory (EHI) self-report questionnaire (Cohen 1961), and participants were without any chronic or recurrent neck, shoulder, or elbow pain for at least 3 months prior to this study, which was confirmed by the Neck Disability Index (NDI) self-report questionnaire (Vernon 2008). This study was approved by the University of Ontario Institute of Technology Research Ethics Board.

Experimental Procedure

Upon arrival to the lab, participants filled out the NDI and EHI questionnaires. Next, they performed a repositioning task of a previously presented elbow angle during non-fatigued and following cervical extensor fatiguing conditions, while the head was controlled in the neutral and upright position.

Instrumentation

Surface electrodes (Meditrace^{TM} 130, Kendall, and Mansfield, MA, USA) were placed bilaterally over the CEM at the level of the C4/C5 spinous process. From superficial to deep, the CEM under the recording electrodes are Upper Trapezius, Splenius Cervicis and Splenius Capitis and the intermediate layer contains Longissimus

Capitis and Cervicis (part of Erector Spinae). The deep CEM include transversospinalis muscles (Semispinalis Cervicis and capitis, Multifidus, Interspinalis, and the Rotatores), which are generally smaller muscles responsible for control and stabilization of the cervical spine (Nolan Jr and Sherk 1988). Access to these deeper muscles via surface recordings would be limited and they are therefore unlikely to significantly contribute to the recorded surface EMG signal. When performing neck flexion, the spinous process of C7 is easily visible and was used as a landmark to palpate the location of C4/C5. Before electrode placement, the areas were prepared by abrading and sterilizing the skin with alcohol. Electrodes were placed 2 cm lateral to the space between the spinous processes of C4 and C5, over the muscle bellies and in line with the muscle fibers (Figure 2). Inter-electrode distance was 2.5 cm. A ground electrode was attached over the skin of the right clavicle. The C4 and C5 were chosen because almost all extensor muscles cross this region.

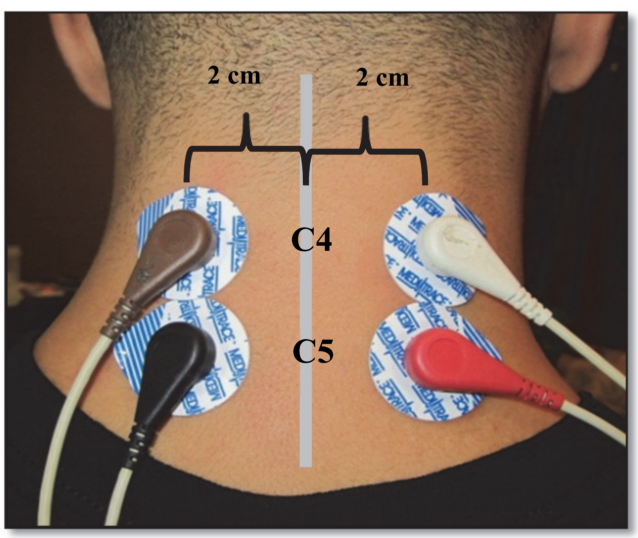


Figure 2: Location of the Surface EMG Electrodes

These electrodes are shown for monitoring changes in EMG spectral parameters during the maximum voluntary contraction (MVC) and 70% of MVC.

Surface EMG signals were differentially amplified and band pass filtered (10 – 500 Hz; CMRR>85 dB @100Hz, input impedance ~1MΩ; Power Lab, AD Instruments, Sydney, Australia). The sampling rate was 1024 Hz and A/D converted using a 16 bit analog–digital converter. Head and elbow joint angles were measured using the 3D Investigator Motion Capture System (Northern Digital Inc., Waterloo, Canada). Three rigid bodies, each consisting of three non-collinear infrared markers were placed on the subjects head, upper arm, and wrist (Figure 3). Twelve anatomical landmarks were digitized on each participant to create anatomical frames of reference for each rigid body. Three-dimensional coordinates for the digitized landmarks were continuously monitored assuming a fixed spatial relationship with the rigid body affixed to the segment. Elbow joint angles were calculated as a change in position of the wrist rigid body relative to the upper arm rigid body during the movements.

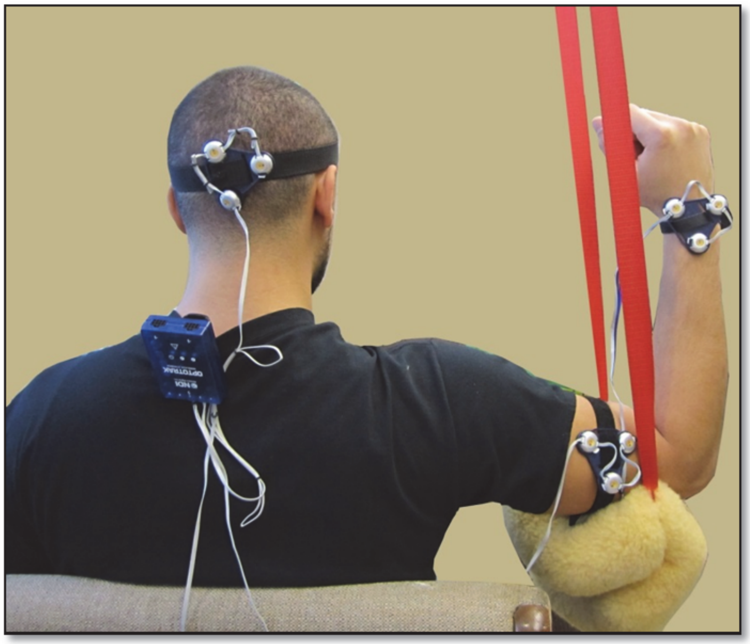


Figure 3: Rigid Body Marker Setup
To create a rigid body, three rigid bodies, consisting of three markers each, were placed over the inion, upper arm, and wrist of the participants. The right elbow was placed at 90° flexion, shoulder at 80° abduction and external rotation and was placed in an adjustable sling.

Fatigue Protocol

Prior to the data collection a pilot study was performed using three healthy participants. The fatigue protocol was holding the CEM contraction with 40% and it took an average 20 minutes for them to fatigue. It was hard to motivate participants to maintain their focus on the contraction over this time period. The same participants were then have been retested 3 to 7 days later using 70% MVC and this result in average of 6 minute to fatigue, which is in line with the time to fatigue reported in the literature.

To produce maximal and submaximal isometric voluntary contractions of the CEM, a wall mounted force transducer (Model: BG 500, Mark-10 Corporation, New York, USA) was attached via a cable, to a Nexgen™ ergonomic strap that was fixed to the participant's head. The cable was attached to the strap, wrapped around a pulley system and attached to the force transducer. The angles between the cable attached to the force transducer and the participant's head was maintained at 90° (Figure 4). Participants sat upright, with both hands on their lap and legs crossed at the ankles to prevent bracing and to eliminate any additional force enhancement. All contractions were performed by resisting cervical extension against the strap without hyperextension of the neck.

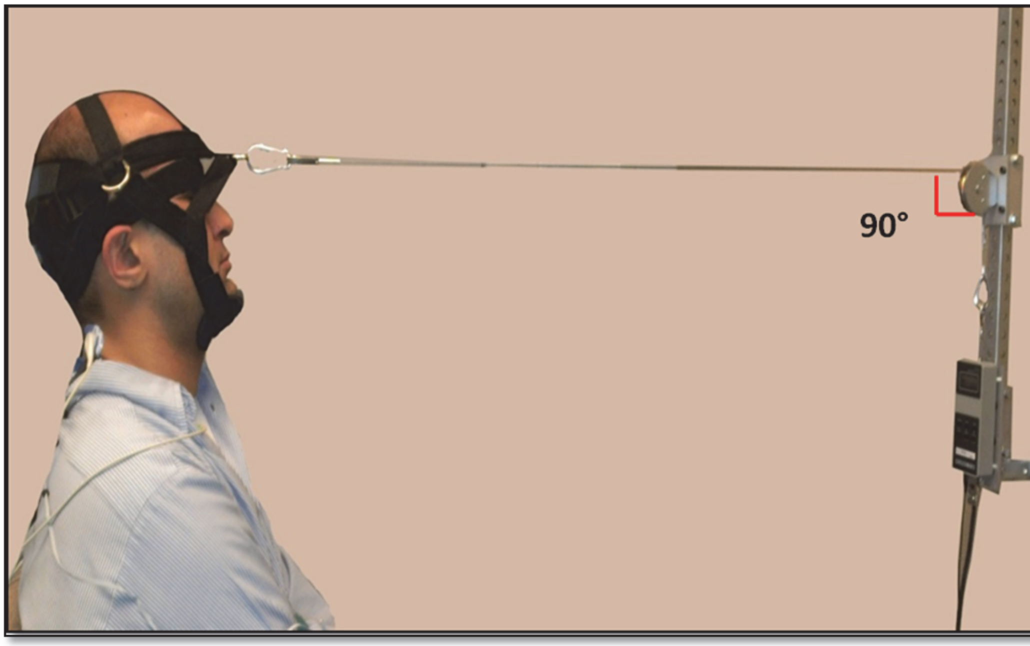


Figure 4: Fatigue Protocol
A wall mounted force transducer was attached to the head of participants to create the maximum and 70% of MVC in the cervical extensor muscles.

To determine MVC, the pulley system was held tight and each participant performed a maximal isometric neck extension exerted against the cable for 3 seconds. The peak force obtained during the MVC trial was determined and after two minutes rest, each participant performed the fatigue protocol, which consisted of an isometric neck extension task at 70% MVC until failure. The force requirement was displayed on a computer monitor in front of the participant and the contraction was held until the participant could no longer maintain the force requirement, until the force fell below the target for a 5-s period, or when noticeable changes in the test position were observed (elbow flexion, lifting the shoulders or spine flexion). EMG activity and force were measured through Lab Chart 7™ (AD Instruments, Sydney, Australia).

Elbow Joint Position Sense

JPS was measured as the participant's ability to recreate a previously presented angle at the elbow. In both fatigued and non-fatigued trials, the participants head was in a neutral position and eyes were closed during the experimental procedure to minimize any external sensory cues. The right arm, with 90° of elbow flexion and the shoulder in 80° abduction and external rotation, was placed in an adjustable sling to minimize upper limb fatigue, muscular activation and postural discomfort (Figure 3).

To eliminate any predictable cues which can come from soft tissue stretch, movement time, and estimating the end of joint range of motion, the JPS task was performed in the mid-range of joint angle movement. The target angle was between 80°-100° and rest angle was between 70°-80° or 100°-110° of elbow flexion. The target and rest angles were randomly selected by the experimenter. The experimenter passively (velocity between 5°-25° per second), moved the participants' forearm to the target elbow joint angle (80°-100°), held for 3 seconds, then passively moved to the rest angle (between 70°-80° or 100°-110°) and again held for 3 seconds. Finally, participants were asked to actively reproduce the previously presented target angle. The reproduced angle was reading when participants notified the experimenter of their predicted target angle and hold it on that position for 3 seconds.

Before starting the JPS protocol, participants were trained using their left arm until they were comfortable with the movement and consistently able to reproduce the previously presented angle. After familiarization, and prior to the fatigue protocol, the JPS protocol was performed, consisting of two sets of three trials each. Four minutes rest was given between each set. The second pre-fatigue set was performed to allow us to measure any potential learning effects that may occur. After the two pre-fatigue sets, participants performed the fatigue protocol. Immediately following the fatigue protocol, participants performed one set of three post-fatigue JPS trials. Figure 5 provides an outline of the procedures.

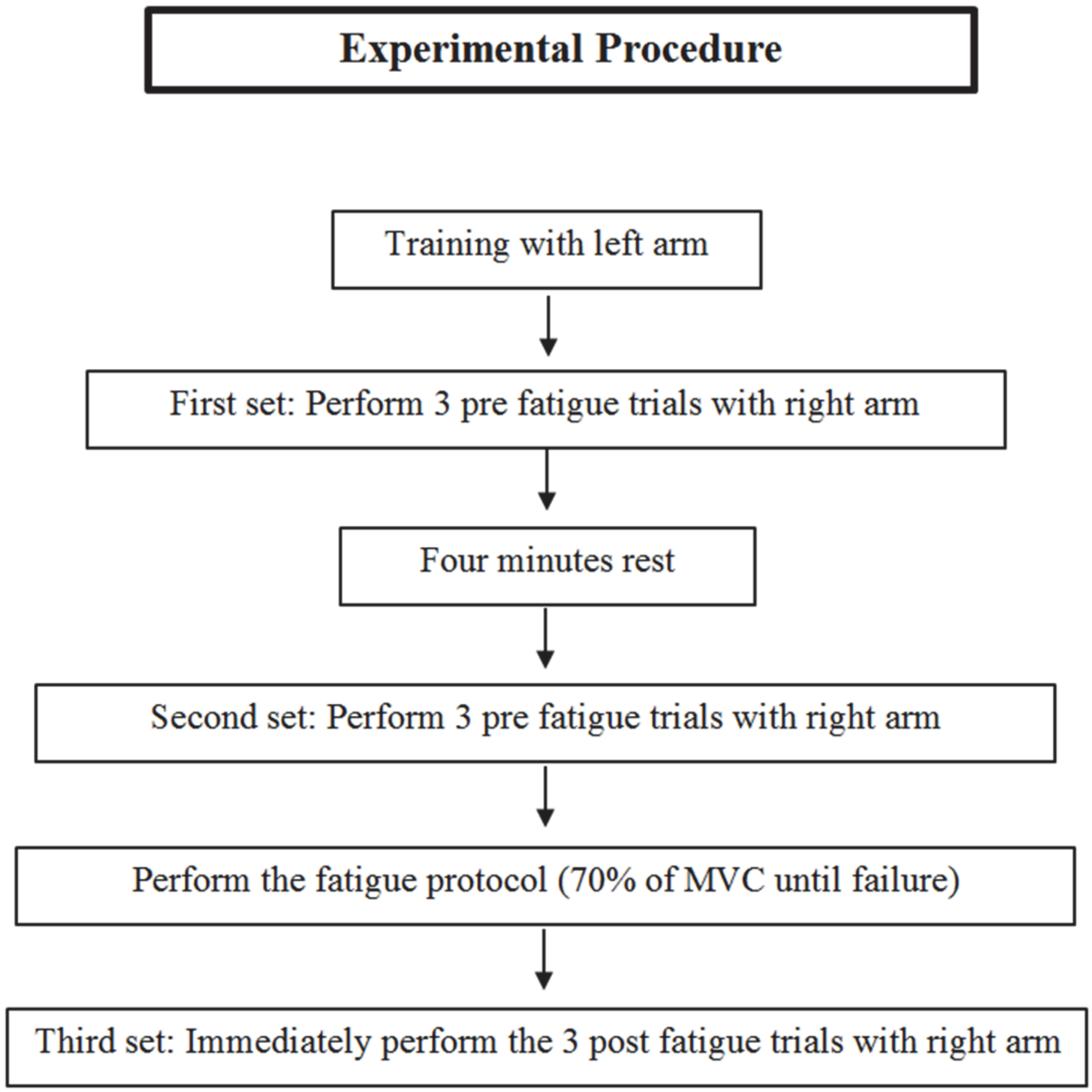


Figure 5: Experimental Procedure

Data Analysis

The kinematics of elbow joint position was processed using NDI First Principles™ motion capture software. The upper arm was placed in a sling so that the shoulder was fully supported and there were no indirect cues about elbow joint position from biarticular muscles; thus only the elbow flexion-extension angle was calculated, which was aligned with the frontal plane and the sagittal axis. Each rigid body had a local axis coordinate system and the rotational data of each rigid body were averaged for each three seconds of target, rest, and reproduced phases to calculate the elbow angles.

Absolute, Variable, and Constant Errors

The accuracy of the angle reproduction was measured using three parameters for each condition, as done by Knox and Hodges (2005). These measures consisted of absolute, variable, and constant errors. Absolute error was defined as the overall deviation between a presented angle and target angle without considering the direction of error. Constant error was defined as the deviation between the presented and reproduced angle, with consideration of the direction of error. Variable error was defined as a measure of the consistency between trials and is the standard deviation of the mean constant error. The average of the three trials in each set was used to calculate absolute, constant and variable error.

Absolute, Variable, and Constant errors were calculated using equations 1, 2, and 3 (Abramowitz and Stegun 2012).

Absolute Error: $\sum \left| \frac{[X - X_0]}{N} \right|$ (1)

Variable Error: $\sqrt{\frac{\sum (X_0 - M)^2}{N}}$ (2)

Constant Error: $\sum \frac{[X - X_0]}{N}$ (3)

Where, X represents raw score, X_0 is criterion score desired, N is number of trials, and M represents mean of the values, respectively.

Electromyography

To evaluate the fatigue protocol, mean power frequency (MNF) and root mean square (RMS) of the cervical extensors were evaluated through Lab Chart 7™ (AD Instruments, Sydney, Australia). Muscle activity during the first 10 seconds, and the last 10 seconds of the fatigue protocol (before the force dropped), was selected and the MNF and RMS values were obtained as measures of pre and post fatigue. (FFT Size: 1

K (1024), Data window: Hann (cosine-bell), Window overlaps: 50%, SEF Threshold: 75%, Upper Frequency: 500 Hz, Lower Frequency: 10 Hz).

Statistical Analysis

A repeated measures analyses of variance (ANOVA) with pre planned contrasts to the first baseline was run for each variable and used to measure JPS between pre and post-fatigue conditions (SPSS v19, IBM Corporation, Armonk, New York, USA). Statistical significance was set at $P \leq 0.05$. Microsoft Office Excel 2010 (Microsoft Corporation, 2010; Redmond, Washington, USA) was used to calculate absolute, constant and variable of elbow joint position error. In addition, to measure force and time, two sample T tests for data with unequal variances were also calculated using Microsoft Office Excel.

Results

The fatigue criterion in this study was set as an 8% decrease in MNF on at least one side of the CEM as previously suggested by (Öberg et al. 1990). From all twelve participants, two females failed to meet this criterion. Thus, the remaining six males and four females are included in the analysis below.

Maximum Force and Duration of the Contraction

The mean MVC extensor force was (mean ± standard deviation) 105.81 ± 38.49 N and the mean contraction time was 5.01 ± 2.50 minutes. There were significant differences between genders for force ($p=0.02$) and no significant differences between contraction time ($P=0.33$). The mean MVC for males was 123.16 ± 39.72 N and for females was 79.51 ±17.57 N. The mean contraction time for males was 4.71 ± 2.65 minutes and for females was 5.46 ± 2.57 minutes. The mean baseline score for the NDI questionnaire was 3.91 ± 0.73 confirming that participants did not have neck pain. The mean score for the EHI Questionnaire was 93.6 ± 4.59 out of 100, demonstrating strong right hand dominance.

Absolute, Variable, and Constant Errors

For absolute error, there was a significant effect of time ($F_{2,18}=19.41$ of time, $p\leq0.0001$). Pre-planned contrasts to the first baseline pre-fatigue measurements indicated that absolute error decreased on the second baseline pre-fatigue measurement ($F_{1,9}=24.62$, $p\leq0.0001$), and exhibited a significant increase following fatigue ($F_{1,9}=36.35$, $p=0.0001$). The mean absolute elbow joint position error (JPE) for the first three (first set) pre-fatigued trials was 4.01° ± 1.87 (95% confidence interval: 2.67–5.35). Absolute error decreased for the last three (second set) pre-fatigued trials with a mean JPE of 2.04° ± 2.04 (95% confidence interval: 1.43–2.66). JPE increased for the three post-fatigue trials with a mean absolute JPE of 6.54° ± 2.69 (95% confidence interval: 4.61–8.47).

There were no significant differences for variable elbow JPE ($F_{2,18}= 0.27$ of time, $p=0.76$). The average error for the first three pre-fatigued trials was 1° ± 0.53 (95% confidence interval: 0.61–1.38) and while not statistically significant, error decreased for the second set of pre-fatigued trials mean variable error of 0.83° ± 0.91 (95% confidence interval: 0.18–1.48) and increased to 0.92° ± 0.76 (95% confidence interval: 0.38–1.47) for the post-fatigue trials.

There were also no statistically significant differences for constant elbow JPE ($F_{2, 18}$=1.16 of time, p≤0.33). The error was greater for the first three pre-fatigue trials in comparison to the other sets, but in a different direction. Error decreased from -2.42° ± 1.73 (95% confidence interval: -3.66 – -1.18) for the first set of pre fatigue trials to -0.06° ± 1.4 (95% confidence interval: -1.06 – 0.93) for the second set of pre fatigue trials, and then to -1.22° ± 5.81 (95% confidence interval: -5.38 – 2.92) for the post fatigue trials. Figure 6 highlights the absolute, variable and constant JPE for each set.

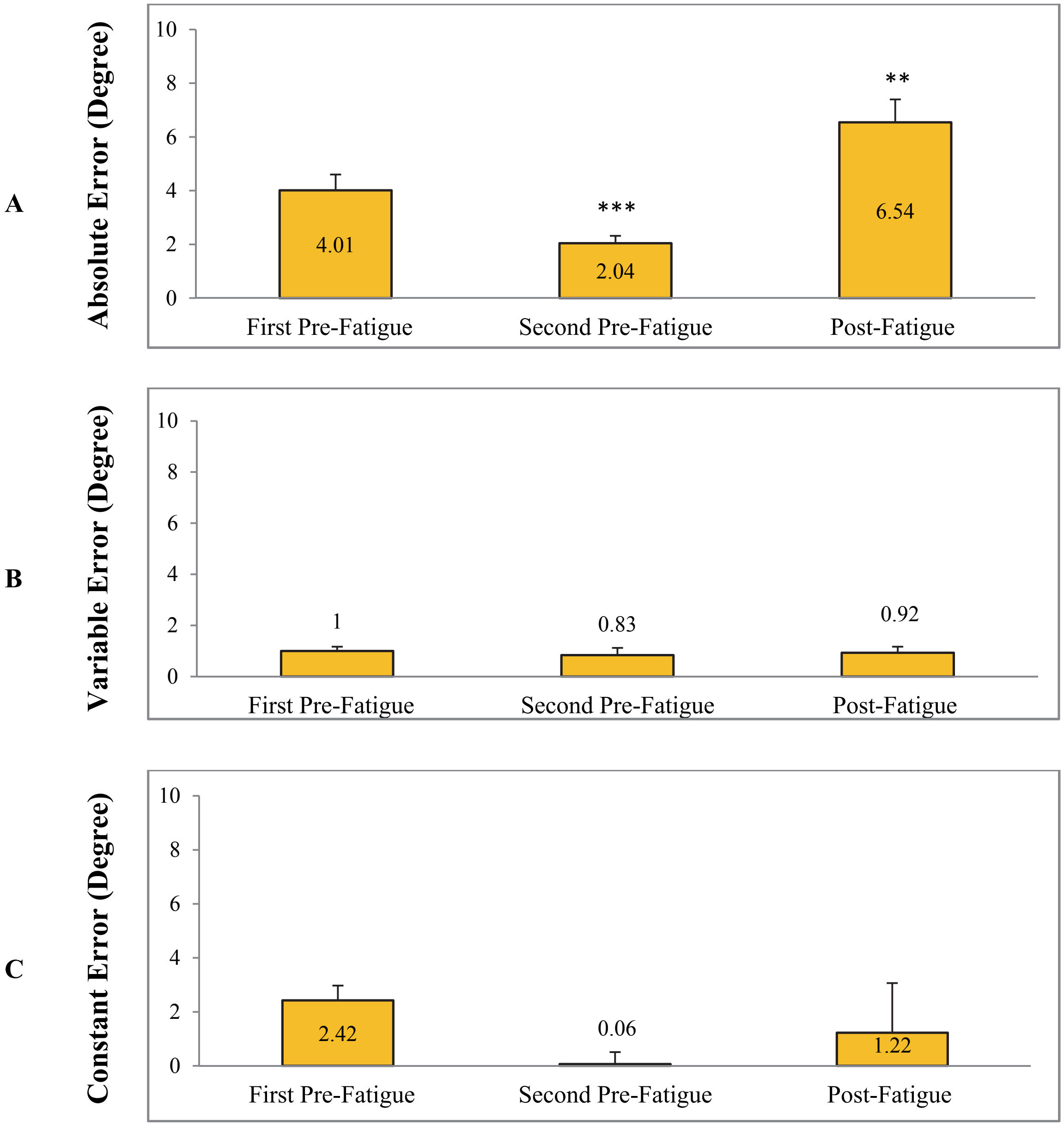


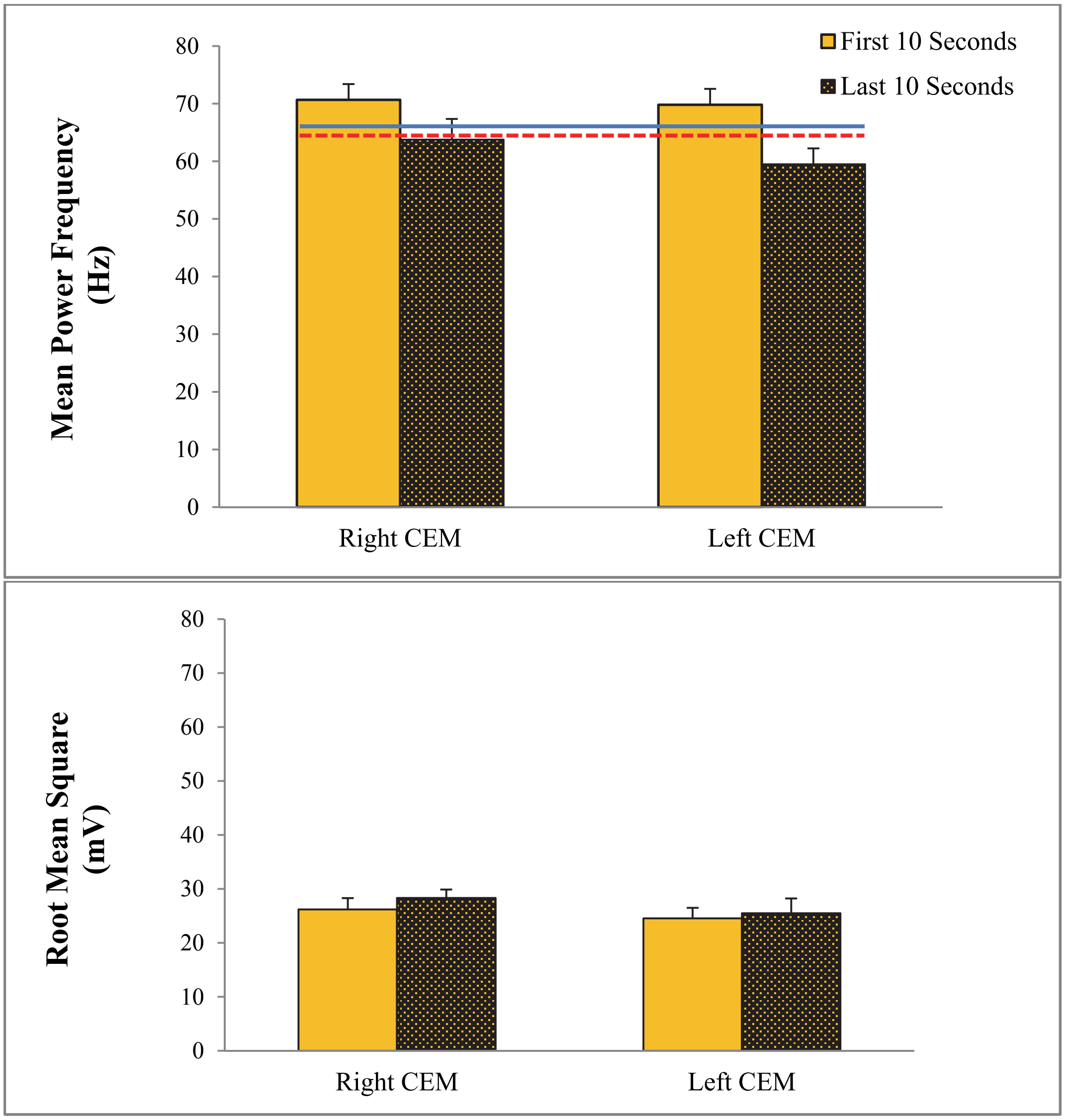
Figure 6 (A, B, C): Absolute, Variable, Constant Errors
Absolute (5–A), Variable (5–B), and Constant (5–C) joint position errors for each set of trials. Error bars represent the 95% confidence intervals. Note that absolute and variable error showed decrease from average of first three baselines of pre-fatigued to the average of second three pre-fatigued trials and then increased in the average of three post-fatigue trials. The constant error for the first set of pre-fatigue trials was greater than two other trials, $P \leq 0.05$. The *** indicates significance ($p \leq 0.0001$) and ** ($P \leq 0.01$).

EMG Activity

The average MNF declined from the beginning of the 70% MVC fatigue protocol to the end. There were no significant differences for MNF of the left and right cervical extensor muscles ($F_{1,18}$= 0.23 of time, p=0.63); however, MNF decreased from 70.66 ± 8.66 Hz to 63.30 ± 11.28 HZ and from 69.83 ± 10.77 Hz to 59.51 ± 8.66 Hz (Figure 7-A). In addition, there were no significant differences for RMS of the left and right cervical extensor muscles ($F_{1,18}$= 0.07 of time, p=0.78); however, for the left and right CEM, RMS increased from 26.2 mV ± 6.59 to 28.33 mV± 4.88 and from 24.55 ± 6.1 to 25.51 ± 8.5, respectively (Figure 7-B).

A

B



Line representing 8% decrease in MNF of right CEM (MNF=65.00)
Line representing 8% decrease in MNF of left CEM (MNF=64.24)

Figure 7 (A, B): Average of MNF and RMS

The average of MNF were decreased and the average of RMS were increased from the first 10 seconds to the 10 last seconds of EMG spectrum for both right (A) and left (B) cervical extensor muscles.

Discussion

Our findings demonstrate that the accuracy of elbow JPS was affected by neck extensor muscle fatigue.

The improvements found in JPE (both absolute and variable errors) between the initial two sets of pre-fatigue trials were most likely a learning effect. This coincides with the idea that training improves joint proprioception sensitivity (Carpenter et al. 1998, Lee et al. 2003). In this study both absolute and variable errors then increased during the post-fatigue trials, indicating that the impact of fatigue overrode any learning or practice effects on upper limb JPS. These findings support the hypothesis that neck muscle fatigue can decrease the accuracy of upper limb position sense. These findings are in accord with those of Allen and Proske (2006) who demonstrated reduced forearm JPS during an arm fatigue protocol.

Awareness of joint position is generated largely by muscle spindles and Golgi tendon organs within the muscles crossing the joint (McCloskey 1978). Muscle tissues can be affected by fatigue more than joint tissues (McCloskey 1978) and it has been suggested that a decline in ability to duplicate joint angles following fatiguing exercises is due to a deficiency in muscle spindle performance (Gear 2011). It is hypothesized that fatigue disturbs the sense of movement which is produced by muscle spindles and the position-matching task in turn is affected (Letafatkar et al. 2009). Fatigue alters the effort needed to maintain the position of the limb and once the fatigued limb attempts to produce a movement, the altered sense of position presents as difficulty in creating the desired joint position (Allen and Proske 2006). These concepts are in parallel to the findings of this current study because CEM fatigue disturbed upper limb joint proprioception by increasing the absolute error in an elbow joint repositioning task. Although participants made their best effort to reproduce the most accurate elbow angle, distorted messages to the CNS from spindles in the fatigued neck muscles may have led to altered afferent feedback to the CNS, affecting the accuracy of the CNS map or schema of the upper limb in relation to the neck (Johnson 2001, Knox and Hodges 2005, Paulus and Brumagne 2008), and impacting the ability to accurately reproduce the elbow joint angle.

It should also be noted that Juul-Kristensen et al. (2007) performed a test-retest reliability of elbow joint proprioception where participants had to actively reproduce forearm position relative to the upper arm. The findings indicated that this approach was a reliable JPS measure for absolute error, indicating that the changes we have observed in JPS following fatigue are likely not simply due to poor reliability of the test. The effect of the fatigue on JPS is further affirmed by the fact that based on the improvement in the two pre-fatigue trials; in the absence of fatigue we would have expected a further improvement in JPS due to learning effects. This further confirms that the decrease in JPS is due to fatigue, rather than poor reliability.

Joint proprioception also plays an important role in movement performance. Afferent signals transfer to the CNS from mechanical receptors that are located in joints and soft tissues (Voight et al. 1996). Near the lateral and medial epicondyle of the elbow joint, there are sets of sensory nerve endings which are responsible for angle changes in elbow movements (Juul-Kristensen et al. 2007). For this reason we chose target angles between 80° to 100° to minimize external clues from other sources that might be transferred to the CNS in predicting of elbow joint angle.

Several authors have investigated the effect of fatigue on limb proprioception. Barker (2011), investigated the effect of neck muscle fatigue (100% MVC for 30 seconds) on elbow JPS, and found that there were no significant differences in JPE between pre and post- fatigue trials. However, given the findings of our study, the possibility exists that participants may have recovered from the fatigue protocol prior to retesting elbow JPS in the Barker (2011) study. In our study, the large differences in absolute error from two baseline conditions to post fatigue trials indicated that our sub-maximal fatigue protocol was sufficient to impair elbow JPE. In addition, the results of our study are in agreement with the idea that after performing continuous submaximal contractions, muscles encounter a long-lasting decline of force production with a slower recovery from the fatigue protocol as compared to maximal contractions (Enoka and Duchateau 2008).

The neck muscles have numerous sensory receptors and in particular, the deep sections of the sub-occipital muscles have the greatest cervical receptor density and are responsible for central and reflex connections to the visual, vestibular, and postural control systems (McCloskey 1978). During limb movement, the kinaesthetic and visual inputs are constantly monitored by the brain to predict the future position of the limb (Proske and Gandevia 2009) and in the absence of visual feedback, the muscle spindles are responsible for limb proprioception. It is known that severe changes in neck and head position up to the end of available joint range of motion may increase elbow JPE (Knox and Hodges 2005). To avoid this effect, our participants performed all passive and active elbow joint movements with their eyes closed and head in a neutral position. In addition, it is also possible that other muscles and passive tissues may have been affected besides fatiguing the CEM; however the focus of the current study was only exploring the effect isometric contractions on the CEM.

Previous studies have reported increases in elbow JPE following various types of forearm muscle fatigue. For instance, Allen and Proske (2006) performed 330 concentric forearm contractions at 30% MVC , Brockett et al. (1997) induced elbow flexor fatigue using eccentric and concentric exercises at 20% MVC, Weerakkody et al. (2003) applied an eccentric contraction to the elbow flexors at 30% MVC and Sharpe and Miles (1993) performed five, 20 second bursts of maximal elbow flexion. All of these studies led to errors in a position matching task at the elbow. The results of our study demonstrated JPS changes following the performance of a submaximal fatigue protocol (70% MVC) of the CEM, which confirms that elbow JPS is sensitive to muscular fatigue, not only from the elbow flexors/extensor muscles, but also from the cervical neck extensors. In addition to a decline in force production, fatigue is often measured by a shift in the EMG power spectrum to lower frequencies (De Luca 1984). In our study, the average MNF declined for both the right and left CEM from the first 10 seconds to the last 10 seconds of the 70% contraction. A decline in MNF of 8% is considered to be indicative of fatigue (Öberg et al. 1990). All participants met the criterion of 8% drop on at least one side of their CEM. It was found that the 8% drop in

MNF occurred more often in the left CE than the right CE. This might be due to weaker left CEM or stronger right shoulder and neck muscles. Our participants were strongly right hand dominant, and are more likely to use their right upper extremity more frequently during activities of daily living, which may have resulted in the right side being more fatigue resistant compared to the left side.

The decrease in upper limb joint proprioception subsequent to neck muscle fatigue is a fundamental insight. It suggests that neck muscle fatigue, which often occurs in work place and recreational settings, may impact upper limb movement accuracy. This has important implications for ergonomics, sport performance and for upper limb injury risk factors.

Strengths of study

This study is the first to examine the effects of submaximal CEM fatigue until failure on elbow joint position sense (JPS). Findings of this study are unique because it confirms that neck muscle fatigue can negatively affect the accuracy of JPS. This study suggests that to maximally fatigue the CEM, isometric contractions have to continue until participants are no longer able to maintain the force level. In addition, because even the small neck movement such as flexion or rotation would affect the elbow JPS (Knox and Hodges 2005), utilizing the motion capture system improved the accuracy of measuring the change in elbow joint angle and tracking the position of head and neck movements through all data collections.

Limitations of the Study

This study had methodological issues that should be considered for future research. Some participants were not comfortable with their arm in complete external rotation when it was hanging in the sling. However, the sling allowed us to move the participant's arm forward slightly to accommodate for this uncomfortable position. In addition, the head strap was uncomfortable for some participants and others reported that it moved against their head when it was pulled against the force transducer in extension contractions.

Conclusion

This study confirms that fatigue of the neck extensor muscles with a sub-maximal fatigue protocol (70% MVC) can influence the accuracy of elbow joint position sense. Between pre and post-fatigue trials, both absolute and variable errors were increased. This suggests that altered afferent input from the neck subsequent to fatigue may impair upper limb proprioception.

MANUSCRIPT 2

NECK MUSCLE FATIGUE ALTERS THE CERVICAL FLEXION RELAXATION RATIO (FRR)

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Abstract

The cervical flexion relaxation ratio (FRR) is a reliable method that is able to distinguish between healthy individuals and chronic/recurrent neck pain (NP) patients. The ratio is increased in NP patients because they are unable to fully relax their cervical extensor muscles (CEM) during full forward neck flexion (Maroufi et al. 2013). Fatigue is known to modulate both the onset and offset angles of the silent period in both the lumbar (Descarreaux et al. 2008) and cervical (Nimbarte et al. 2014) spine in healthy individuals; however, its impact in the cervical spine in NP patients has not yet been studied.

The purpose of this study was to determine if fatigue of the CEM using a submaximal fatigue protocol alters the parameters of the FRR. Thirteen healthy control volunteers and twelve subclinical neck pain patients participated. The activity of the CEM was examined bilaterally using surface electromyography (EMG) and kinematics of neck and head were collected. An isometric neck extension task at 70% of maximum was used to elicit fatigue.

The FRR for both the left and right CEM was significantly lower for the neck pain group in comparison to the healthy controls ($F_{1,40} = 38.25$ of time, $p \leq 0.0001$). The FRR for both left and right CEM changed significantly ($F_{1,40}=21.38$ following fatigue, $p \leq 0.0001$) and onset and offset angles for the silent period significantly decreased ($F_{1,40}=5.69$ of time, $p=0.02$). In addition, there were no significant interactions in FRR and onset and offset angles from pre to post fatigue on dominant and non-dominant hand between control and NP participants. Moreover, from the beginning to the end of CEM isometric contractions for both groups, the mean power frequency (MNF) significantly decreased ($F_{1,46}=56.98$ of time, $p \leq 0.0001$) and the root mean square (RMS) significantly increased ($F_{1,46}=27.75$ of time, $p \leq 0.0001$).

Cervical extensor fatigue is a modulator of FRR and onset-offset angles of muscular activity. Fatigue increases the function of the passive tissues and surrounding muscular structures on the cervical spine, which as a result, decreases spinal stability.

Key words

Flexion Relaxation Phenomenon (FRP), Flexion Relaxation Ratio (FRR), Cervical Extensor Muscles, Fatigue, Subclinical Neck Pain

Introduction

Advances in technology within many industries have led to an increased risk of musculoskeletal disorders in the general population (Falla 2004). Neck pain is extremely prevalent in society and it affects about 30-50% of Canadians every year, while also placing a large financial burden on healthcare organizations (Hogg-Johnson et al. 2008). In many cases, NP is initiated in the workplace due to prolonged, abnormal flexion in sitting or standing postures (Yoo et al. 2011) (Ming et al. 2004), or from a sedentary life style. Additionally, our dependence on technology such as computers, laptops, tablets and cell phones have verified the issue (Ming et al. 2004)

Abnormal neck muscle recruitment patterns is a proposed mechanism for persistent NP (Murphy et al. 2010). Specifically, the activation patterns of the cervical Erector Spinae (ES) muscles, which are very important for supporting the head and neck, frequently change due to abnormal postures such as working at a computer with forward (anterior) head position (Yoo et al. 2011). The strength and endurance of the cervical flexor muscles are reduced in NP patients (Falla 2004) and it has been associated with pain during the performance of dynamic movements (Brandt et al. 2004). The most common objective assessment methods that can discriminate between NP patients and asymptomatic controls are active cervical range of motion tests (Yoo et al. 2011), the cervical flexion–relaxation phenomenon (FRP) (Pialasse et al. 2009) and the cervical flexion-relaxation ratio (FRR) (Maroufi et al. 2013).

Activity of the ES muscles, which controls the lumbar during flexion and extension, is reduced or completely shut off, once full trunk flexion is reached with a slow and controlled movement (Floyd and Silver 1955, Gupta 2001, Othman et al. 2008). This occurrence is known as the FRP, which transfers the extensor moment from the active elements (muscles and tendons) to the passive (vertebral bones, intervertebral discs, ligaments and fascia) structures of the spine. To ensure spinal stability, these two subsystems (active and passive) must be coordinated, along with the neural subsystem, or dysfunction may result (Panjabi 1992, Panjabi 1992, Descarreaux et al. 2008, Hashemirad et al. 2009). However, this phenomenon does not always occur back pain patients (Marshall and Murphy 2006). Back pain (Othman et al. 2008) and neck pain (Murphy et al. 2010) patients have a higher magnitude of myoelectric activity in full forward trunk and neck flexion when compared to a healthy control group. Therefore, the FRP can be used as a reliable marker to discriminate individuals with neck pain from asymptomatic individuals (Murphy et al. 2010, Maroufi et al. 2013).

The FRR, which is maximum EMG activity in re-extension to the average EMG activity in the relaxation phase (Murphy et al. 2010, Nimbarte et al. 2014), has been reported to have a lower value in low back pain (LBP) and NP patients in comparison to healthy control groups (Marshall and Murphy 2006, Murphy et al. 2010). It has been found that chronic or recurrent NP patients are unable to fully relax their CEM during full forward flexion (Murphy et al. 2010, Maroufi et al. 2013). There is some evidence that this impairment can be rehabilitated following spinal manipulation and exercise interventions. Improvements in the FRR have been reported in both the lumbar

(Marshall and Murphy 2006, Marshall and Murphy 2008), and cervical (Barker 2011) spine after treatment.

Muscular fatigue is often defined as a reduced capacity to produce a maximal voluntary contraction (MVC) (De Luca 1984) or a failure to maintain a repetitive or long-duration submaximal contraction (Enoka and Duchateau 2008). Frequently, after submaximal contraction to fatigue, the muscle experiences a long-lasting depression of force production. Constant repetitive or long-duration contractions have been suggested to expose an interaction of actin-myosin that impairs the typical excitation-contraction coupling, and can lead to an enhanced delay or difficultly in recovery from fatigue (Westerblad and Allen 2002). Fatiguing the cervical extensor muscles has declined the ability to stabilize the cervical spine and probably transfer load sharing from the active to passive tissues (Nimbarte et al. 2014).

Few studies have investigated the effects of cervical extensor muscle fatigue on the FRR, as well as, the onset and offset of myoelectric silence. In one study, two shoulder postures (neutral and shrugged) were explored in healthy individuals (Nimbarte et al. 2014). Neck muscle fatigue was generated by participants lying prone on a table and holding their head parallel with the floor, against gravity. The authors found that the FRR only changed when the shoulders were in the neutral position. The FRR significantly declined after fatigue and this effect was not found in the shrugged position. There was also an earlier onset and later offset of the silent period, which resulted in an increased duration of the silence period following fatigue in the cervical flexion relaxation trials. This work indicates that neck extensor fatigue and shoulder position modulates the FRP and increases activity of the active cervical extensor tissues such as ES in cervical spinal stability under fatigue condition in full forward cervical flexion (Nimbarte et al. 2014).

Participants with mild back and neck pain represent an interesting group to study because they might be at greater risk of fatigue related injuries. A recent study comparing healthy individuals and those with mild neck or back pain and found that the cervical FRR significantly decreased following ten minutes of a below knee lifting task at a work station positioned 32 cm above the floor. The visual analog pain scores were also significantly increased for participants who had mild neck or back pain prior to performing the task (Shin and Yoo 2014).

Both spinal disorders (Murphy et al. 2010) and muscle fatigue (Nimbarte et al. 2014) play a significant role in poor spinal stabilization. However, the link between neck muscle fatigue and the effects on neck motor control are underexplored in those with mild neck pain. This study attempts to address this by investigating the effect of CEM fatigue on neuromuscular responses in both healthy participants and those with neck pain.

Methods

Participants

Thirteen healthy volunteers and twelve subclinical NP patients participated. Handedness was confirmed by the Edinburgh Handedness Inventory (EHI) self-report questionnaire (Cohen 1961). Healthy control participants were without any chronic or recurrent neck, shoulder, or elbow pain for at least 3 months prior to this study, and the sub-clinical NP patients had suffered from mild to moderate NP for at least 3 months prior to this study. This was confirmed with the Neck Disability Index (NDI) self-report questionnaire (Vernon 2008), where scores between 5-14 indicate mild neck pain and 15-24 indicate moderate neck pain. Participant age, height, weight, NDI and EHI summary data are found in Table 1. There were not any significant differences and interaction between age, height, weight and handedness; while there were as expected, significant differences in NDI score (F=39.9 of time, p=0.005) between two groups. This study was approved by the University of Ontario Institute of Technology Research Ethics Board.

Table 1: Demographics and Self-Report Measures

		Healthy Control Group (7 males – 6 Females)	**Neck Pain Group (5 males – 7 Females)**
		Mean ± SD	**Mean ± SD**
Age	Years	25.76 ± 4.51	23.5 ± 3.81
Height	cm	168.69 ± 8.91	168.75 ± 15.38
Weight	kg	66.15 ± 13.41	73.16 ± 21.57
NDI Score		1.15 ± 1.51	9.75 ± 3.88
Duration of NP	Years	0	3±2
Repetition of NP	Time per week	0	4±2
EHI Score		72.72 ± 25.72 One participants (-100) was strongly left hand dominant and one with (+20) was ambidextrous and the rest were strongly right hand dominant	71 ± 17.91 One participant (-30) was strongly left hand dominant and one with (+30) was ambidextrous and the rest were strongly right hand dominant.

Instrumentation

Upon arrival to the lab, participants filled out the informed consent, NDI, and EHI questionnaires.

EMG set up

A Trigno^{TM} Wireless EMG System with two parallel-bar surface electrodes (41$\times$ 20 $\times$ 15mm, 15g) and a 10 mm inter-electrode distance was used to collect EMG activity from the CEM (20-450 Hz, CMRR > 80 dB, input impedance 1015Ω, Delsys Inc., Boston, USA). To measure activity of the CEM, electrodes were placed bilaterally over the CEM at the level of the C4/C5 spinous process. From superficial to deep, the CEM under the recording electrodes are Upper Trapezius, Splenius Cervicis and Splenius Capitis and the intermediate layer contains Longissimus Capitis and Cervicis (part of Erector Spinae). The deep CEM include transversospinalis muscles (Semispinalis Cervicis and Capitis, Multifidus, Interspinalis, and the Rotatores), which are generally smaller muscles responsible for control and stabilization of the cervical spine (Nolan Jr and Sherk 1988) and are therefore unlikely to significantly contribute to the recorded surface EMG signal. When performing neck flexion, position of the C7 is visible and was used to palpate the location of C4/C5 (Figure 8). Before electrode placement, the areas were prepared by abrading and cleaning the skin with alcohol (BSN medical Medi-Swabs). In order to improve contact between the skin and the EMG sensors, Hypafix tape™ was applied over each electrode. EMG data were collected using the EMG works 4.0 Acquisition software (Delsys Inc., Boston, USA), synchronized with the kinematic data and sampled at 4000 Hz.

Kinematic marker set up

Kinematic data were collected using two 3D Investigator™ Motion Capture Systems (Northern Digital Instruments (NDI), Waterloo, Ontario, Canada). Three rigid bodies, each consisting of three non-orthogonal infrared markers were used to collect kinematic data of head, neck, and thoracic spine. Three sets of non-orthogonal infrared markers were placed on the following anatomical sites: one set of three markers on C7, one set of three markers on the right side of the head (above the right ear), and one set of four markers on the upper thoracic at the level of T4 (Figure 8). Using a digitizing probe, eleven anatomical landmarks (right and left top of head, right and left tragus, C7, right and left acromion, right and left iliac crest, supra sternal notch, and xiphoid process) were digitized on each participant to create anatomical frames of reference for each modeled segment. These coordinates for the digitized landmarks were continuously monitored using the NDI First Principles software, assuming a fixed spatial relationship with the rigid body affixed to each segment. Cervical spine Euler angles were calculated as a change in orientation of the head relative to the C7 during the flexion-relaxation tasks.

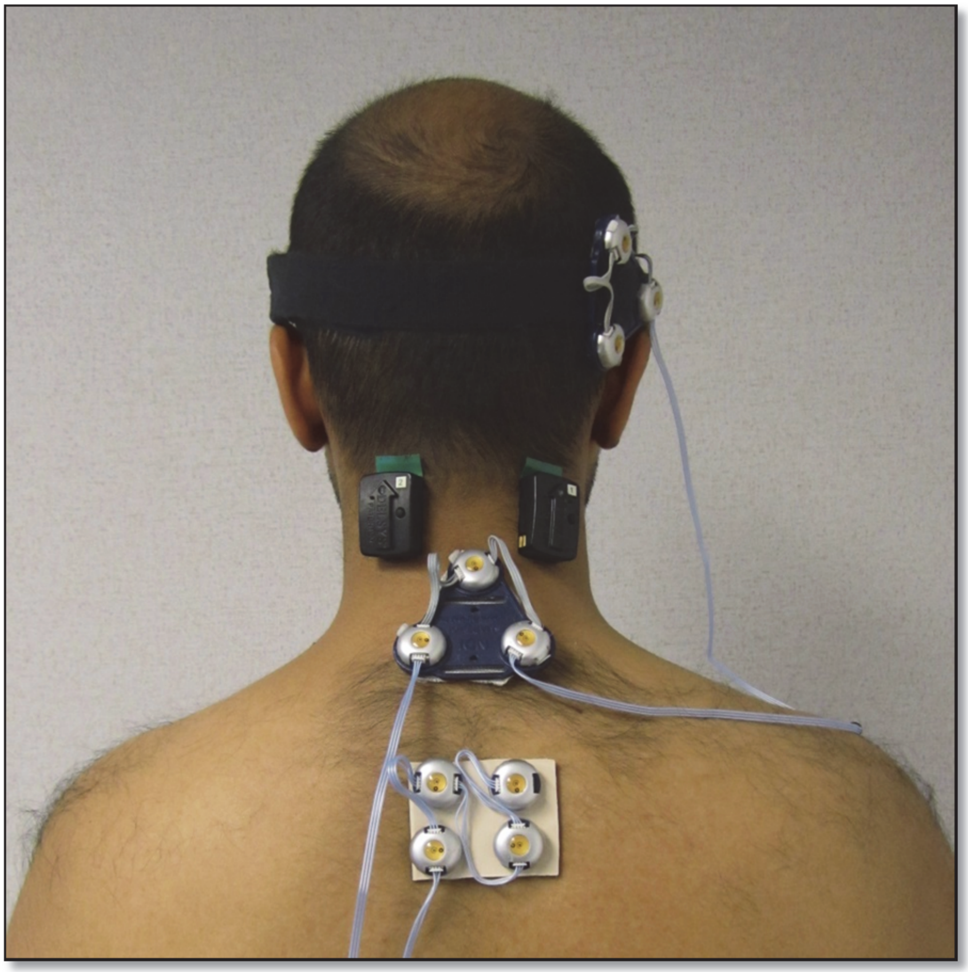

Figure 8: EMG Kinematic Marker Setup
Surface EMG electrodes were placed bilaterally over the CEM at the level of the C4/C5 spinous process Three sets of non-orthogonal infrared markers were placed on the following anatomical sites: one set of three markers on C7, one set of three markers on the right side of the head (above the right ear), and one set of four markers on the upper thoracic at the level of T4

Fatigue protocol

A recently completed study (Manuscript one of the current thesis) showed that a 70% isometric fatigue protocol caused fatigue, however the protocol did not decrease the mean power frequency in every participant by the recommended level of at least 8%. Our observation was that some participants may have “given up” before they were fully fatigued partly due to boredom and/or inattention. Therefore we designed a “ramp and hold” protocol at the 70% MVC level in order to increase participant engagement in the fatiguing task for this study. A maximal isometric voluntary contraction (MVC) was performed for CEM to both normalize our EMG data and to provide a reference for the force level of our submaximal fatigue protocol. For the CEM maximal contraction, participants were seated on a chair with a backrest with no upper thoracic or cervical support. The hips and knees were at 90°, feet on the floor and positioned shoulder width apart, hands relaxed by laps, and were instructed to view a designated point straight ahead at eye level. This position was chosen to prevent bracing and to eliminate any additional force enhancement from muscles other than the cervical extensors. The participants’ head, at the level of the inion, was positioned against an adjustable wall mounted and padded head piece that was attached to a load cell (SML 100, Interface, Scottsdale, Arizona, USA) and interfaced with a Delsys wireless load cell adapter (Delsys Inc., Boston, USA). Participants produced two MVCs of the CEM for three seconds each, separated by one minute rest (Figure 9).

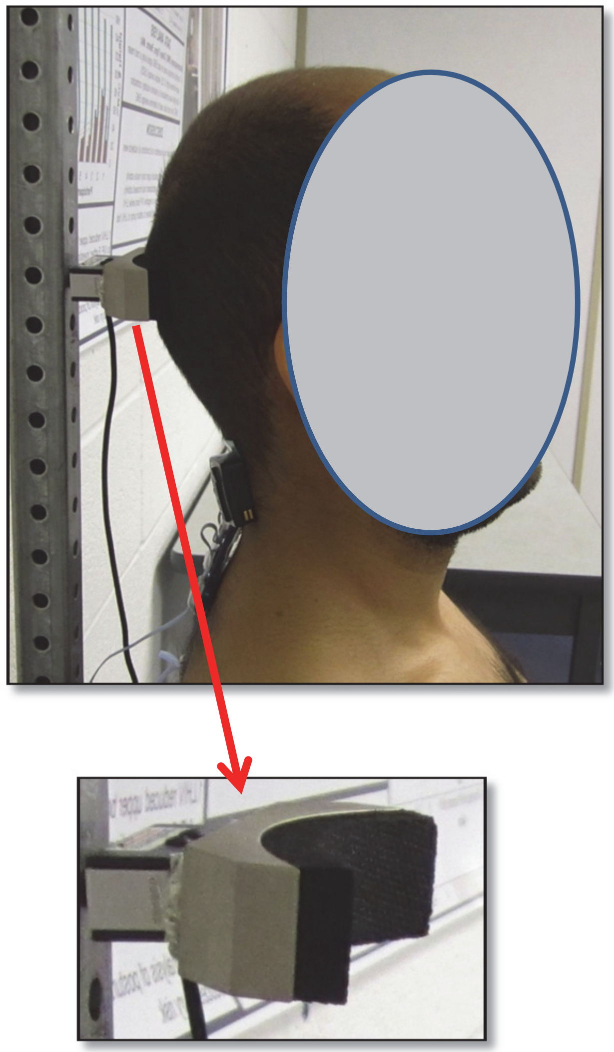

Figure 9: Fatigue Protocol
The participants' head, at the level of the inion, was positioned against an adjustable wall mounted and padded head piece that was attached to a load cell.

After an additional one minute of rest, the fatiguing protocol was performed, which consisted of a repetitive, submaximal, isometric contraction against the load cell at 70% MVC in the same posture as the MCV trials, participants exerted against the load cell and traced a force profile on a computer screen in front of them. One complete repetition lasted for 4 seconds, one second ramp up to the 70% MVC target, followed by a 2 second rest interval (Figure 10). The force requirement was displayed on a computer monitor in front of the participant. The contractions were held until the participant could no longer maintain the force requirement of 70% MVC for two consecutive contractions. Care was taken to eliminate any noticeable changes in the test position (elbow flexion, lifting the shoulders, spine flexion, or using the feet).

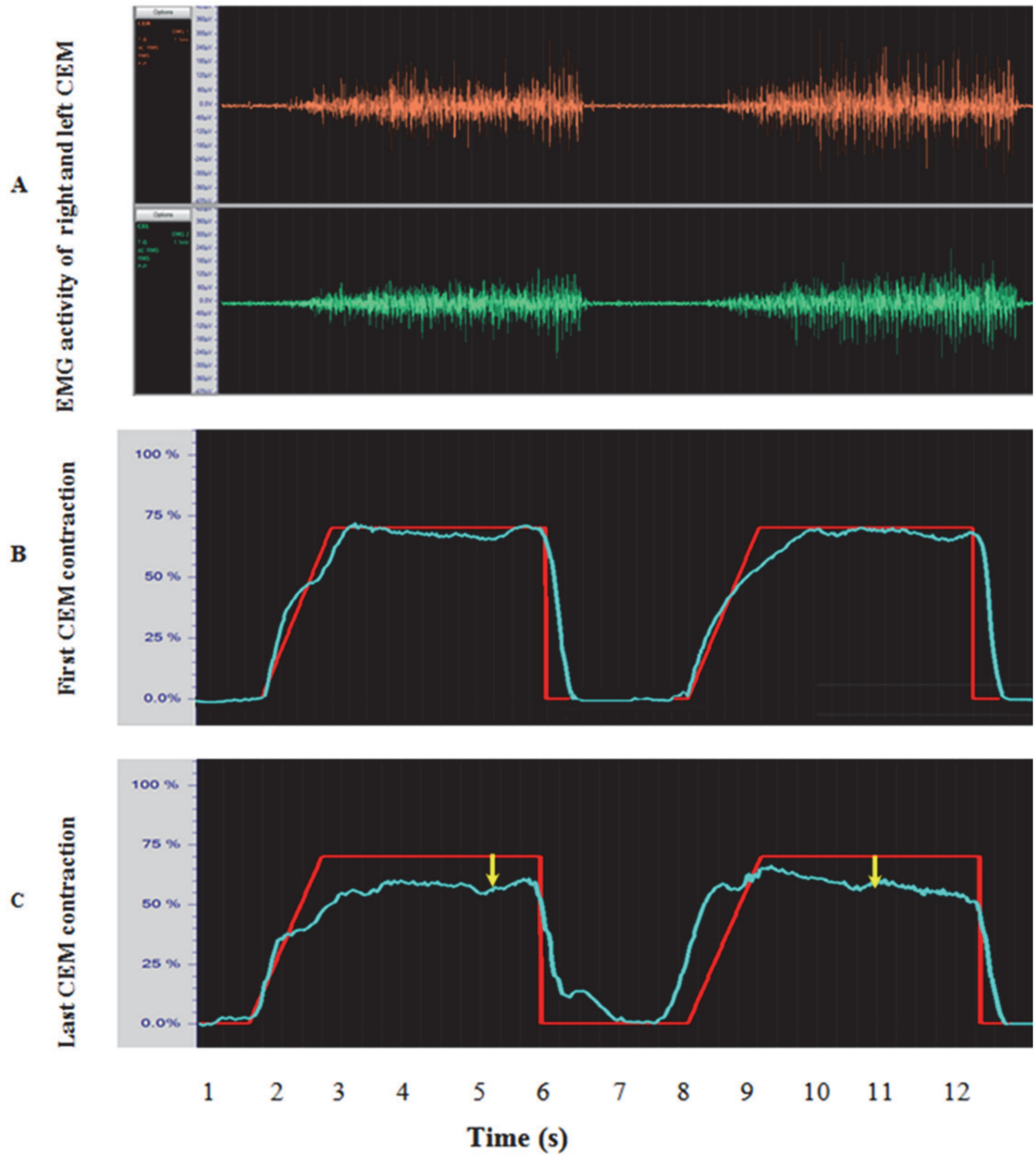

Figure 10: EMG Activities of the Right and Left CEM and Force Template during the Fatigue Protocol

The EMG activities for both right and left of CEM contractions (Panel A), and the designed trajectory fatiguing protocol (red line) and subject's following that trajectory (blue line) from the first (B) to the last (C) isometric submaximal contractions. Yellow arrows indicate that the participant could no longer maintain the required force (Delsys Inc., Boston, USA).

Flexion Relaxation protocol

The cervical flexion-relaxation task measured the participant's full cervical forward flexion. Participants began in an upright, neutral neck position, flexed forward to end range, and then re-extended to the neutral head position. Each participant was asked to sit upright on a stool with hip and knees at 90°, feet on the floor and positioned shoulder-width apart. The shoulders were aligned with the torso in a position of approximately 90 degree internal rotation, with the forearm in a pronated position and hands relaxed on their upper thighs.

The cervical flexion-relaxation protocol was divided into five phases. Each phase lasted for three seconds. In phase 1, participants maintained a neutral head position, phase 2, maximal cervical flexion, phase 3, a hold at the end range of phase 2, phase 4, cervical extension (returning to the neutral position) and phase 5, a hold at the neutral position (Figure 11). In order to standardize the speed and duration of all phases, the pace were controlled with a metronome set at one beat per second, as well as the experimenter counting to the beat to reduce intra and inter participant variability in movement speed. In addition, participants were asked to maintain a fixed upright trunk posture throughout all neck flexion-extension tasks to prevent bending or tilting of the trunk, and they were instructed to look at a fixed point straight ahead to control the starting head position.

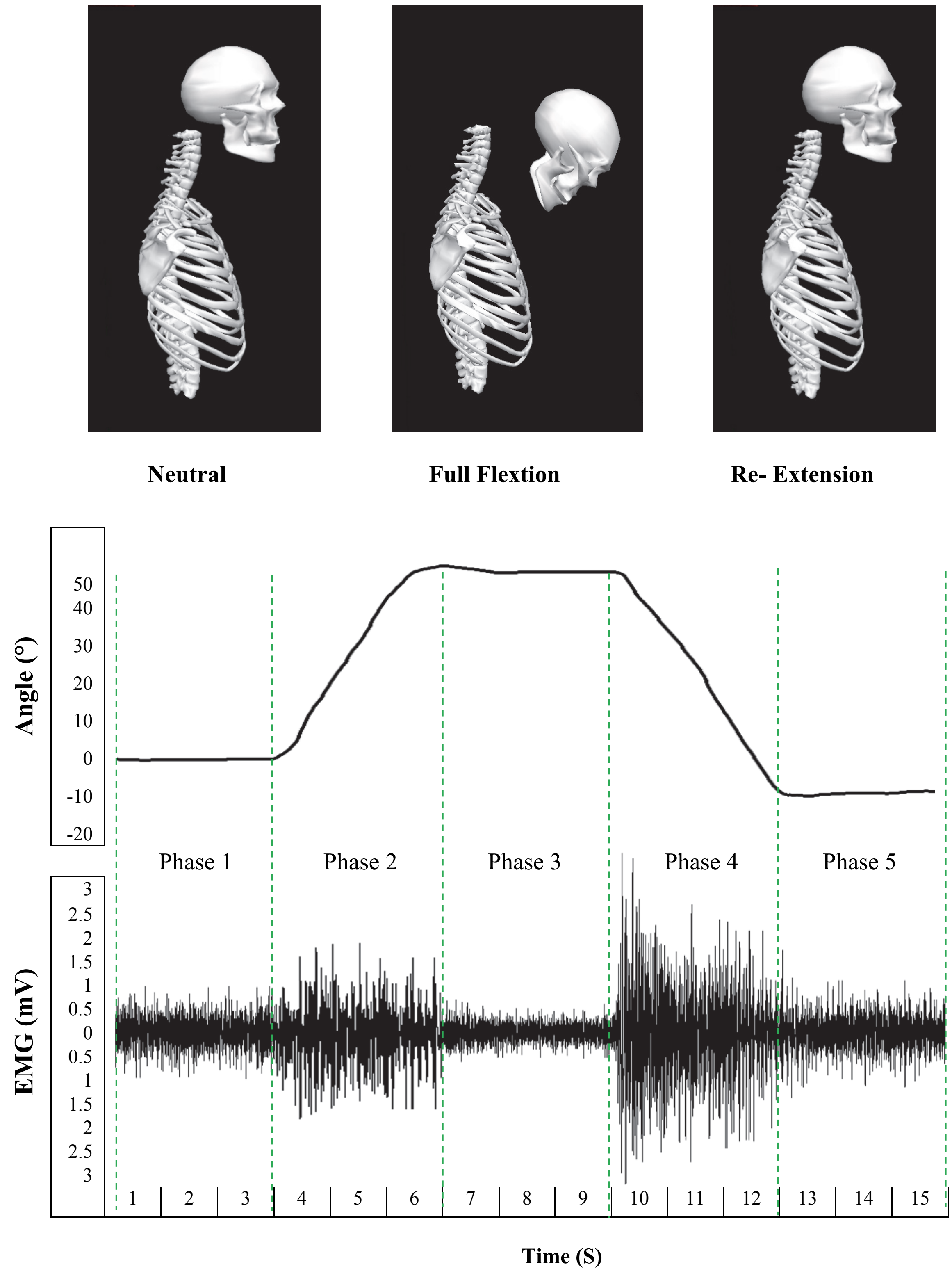

Figure 11: Typical EMG Data during the Cervical Flexion Relaxation Phenomenon.

(Top trace shows movement pattern recreated in Visual 3D (Visual 3D, C-Motion, Professional v 5.01.6), middle trace shows neck angle and bottom trace shows CEM EMG pattern).

Before starting the flexion-relaxation task, participants were trained to get used to the sound of the metronome and the pace of the head movements until they were comfortable with the ability to consistently perform the tasks. After familiarization, the flexion-relaxation task was performed, consisting of three sets of full cervical flexion and back to neutral with 30 seconds of rest between each set. Next, the cervical extensor fatigue protocol was performed and participants performed three post fatigue flexion-relaxation trials (Figure 12).

Familiarization with cervical FRR	Phase 1, Starting position for 3 seconds Phase 2, Maximal cervical flexion for 3 seconds Phase 3, Sustain cervical full flexion for 3 seconds Phase 4, Cervical extension for 3 seconds Phase 5, Hold in the neutral position
1 min rest	
Preforming 3 Pre fatigue FRR trials with 30 seconds interval	
Fatigue protocol	→ 2 MVC of 3 seconds duration with1 minutes interval → Performing neck extensors fatigue with 70% repetitive contractions
Preforming 3 post fatigue FRR trials with 30 seconds interval	

Figure 12: Experimental Procedure

Data analysis

EMG and kinematics data were synchronized using an automatic trigger. The kinematic data were processed using Visual 3D (C-Motion, Professional v5.01.6). The raw kinematic data were low-pass filtered with a six-order Butterworth filter with a cut-off frequency of 6 Hz. Our fatigue protocol lasted until participants could no longer maintain the desired contraction level of 70% MVC for two consecutive contractions, or if there was an 8% drop in mean power frequency (MNF) on at least one side of CEM. For the fatigue task, the MNF and RMS of the first three and last three contractions were processed.

The FRR was calculated using Eq. (1) and it was defined as maximum EMG activity in phase 4 (re-extension) to the average EMG activity in phase 3 (full flexion or relaxation) (Nimbarte et al. 2014), (Murphy et al. 2010). The maximum RMS of the one first second of phase 4 (re-extension) and the average RMS of one middle second period of phase 3 (relaxation) was calculated. The FRR was averaged across the three trials for each pre and post fatigue condition.

$$\mathrm{FRR} = \frac{\text{Maximum EMG in phase 4}}{\text{Average EMG in phase 3}} \tag{1}$$

The onset angle of the silent period (corresponding to a decrease in EMG activity in the flexion phase) and offset angle of the silent period (corresponding to an increase in EMG activity in the extension phase) were visually identified without any clue of experimental condition, (Pialasse et al. 2010). Theses angles were analyzed in degree using the EMG works 4.0 analysis software, by changing the scale on the EMG signals display to the mean of absolute value to help visual inspection.

The kinematic data were processed using Visual 3D and anatomical landmarks were digitized to create a local coordinate system for each rigid body. In addition, Euler angles, which describe the orientation of a rigid body, were calculated using XYZ rotation sequences. The sequence of rotations for determining the neck angles was (Z) Flexion/Extension, (X) Lateral Bend, (Y) Axial Rotation (Figure 13).

There were two axis systems and the XYZ axis systems were a dummy coordinate system that was defined from the head's anatomical landmarks and tracked using the C7 rigid body. Essentially this meant that the neck angle would be close to zero in the upright and neutral posture. The neck angles were then determined as the dummy coordinate system (tracked by the C7 rigid body) relative to the head (tracked by the head rigid body). The visual 3D program calculated all the XYZ angles, but for this study only the flexion-extension angle (Z axis) was processed (Figure13).

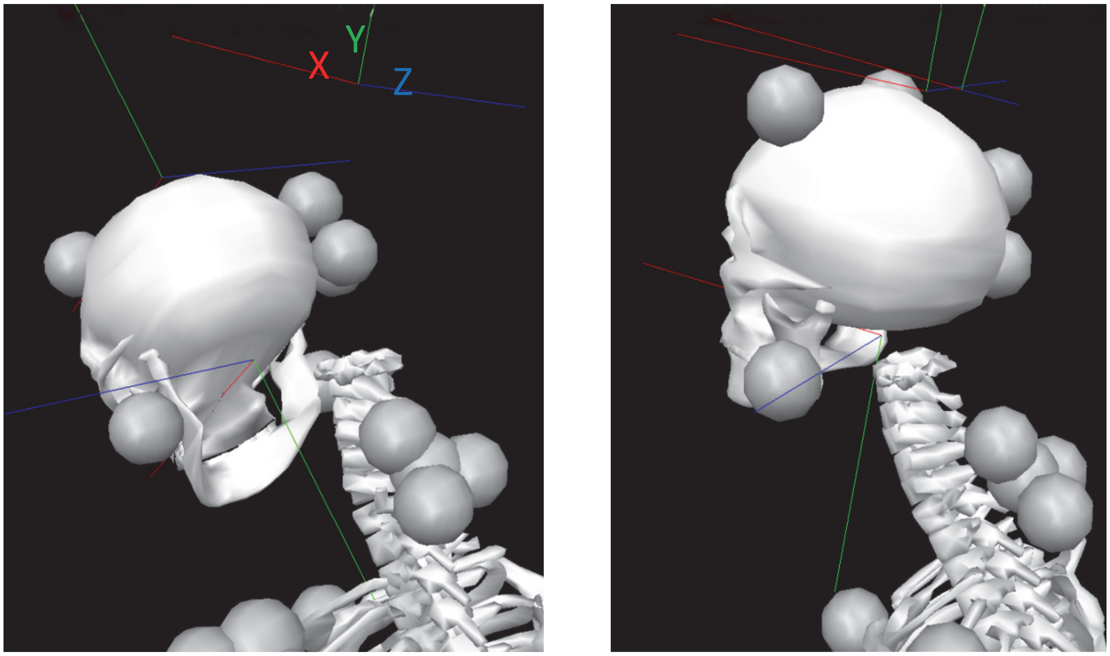

Figure 13: Euler Angles
The sequence of rotations for determining the neck angles is:
(Z) Flexion/Extension, (X) Lateral Bend, (Y) Axial Rotation

Statistical Analysis:

A two way measures analyses of variance (ANOVA) test (SPSS v.21, IBM Corporation, Armonk, NY, USA), was used to calculate the statistical significance of the differences in MNF, RMS, and onset and offset angles of the myoelectric silence and a three way ANOVA test was used to calculate the FRR during pre and post fatigue conditions. Statistical significance was set at $P \leq 0.05$.

Results

Fatigue protocol

For the control group, the average number of repetitions until fatigue was (mean ±SD) (56 ± 41) with the average time of (671 ± 497) seconds or (11 ± 8) minutes. For the neck pain group, the average number of repetitions was (39 ± 31) with the average time of (473 ± 376) seconds or (8 ± 6) minutes. All participants met the criterion of an 8% drop from their initial MNF and an increase in RMS on at least one side of CEM.

All participants at the end of the fatiguing protocol displayed a decrease in MNF and an increase in RMS on at least one side of CEM. There was a significant decrease in MNF from the beginning to the end of the fatigue task for both the control and neck pain groups ($F_{1,46}$=56.98 of time, p≤0.0001). However, there were no significant differences in MNF between the dominant and non-dominant side ($F_{1,46}$ =0.13, P=0.71), and between the control to the neck pain participants ($F_{1,46}$=1.69, p=0.19). In addition, at least on one side of CEM there was a significant increase in RMS from the beginning to the end of the fatigue task for both the control and neck pain groups ($F_{1,46}$=27.75 of time, p≤0.0001), with no significant differences in RMS between the dominant to non-dominant sides ($F_{1,46}$=1.54 of time, P=0.22) or between the control and neck pain participants ($F_{1,46}$=1.12 of time, p=0.29).

For the healthy control group, the mean of the MNF on the dominant side declined from the first trial (mean ± SD) 77.56 ± 14.22 Hz (95% confidence interval (CI): 69.64 – 85.42) to the last trial 69.12 ± 11.53 Hz (95% CI: 61.61 – 76.64). Likewise, it dropped on the non-dominant side from the first trial 80.21 ± 12.59 Hz (95% CI: 72.29 – 88.14) to the last trial 72.05 ± 11.01 Hz (95% CI: 64.53 – 79.56). The mean RMS for the dominant side increased from the first trial 33.82 ± 21.75 mV (95% CI: 23.16-44.48) to the last trial 46.41 ± 31.8 mV (95% CI: 33.41-59.42). Similarly, RMS increased for the non-dominant side from the first trial 33.48 ± 19.98 mV (95% CI: 22.82 -44.15) to the last trial 39.31 ± 22.97 mV (95% CI: 26.31-52.31) Figure 14-A.

For the neck pain group, the mean of the MNF on dominant side declined from the first trial 81.99 ± 15.85 Hz (95% CI: 73.73- 90.24) to the last trial 71.35 ± 15.81 Hz (95% confidence interval: 63.53 – 79.17). Similarly, MNF dropped on non-dominant side from the first trial 88.71 ± 14.04 Hz (95% CI: 80.46 – 96.95) to the last trial 75.8 ± 15.16 Hz (95% CI: 67.89 – 83.62). The mean RMS on the dominant side increased from the first trial 32.83 ± 15.57 mV (95% CI: 21.73 -43.92) to the last trial 48.73 ± 18.41 mV (95% CI: 35.19 -62.26). Also, the mean RMS increased for the none-dominant side from the first trial 34.82 ± 18.17 mV (95% CI: 23.73 – 45.92) to the last trial 46.62 ± 15.82 mV (95% CI: 33.08-60.15) Figure 14-B.

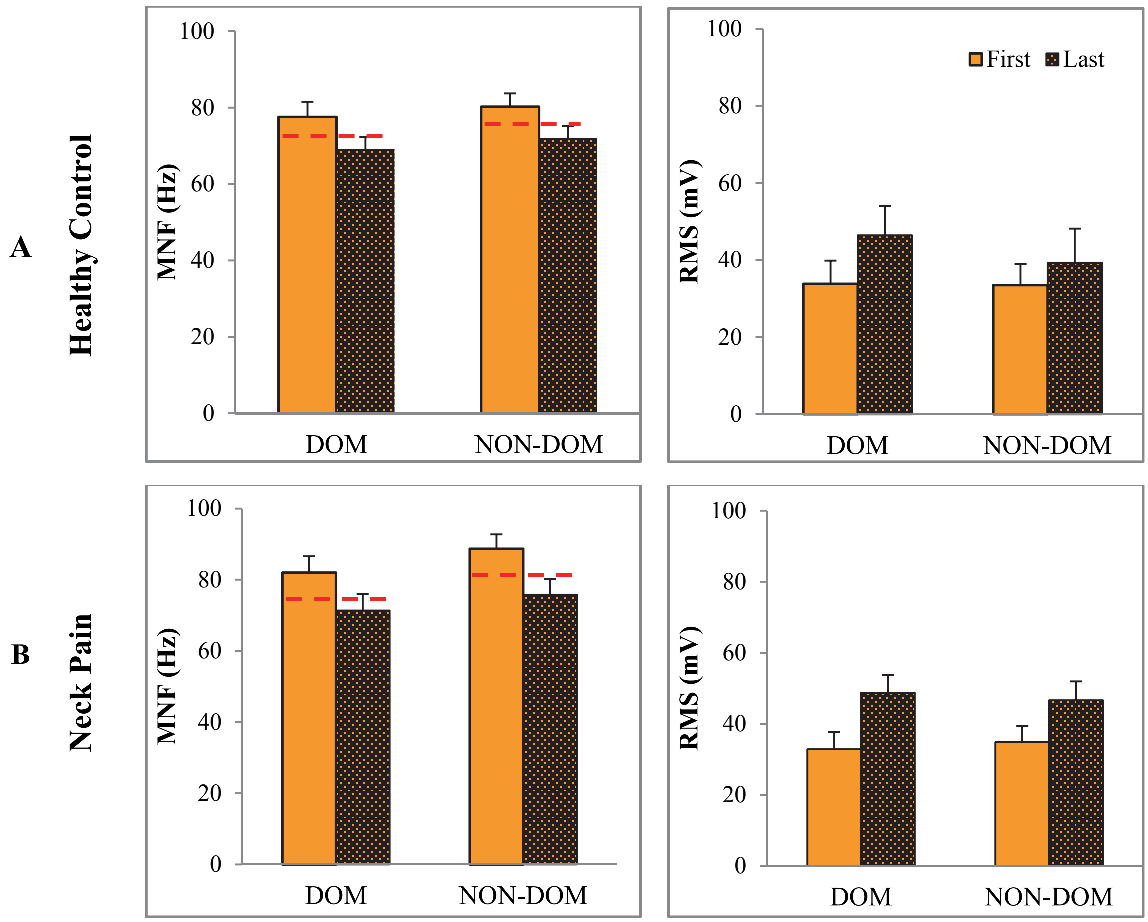

Figure 14: Average of MNF and RMS of Fatiguing CEM

- - - - Represents the level that would be an 8% drop of initial values.
(Control group: Dominant hand 71.36 and Non-Dominant hand 73.8)
(Neck Pain group: Dominant hand 74.83 and Non-Dominant hand 81.61)

MNF: Mean Power Frequencies
RMS: Root Mean Square
DOM: Dominant hand
NON-DOM: Non Dominant hand

Flexion Relaxation Ratio (FRR)

One of the neck pain patients and two healthy control participants had EMG traces with a high level of background noise throughout the flexion-relaxation tasks to the point that either onset or offset of silenced periods were indistinguishable. Therefore, their results were excluded from the calculations of the FRR, offset, and onset angles.

The FRR changed significantly from the pre to the post fatigue trials ($F_{1,40}$=21.38 of time, p≤0.0001). There was a significant decrease in FRR from control to the NP participants ($F_{1,40}$ =38.25 of time, p≤0.0001). For both groups, there were no significant differences in FRR from dominant to non-dominant side (F1,40 =0.29 of time, P=0.594). At baseline, the FRR for both the dominant and non-dominant sides differed between the control (4.21±1.63, 4.73±1.84) and NP (2.06 ± 0.49, 2.42 ± 0.47) participants. Following fatigue, the FRR decreased for the healthy control group (2.36 ± 0.69, 3.2 ± 0.79) and slightly increased for the NP patients (2.29 ± 0.6, 2.68 ± 0.73) Figure 15.

The healthy controls had higher FRR than the NP patients. For the control group, the mean of FRR from pre to post fatigue declined on the dominant side from 4.21 ± 1.63 (95% CI: 3.42-4.98) to 2.36 ± 0.69 (95% CI: 1.93-2.79) and on the non-dominant side from 4.73 ± 1.84 (95% CI: 3.95-5.51) to 3.2 ± 0.79 (95% CI: 2.77 – 3.64). For the NP group, the mean of FRR from pre to post fatigue trials increased on dominant side form 2.06 ± 0.49 (95% CI: 1.28-2.84) to 2.29 ± 0.6 (95% CI: 1.86-2.72) and on the non- dominant side from 2.42 ± 0.47 (95% CI: 1.64-3.2) to 2.68 ± 0.73 (95% CI: 2.25-3.11). In addition, there were no significant interaction in FRR from pre to post fatigue on Dominant and non- Dominant hand between control and NP participants ($F_{1,40} = 0.21$ of time, $p \leq 0.646$) Figure 15.

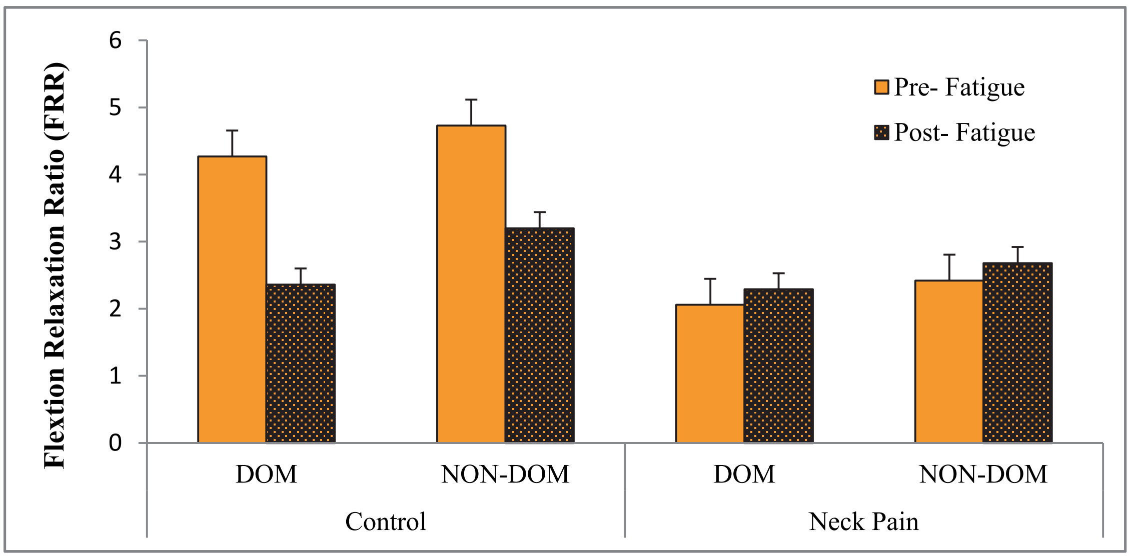

Figure 15: Flexion Relaxation Ratio (FRR)
FRR of dominant and non- dominant hands, pre and post fatigue trials for both Control and neck pain participants

Onset and Offset angles of silent period

A significant effect of muscular fatigue was found for both FRP onset and offset angles of the silent period on the cervical extensor muscles. The onset and offset angles of silent period significantly declined from pre to post fatigue flexion- relaxation trials for both the NP and healthy control participants ($F_{1,40}$=5.69 of time, p=0.001). However, there were no significant differences in onset and offset angles between NP and healthy controls (F1,40=1.57 of time, p=0.21). The onset angle of myoelectric silence decreased following fatigue for the healthy group from 43.40 (95% CI: 38.83-47.96) to 36.50 (95% CI: 31.94-41.07) and for the NP group from 42.71 (95% CI: 38.18-42.27) to 33.90 (95% CI: 29.34-38.47). The offset angle decreased following fatigue in the healthy group from 48.60 (95% CI: 42.21-55) to 46.07 (95% CI: 39.68-52.47) and for the NP group from 46.38 (95% CI: 39.99-52.78) to 40.94 (95% CI: 34.54-47.33) Figurer 16 (A-B). In addition, there were not significant interaction in onset and offset angles between NP and healthy controls groups from pre to post fatigue trials (F1,40=0.97 of time, p=0.75)

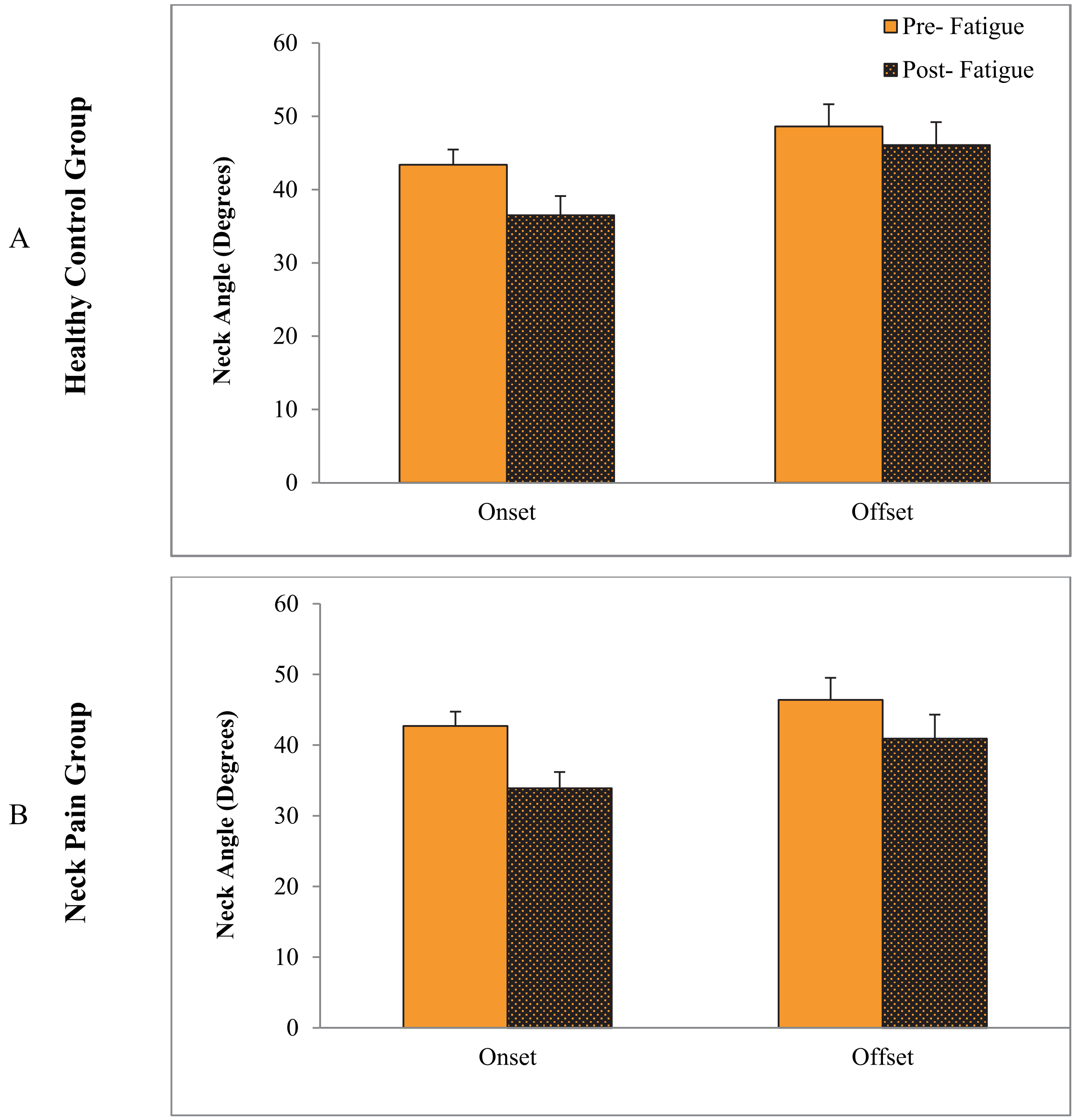

Figure 16 (A,B): Onset and Offset Angles of the Silent Period
Onset and Offset angles for both pre and post fatigue conditions for the neck pain group (A) and the healthy control group (B).

Discussion

A decrease in MNF as a result of muscle fatigue is considered to be significant when the final value is less than 8% of the preliminary result (Öberg et al. 1990). The MNF from the first to the last fatiguing contractions for both groups was equivalent to at least an 8% drop from initial value. In addition, the increase in RMS from the first to the last trials for both groups demonstrates that the repeated submaximal contractions were sufficient to generate fatigue of the CEM. The NP group showed similar decreases in MNF and increases in RMS after a much shorter time with lesser number of contractions, which suggests that physiological differences in the ability to resist fatigue exits in the NP group.

In addition, for both the healthy controls and NP pain participants the FRR for the non-dominant side of the body was higher than on the dominant side in both the pre and post fatigue conditions. It is documented that the dominant limb is generally able to generate greater force than the non-dominant limb (Ertem et al. 2005). In our study, between all participants, only two were strongly left handed and two were ambidextrous. The majority of the participants were strongly right handed and used preferentially the right upper limb in their daily activities. The MNF was lower for the CEM on the dominant side than the non-dominant both before and after fatigue (Figure 11). This suggests that the dominant side may have to work harder during day to day activities to stabilize the neck during upper limb movements.

In this study, for both the right and left CEM, the FRR for the healthy controls pre fatigue was significantly higher than for the NP patients. These results are consistent with previous findings by Murphy et al. (2010) who also compared NP to controls (Murphy et al. 2010). They reported that the cervical FRR can be used as a reliable marker for altered neuromuscular functions in NP populations, even in the absence of pain or in cases of mild disability (Murphy et al. 2010), and can be employed to distinguish the healthy individuals from the NP patients (Murphy et al. 2010, Maroufi et al. 2013). Similarly, it is also documented that low back patients (LBP) have a lower lumbar extensor FRR in comparison to pain free participants (Gupta 2001). It has been suggested that passive structures may become damaged and the altered load sharing between active and passive tissues in neck pain patients might put the previously injured structures at a risk of greater injury when performing prolonged or repetitive activities to fatiguing efforts (Nimbarte et al. 2014). The FRR is represented as a numerical ratio and reported as a lack of silence or lower values in full forward flexion in those with lumbar spine disorders as compared to healthy controls (Marshall and Murphy 2006, Ning et al. 2011). Full relaxation during flexion does not happen in NP patients due to either increased stretch sensitivity (Marshall and Murphy 2006) and in full forward cervical flexion chronic neck pain participants have shown a lack of myoelectric silence compare to healthy individuals (Marshall and Murphy 2006). Maroufi et al (2013) found relaxation of the cervical ES muscles in 85.7% of healthy and in only 36.3% of chronic NP patients. This confirms the concept that NP patients have some inability in relaxing their CEM during full forward flexion. The authors also reported that the surface EMG activity of the cervical ES in chronic NP patients was higher during movement than for the control group. The higher extensor activity may represent an altered pattern of motor control that enhances the activity of the cervical ES muscles to protect the spine from further injury in full forward neck flexion (Maroufi et al. 2013). Finding from our study are in accordance with previous findings of a lower FRR in NP patients compared to healthy controls.

The control group showed decreases in both the right and left CEM FRR following fatigue. The results of this study are similar to those who used a below- knee assembly task for healthy participants to fatigue the cervical and lumbar musculature and demonstrated a significant decline in the cervical FRR following fatigue (Shin and Yoo 2014). This is in keeping with the findings of Nimbarte et al (2014) who performed a study on healthy individuals and when fatiguing the CEM, with a neutral shoulder position, the FRR significantly declined following fatigue (Nimbarte et al. 2014). Interestingly, the NP patients in fact showed some increases in their FRR for both right and left CEM following the fatigue task. The FRR can decrease either due to increased EMG activity in the relaxation phase compared to the re-extension phases or decreased EMG activity in the re-extension phases compared to the relaxation phase (Granata et al. 2005, Othman et al. 2008).

Seven of our NP participants reported some muscular discomfort and extra pain in their cervical region after the fatigue task for up to two to three days later. Prolonged submaximal muscular contraction impairs oxygen transportation that might be associated with muscle pain and injury (Callaghan and Dunk 2002). Muscle fatigue is partially triggered by failure release of sarcoplasmic reticulum Ca2+ (Allen 2004). Fatigue alters the concentrations of lactic acid and calcium ions to the point of destructive muscle fiber excitation contraction coupling. Therefore, the motor unit firing rate increases to maintain the same force generation in isometric muscular contractions (Allen 2004, Nimbarte et al. 2014). Increases in the FRR in this group might be from muscular stiffness, pain, or injury in the cervical region or higher myoelectric activities in the active phases in comparison to the relaxation phase. In comparison to pre fatigue, the CEM activity was increased in the relaxation phase, which was expected. However, the activity in the re-extension phase was also higher than during the pre-fatigue trials. Consequently, the FRR, which compares the maximum EMG activity during re-extension to the average EMG activity during relaxation (Marshall and Murphy 2006, Murphy et al. 2010, Ning et al. 2011), showed a slightly increased ratio following fatigue for the neck pain patients.

During the exertions of isometric cervical extension the forceful CEM are Semispinalis Capitis and Cervicis, Upper Trapezius, Splenius Capitis, Multifidus (Choi and Vanderby Jr 2000). The Erector Spinae muscles are responsible for slow and constant contractions with smaller force productions, and they contain a greater number of slow twitch (type I) fibres due to their function as postural control (Mannion et al. 1997). Slow twitch fibres increase in back extensor muscles from lumbar to thoracic areas (by approximately 30%) (Mannion et al. 1997). In addition the Longissimus and Multifidus muscles in the lumbar region (Thorstensson and Carlson 1987) and the cervical flexor muscles, Multifidus and Longus Colli, at the level of C5-C7 (Boyd-Clark et al. 2001) also contain a significantly greater number of slow twitch, fatigue resistant (type I) fibres than fast twitch (type II) fibres in healthy participants.

Sternocleidomastoidand (SCM) and the anterior Scalenes activity following a fatiguing contraction with 25% and 50% MVC, was investigated between chronic NP patients and a control group (Falla et al. 2003). The slope of the MNF of NP patients was greater than the control group, which suggested an increase in number of fast twitch fibers and greater fatigability of the cervical flexor muscles in NP patients due to decrease in tonic holding ability of muscles (Falla et al. 2003). These results are coincident with the idea that a smaller number of slow-twitch fibres increase the rate of fatigue and increases the slope of the Median Frequency (Mannion et al. 1998). Another study investigated paraspinal Multifidus muscle fibre type at the level of L3- L4 and found that the LBP group had a greater proportion of fast twitch fibres than slow twitch fibres, compared to a control group (Mattila et al. 1986, Mannion et al. 1997). The fast twitch muscle fibers get atrophied in LBP patients, which render their back extensor muscles to be less fatigue resistant than healthy controls (Saltin and Gollnick 1983, Mannion et al. 1997, Mannion et al. 1997).

The mechanism of the FRP is defined as transferring the extension moment force from active superficial para-Spinal muscles to deeper muscles or passive structures of the spine (viscoelastic, ligaments, tendons, intervertebral disks, vertebral bones, and fascia) (Pialasse et al. 2009, Maroufi et al. 2013). In forward trunk flexion, posterior muscles work harder and the passive tissues stretch to silence the muscle forces to prevent the trunk from uncontrolled forward bending (Burnett et al. 2009). In order to maintain forward trunk flexion, afferent feedback from passive structures leads to reduced or silence of the extensors due to stretch reflex inhibition (Olson et al. 2004). Pain can lead to altered motor control and load transferring between tissues (Maroufi et al. 2013). The increased FRR in NP patients after fatigue suggests altered neuromuscular activity which has been associated with increased excitation of superficial and inhibition of deep neck extensor muscles (Maroufi et al. 2013).

The FRR has been comprehensively examined in the low back Erector Spinae muscles. The FRR can be changed in response to therapeutic interventions. Some improvements were reported in the relaxation phase (decreases in myoelectric activity) following an exercise intervention and spinal manipulation in LBP (Othman et al. 2008, Murphy et al. 2010), and NP patients (Murphy et al. 2010). The FRP in chronic LBP patients can be improved under rehabilitation treatment (Neblett et al. 2003). After a 12-week exercise intervention and manipulation on LBP patients, significant improvements were seen in FRR by approximately a 67% decline in the relaxation activation and almost no changes in the active components (Marshall and Murphy 2006). In a comparison between chronic low back pains (CLBP) patients and asymptomatic individuals, where the CLBP group received lumbar spinal manipulation and the control group have rested in a side-lying, the CLBP patients who received spinal manipulation demonstrated a significant decrease in EMG activity in full forward trunk flexion compared to the control group. It was concluded that lumbar spine manipulation can control neuromuscular reactions of the lumbar spine even for a brief period of time (Lalanne et al. 2009). Therefore, if treatment can improve the FRP by a decline in EMG activity in relaxation phase, fatigue might play an opposite role in spinal stabilization with increases in EMG signals on relaxation and active phases similar to the finding of this study for NP patients.

This current study demonstrated that both onset and offset angles of the silent period declined following the fatigue, resulting in expansion of silence period by earlier onset and later offset angles. The fatigued CEM are unable to stabilize the cervical spine and transfer the load to the passive structures and deeper neck muscles in full forward flexion. It causes appearance of muscular silence with an earlier onset during the flexion moment and a later offset during the extension moment resulting in a longer duration of the silent period (Nimbarte et al. 2014).The CEM fatigue altered the phases of FRR timing by increasing the duration of myoelectric silence period during cervical flexion-extension tasks. In the relaxation phase, increased firing rate of motor units augments muscular activation (Nimbarte et al. 2014).

The results of this study are consistent with Panjabi's theoretical model of spinal stability that by fatiguing one of the spinal stabilizing system (neural, passive, active), the other two systems will compensate for it. Therefore, earlier onset following the CEM fatigue is an indicator of transferring the load sharing from the active to the passive and neural control systems to balance destabilizing forces sooner in full forward flexion and later in extension moments (Panjabi 1992, Panjabi 1992). The results of this study are similar to those of (Nimbarte et al. 2014) who fatigued the neck muscles by subjecting the head and neck to gravity and Barker (2011) who performed a maximum isometric CEM contraction for duration of 30 seconds. Both of these studies reported some level of decrease in offset and onset angles following fatigue.

An increase in muscular silence period during a cervical flexion-extension task is similar to that described in the lumbar region, which either used an isometric contraction (Descarreaux et al. 2008) or prolonged cyclic lumbar flexion to fatigue the low back musculature (Olson et al. 2004). In the lumbar spine, prior to fatigue the superficial back muscles, and following fatigue the deeper back muscles were more involved to initiate the trunk extension (Descarreaux et al. 2008). The cyclic or static flexion decreases the stability of passive articular tissues and increases creep development in lumbar viscoelastic tissues (Solomonow et al. 2003, Olson et al. 2004). A study by Pialasse et al. (2010) documented that an augmented cervical load incremented both the offset and onset angles of the FRR, and there were no significant effect of speed on both onset and offset angles, but speed increased the RMS values in the extension phase. Therefore, in the current study, to eliminate any possibility of creep development, which decreases the ability of the passive structures to generate the desired force to stabilize the spine (Solomonow et al. 2003), a submaximal isometric contraction in neutral posture was used to fatigue the CEM. In addition, using the metronome created a constant pace for all participants to have the same speed on all FRR cycles.

Consequently, healthy participants performed the CEM contractions for a longer duration than NP patients. The NP group may have had physiological changes that reduced their ability to hold the contractions for an extended period of time. Muscle pain and fatigue may have increased the activity of muscle spindles. The CNS increases muscle stiffness by increasing the myoelectric activity to maintain spinal stability (Cholewicki and McGill 1996, Cholewicki et al. 1997). Although the self-perceived levels of functional disability, obtained from NDI self-report questionnaire, placed the NP participants in the mild to moderate disability category at the beginning of experiment, they did not stop due to pain but due to an inability to hold the contraction, suggesting differences in the ability to hold a fatiguing contraction in people with recurrent neck pain.

Strength of study:

It has been suggested that the lumbar and cervical FRR can be used as a reliable and reproducible measurement to discriminate between healthy subjects and chronic low back pain patients (Marshall and Murphy 2006, Murphy et al. 2010). Previous studies explored low back FRR in both healthy and chronic back pain populations (Murphy et al. 2010). Also, the effect of cervical fatigue in the FRR was examined in healthy individuals (Barker 2011). However, this current study is the first to examine altered timing in the phases of neck FRR as produced by submaximal CEM fatigue in subclinical neck pain patients. The concepts of this research demonstrate that the cervical FRR can be applied as an indicator for neuromuscular function which is altered by fatigue.

Repetitive submaximal contractions with 70% MVC were sufficient to fatigue the CEM on all participants. A few of the healthy participants had previously been involved in a study where they fatigued the CEM by pulling back on a head strap and they reported that pushing back on the force transducer was more comfortable and they were better able to perform the task, being limited by fatigue rather than discomfort.

Limitations of the Study

The wireless surface electrodes were very sensitive and would sometimes record a lot of noise in addition to signal, making it challenging to determine EMG onset and offset in some participants. Another issue is that the wireless electrodes have a 10 mm inter-electrode distance whereas a lot of previous work has recorded from a 20 mm inter-electrode distance, meaning that the wireless electrodes reflect activity from a smaller surface area.

Conclusion:

The results of this experimental investigation indicate that cervical muscular fatigue is a modulator of the cervical FRR, which may play a significant role in insufficient stabilization of the cervical spine and surrounding structures. Fatigue, even for a short period of time, might alter the stability of the cervical spine by employing the load to the passive tissues and substantially increasing the activity of the muscles to maintain stability. The FRR can be altered by submaximal fatigue and fatigue can increase the duration of the period of myoelectric silence in the relaxation phase by earlier onset and later offset angles of the silent period, placing greater load on passive structures and potentially placing them at risk of injury.

SECTION 4

Thesis Summary

Dependence on computer technologies is growing very fast in many societies. Sedentary life style is one of the main causes of musculoskeletal disorders in the general population. Neck, shoulder and back pain are the most frequently reported medical problems, which put a great burden on healthcare organizations and can decrease an individuals performance and their quality of life at home, work, and school. In daily activities, neck muscles are critical for stabilizing the cervical spine and for postural balance. To stabilize the cervical spine requires a very complex combination of active and passive components work together, and their performance might be altered by injury, pain, or fatigue. Neck muscles with a high density of sensory receptors contribute to the reference frame or internal body map which contributes to the sense of upper limb joint position. Therefore, cervical muscular fatigue altered the sensory inputs to the CNS and impairs the joint proprioception.

Neck pain patients frequently complain of reduced endurance and strength in their neck muscles, but it is unclear whether this is due to altered neuromuscular factors or lack of use due to the pain. The flexion relaxation phenomenon is one method to explore the EMG activity of the cervical extensor muscles in neck flexion–relaxation tasks. In pre- fatigued trials, healthy individuals have reduced myoelectric activities on full forward cervical flexion, which this phenomenon has not happened in neck pain patients. This might be used to discriminate the neck pain patients from healthy individuals prior to performance of fatigue protocol. Postural alterations can impact upper limb performance and fatigue can have a negative impact on the stabilization mechanisms of the neck; however, still little is known on the direct effect of CEM fatigue on upper limb JPS and cervical FRP.

The experimental investigation in this research developed a submaximal fatigue protocol to evaluate CEM. In study one, fatigue altered the ability to recreate a previously presented elbow joint angle and in study two it had a significant effect on the FRR, discriminating the neck pain patients from healthy individuals. Generally, these two studies suggest that altered afferent input from the neck, subsequent to fatigue, may impair upper limb proprioception and cervical neuromuscular function.

A number of limitations were acknowledged with the design and instrumentation in these two studies that in future research is better to be considered. In addition, a larger investigation needs to be conducted to explore the effects of postural changes of the head on JPS and FRR before and after fatiguing CEM.

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SECTION 5

APPENDICES

APPENDIX 1: Neck Disability Index (NDI)

Neck Disability Index

This questionnaire has been designed to give your therapist information as to how your neck pain has affected your ability to manage in everyday life. Please answer every question by placing a mark in the **ONE** box which applies to you. We realize that 2 of the statements may describe your condition, but please mark only the **ONE** box that most closely describes your current condition.

SECTION 1 - PAIN INTENSITY
☐ I have no neck pain at the moment.
☐ The pain is very mild at the moment.
☐ The pain is moderate at the moment.
☐ The pain is fairly severe at the moment.
☐ The pain is very severe at the moment.
☐ The pain is the worst imaginable at the moment.

SECTION 2 - PERSONAL CARE
☐ I can look after myself normally without causing extra neck pain.
☐ I can look after myself normally, but it causes extra neck pain.
☐ It is painful to look after myself, and I am slow and careful
☐ I need some help but manage most of my personal care.
☐ I need help every day in most aspects of self -care.
☐ I do not get dressed. I wash with difficulty and stay in bed.

SECTION 3 – LIFTING
☐ I can lift heavy weights without causing extra neck pain.
☐ I can lift heavy weights, but it gives me extra neck pain.
☐ Neck pain prevents me from lifting heavy weights off the floor but I can manage if items are conveniently positioned, ie. on a table.
☐ Neck pain prevents me from lifting heavy weights, but I can manage light weights if they are conveniently positioned
☐ I can lift only very light weights.
☐ I cannot lift or carry anything at all.

SECTION 4 – READING
☐ I can read as much as I want with no neck pain.
☐ I can read as much as I want with slight neck pain.
☐ I can read as much as I want with moderate neck pain.
☐ I can't read as much as I want because of moderate neck pain.
☐ I can't read as much as I want because of severe neck pain.
☐ I can't read at all.

SECTION 5 – HEADACHES
☐ I have no headaches at all.
☐ I have slight headaches that come infrequently.
☐ I have moderate headaches that come infrequently.
☐ I have moderate headaches that come frequently.
☐ I have severe headaches that come frequently.
☐ I have headaches almost all the time

SECTION 6 – CONCENTRATION
☐ I can concentrate fully without difficulty.
☐ I can concentrate fully with slight difficulty.
☐ I have a fair degree of difficulty concentrating.
☐ I have a lot of difficulty concentrating.
☐ I have a great deal of difficulty concentrating.
☐ I can't concentrate at all.

SECTION 7 –WORK
☐ I can do as much work as I want.
☐ I can only do my usual work, but no more.
☐ I can do most of my usual work, but no more.
☐ I can't do my usual work.
☐ I can hardly do any work at all.
☐ I can't do any work at all.

SECTION 8 – DRIVING
☐ I can drive my car without neck pain.
☐ I can drive my car with only slight neck pain.
☐ I can drive as long as I want with moderate neck pain.
☐ I can't drive as long as I want because of moderate neck pain.
☐ I can hardly drive at all because of severe neck pain.
☐ I can't drive my car at all because of neck pain.

SECTION 9 – SLEEPING
☐ I have no trouble sleeping.
☐ My sleep is slightly disturbed for less than 1 hour.
☐ My sleep is mildly disturbed for up to 1-2 hours.
☐ My sleep is moderately disturbed for up to 2-3 hours.
☐ My sleep is greatly disturbed for up to 3-5 hours.
☐ My sleep is completely disturbed for up to 5-7 hours.

SECTION 10 – RECREATION
☐ I am able to engage in all my recreational activities with no neck pain at all.
☐ I am able to engage in all my recreational activities with some neck pain.
☐ I am able to engage in most, but not all of my recreational activities because of pain in my neck.
☐ I am able to engage in a few of my recreational activities because of neck pain.
☐ I can hardly do recreational activities due to neck pain.
☐ I can't do any recreational activities due to neck pain.

PATIENT NAME ______________________________________ DATE ____________

SCORE _________ [50]

APPENDIX 2: Edinburgh Handedness Inventory (EHI)

Edinburgh Handedness Inventory[1]

Your Initials:______________

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: $R < -40$) (Ambidextrous: $-40 \le R \le +40$) (Right Handed: $R > +40$)		

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychololgia, 9, 97-113.