A systems-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion

by

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DEDICATION

I dedicate this dissertation to my parents and brothers, who are the most important to me. I want to let my friends know that I'm thinking about them while writing this part of my dissertation, and I want them to know that I'm happy to have them as my friends. I also dedicate this dissertation to all the people who gave me an opportunity to get a bit closer to the truth and accept the reality, no matter how different it could be from my desires, wishes, expectations, and imaginations.

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ABSTRACT

The objective of this research was to develop a systems-level characterization of the biomechanical response of the neck in flexion. Several preliminary studies formed a strong foundation to explore this research objective. First, a systematic review of the literature was conducted (Chapter 2) to evaluate the relationship between neck flexion and neck problems and define appropriate angular thresholds for neck flexion as a risk factor for neck problems. A review of 21 papers revealed a consistent positive correlation between neck flexion and neck problems. This systematic review found a neck flexion angle of 20º with the greatest support as the cut-off angle separating high- and low-risk neck flexion postures. This systematic review also helped identify the gaps in the research area: How much is known about the importance of the frequency and duration of the neck postural exposure for the development of neck muscle fatigue? How accurate is the neck postural exposure defined in the previous studies and work assessment tools? What role do passive tissues (ligaments, fascia, etc.) play in the support of the neck in flexion postures? From this systematic review, two additional research questions were developed. The first research question was, "What are the effects of different work-rest cycles on neck muscle fatigue during static neck flexion tasks?" The second research question was, "What role do the passive tissues play in the support of the head/neck during flexion postures?"

The first research question was evaluated in our second preliminary study (Chapter 3). The main goal was to investigate the impact of varied work-rest intervals and how they can affect the development of neck and shoulder muscular fatigue (evaluated using surface electromyography (sEMG)) during a simple standing task that required static neck flexion. Participants maintained a 45º neck flexion posture for a total of 60 minutes and were provided three minutes of rest distributed in different ways throughout the experiment [LONG (one, three-

minute break), MEDIUM (two, 1.5-minute breaks), or SHORT (five, 36-second breaks)]. Results of the analysis of the EMG data revealed that the SHORT condition did not show increased activity, while LONG [21% increase] and MEDIUM [10% increase] did, providing objective data supporting the guidance of short, frequent breaks to alleviate fatigue. Our results may provide insights into the development of an optimal work-rest cycle strategy that minimizes fatigue but does not affect the work performance negatively.

Chapter 4 was a paper that focused on an important methodological consideration in performing EMG-based studies. When performing an experiment across several days, normalization of EMG is an important procedure to control for the day-to-day variability. Performing maximum voluntary contractions on each of these days is problematic, particularly for sensitive regions of the body like the cervical spine. The study outlined in Chapter 4, provided a novel method for predicting maximum voluntary contraction EMG through the extrapolation of submaximal voluntary contraction EMG values. The results of this study showed promise for creating a margin of safety for those that conduct research on the cervical spine that requires multiple days of data collection.

The final and primary contribution of this dissertation (Chapter 5) investigated the second research question that focused on the exploration of the role of passive tissues in the support of head/neck. The main goal was to explore the biomechanical differences (considering both active and passive tissues) between neck flexion when it is defined relative to the trunk vs. when it is defined relative to gravity. In the first experimental procedure, the flexion-relaxation phenomenon (FRP) of the cervical spine was investigated when the participant was standing upright with their trunk at a neutral posture and then when they leaned against a fixture that generated a 45º of trunk flexion posture. In the second experimental procedure, the fatigue of cervical musculature during a 30-minute static neck flexion task was studied. Two scenarios were defined and compared: 1) head and neck are flexed so that head is at 45º flexion relative to trunk while the trunk is standing upright (called "HN-45"), and 2) head and neck are not flexed relative to trunk, while trunk is flexed 45º (called "T-45"). The EMG activity of the cervical spine muscles were collected to investigate the pattern of the neck muscle activity during the FRP task and the neck muscles fatigue during the static neck flexion task. The EMG data during the first three minutes of the static neck flexion task were used as inputs into an EMG-assisted biomechanical model of the cervical spine to compute joint reaction forces at C4/C5 level. Also, a discomfort (neck, upper back, and lower back) and overall fatigue survey recorded the subjective evaluation of the static neck flexion task. The results showed that the cooperation between neck muscles and passive tissues will happen with and without 45º of trunk flexion. The findings also revealed that the T-45 condition causes higher neck muscle fatigue and neck subjective discomfort compared to the HN-45 condition during static neck flexion, indicating an important role of the passive tissues in this condition. The long-term effects of these two conditions is not clear as the difference in the role of passive tissues in holding these postures may have negative implications for neck health. The neck C4/C5 joint reaction compression force was the same for conditions HN-45 and T-45, while the joint reaction shear force was significantly higher in condition T-45 compared to condition HN-45.

The importance of a system-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion was presented. The cervical spine was not investigated separately, but the combination of head/neck and trunk were explored in sagittal plane flexion postures. Also, active and passive tissues were both considered in our evaluation. The work assessment tools should note that the body segments shouldn't be assessed separately. For example, trunk flexion can lead to neck muscle fatigue; however, the neck might be in a neutral posture relative to trunk. From the findings of this study, we recommend that the work assessment tools should consider both neck flexion relative to trunk and neck flexion relative to gravity in their assessment of neck postural exposure. Also, in implementing ergonomic interventions, the human body should be considered as a linkage. For example, if the height of a workstation is adjusted to decrease trunk flexion angles, it would affect neck postural exposure too.

CHAPTER 1. GENERAL INTRODUCTION

Motivation

While working on a project at Mayo Clinic as an intern during summer 2019, it was noted that neck pain and discomfort was a prevalent problem among surgeons. My responsibility as a graduate intern was to collaborate in an experiment that was designed to study surgeons' postures during different surgeries. As a part of that project, surgeons' neck postural data were collected using inertial measurement units (IMUs), which enabled the continuous recording of the postures. Using these continuous data, risk scores were calculated for neck postural exposure not only based on the angles but also according to the pattern of the postures (frequency and duration of each posture). Thus, a risk score for the neck was suggested based on neck angles while the contribution of the duration and frequency of the postures were included in our calculations, too. Also, subjective neck discomfort scores were collected using questionnaires scaled from 1-20 before and after surgery. The correlation between these risk scores and subjective discomfort scores were evaluated. Analyzing the data for 41 vascular surgeries led to interesting results that showed significant correlations between neck postural risk scores and neck discomfort scores. The results were interesting, but they raised important questions: What does the previous literature tell us about a correlation between neck postural exposure and neck problems? Can we define cut-off angles for neck postural exposures regarding neck problems? What are the gaps in this research area? How much do we know about the importance of the frequency and duration of the neck postural exposure for the development of cervical muscle fatigue? How accurate is the neck postural exposure defined in the previous studies and work assessment tools? What role do passive tissues (ligaments, fascia, etc.) play in the support of the neck in flexion postures? In order to answer these questions, the first step was to conduct a systematic review (Chapter 2) of the literature. This systematic review not only provided some answers for our research questions, but it also identified gaps in this research topic. Consequently, three studies were designed and performed in an effort to clarify these unknowns (Chapters 3-5). Chapter 3 explores the role of different work-rest cycle strategies on neck muscle fatigue developed during a static neck flexion task. Chapter 4 is a methodology paper that seeks to develop a regression model that estimates the muscle maximum voluntary contraction (MVC) EMG based on the EMG elicited during submaximal voluntary contractions (SVCs). Our motivation was to develop a method to avoid multiple neck MVCs exertions across days and thereby reduce the risk of injury to our human participants. Chapter 5 studies the biomechanical difference (considering both active and passive tissues) between neck flexion relative to trunk and neck flexion relative to gravity. Before reviewing the results of this scientific journey throughout this dissertation, it would be very helpful to review the basic and required information about the cervical spine. The remainder of Chapter 1 provides the readers with this information.

Cervical Spine and Neck Anatomy

Bones

The spine is a column of 33 bones, each named a vertebra. These 33 bones make up the vertebral column, which is divided into five segments: the cervical spine with seven vertebrae (C1-C7), the thoracic spine with twelve vertebrae (T1-T12), the lumbar spine with five vertebrae (L1-L5), the sacral curve or sacrum with five fused vertebrae (S1-S5), and the coccyx also known as coccygeal vertebrae with four fused bones. The first cervical vertebra is named the atlas (C1), and the second cervical vertebra is named the axis (C2). (Chaffin, 1999; Dorland, 2007; Gray, 1918). Figures 1.1-1.4 illustrate the spine, atlas, axis, and details of a typical cervical spine (from 1918 Gray's Anatomy).

Ligaments

Ligaments connect vertebrae through all levels of the spine. In general, these ligaments can be divided into five categories according to the parts that they are connecting: 1. Bodies of the vertebrae, 2. Lamina, 3. Articular processes, 4. Spinous processes, 5. Transverse processes. Figures 1.5-1.7 illustrate the spinal ligaments in more detail (from 1918 Gray's Anatomy).

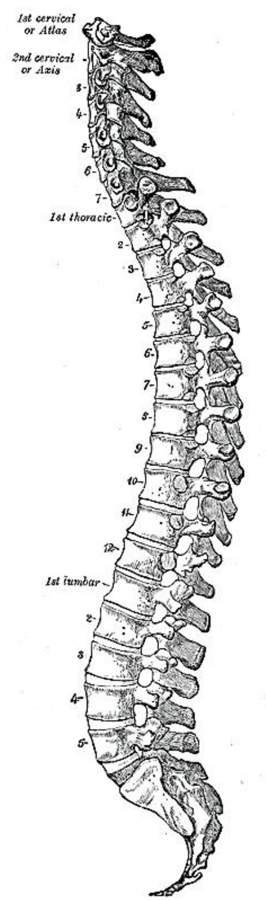

Figure 1.1 Lateral view of the vertebral column (from 1918 Gray's Anatomy)

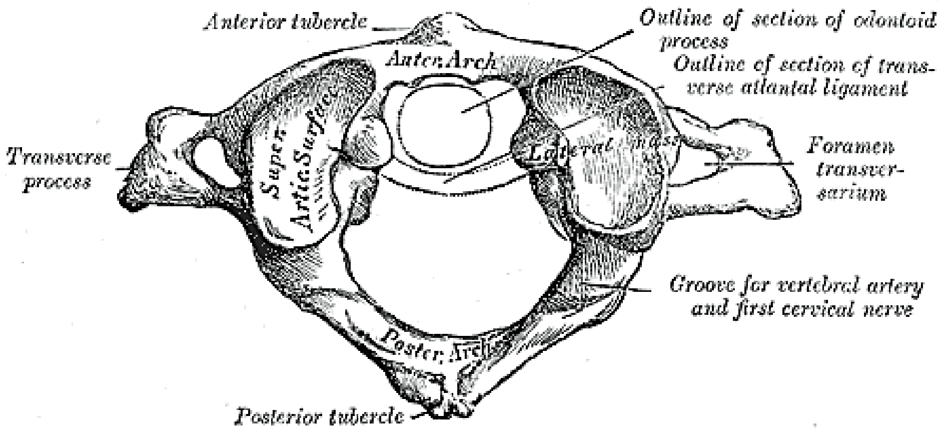

Figure 1.2 First cervical vertebra, or atlas (from 1918 Gray's Anatomy)

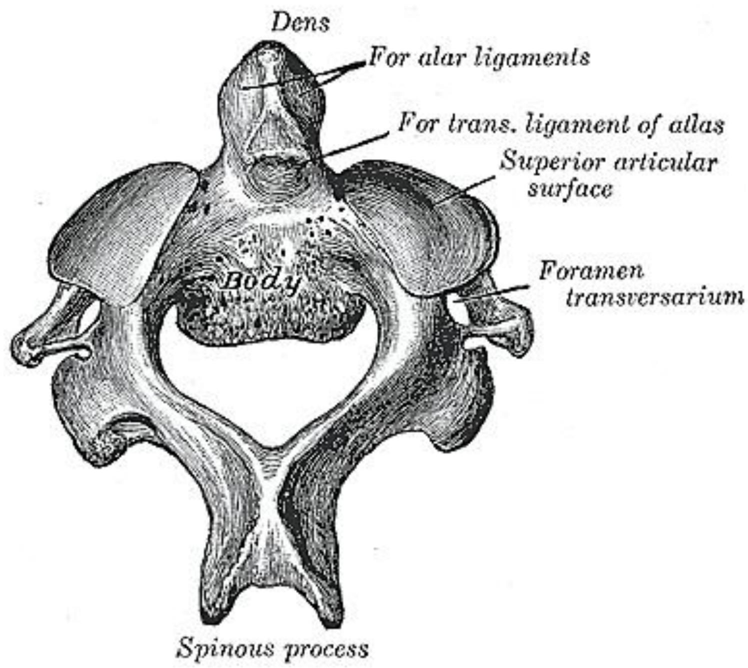

Figure 1.3 Second cervical vertebra, or axis, from above (from 1918 Gray's Anatomy)

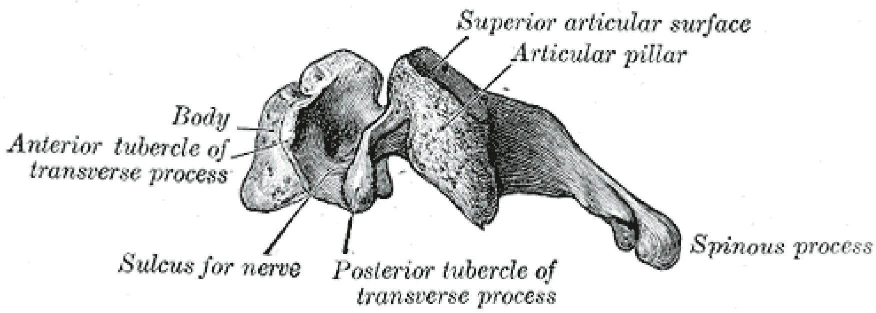

Figure 1.4 Side view of a typical cervical vertebra (from 1918 Gray's Anatomy)

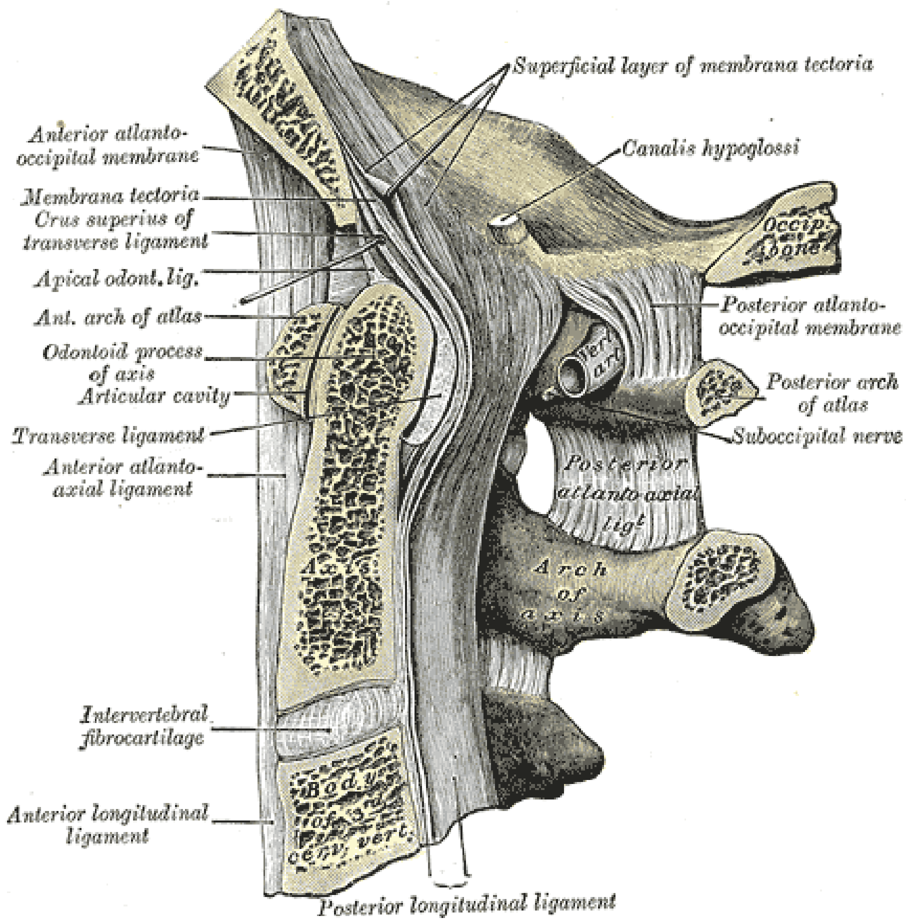

Figure 1.5 Median sagittal section through the occipital bone and first three cervical vertebrae (from 1918 Gray's Anatomy)

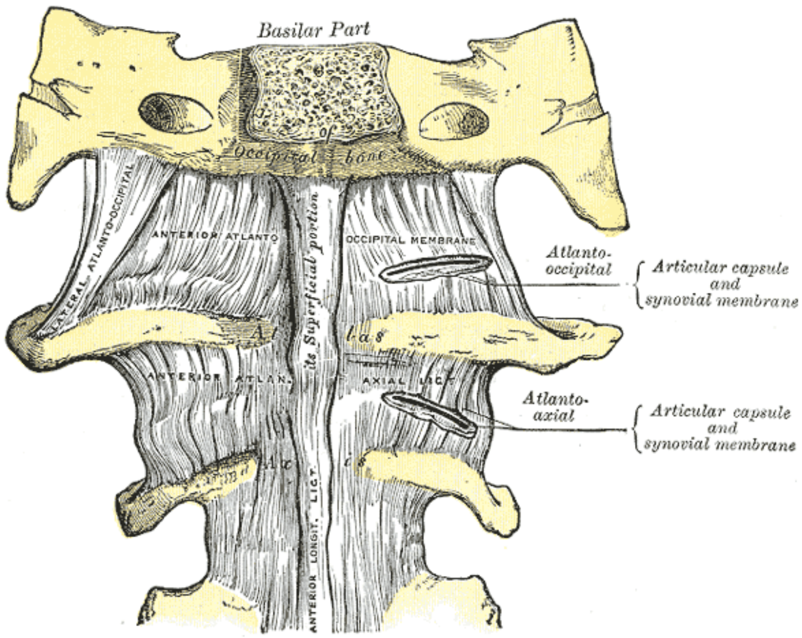

Figure 1.6 Anterior atlantooccipital membrane and atlantoaxial ligament (from 1918 Gray's Anatomy)

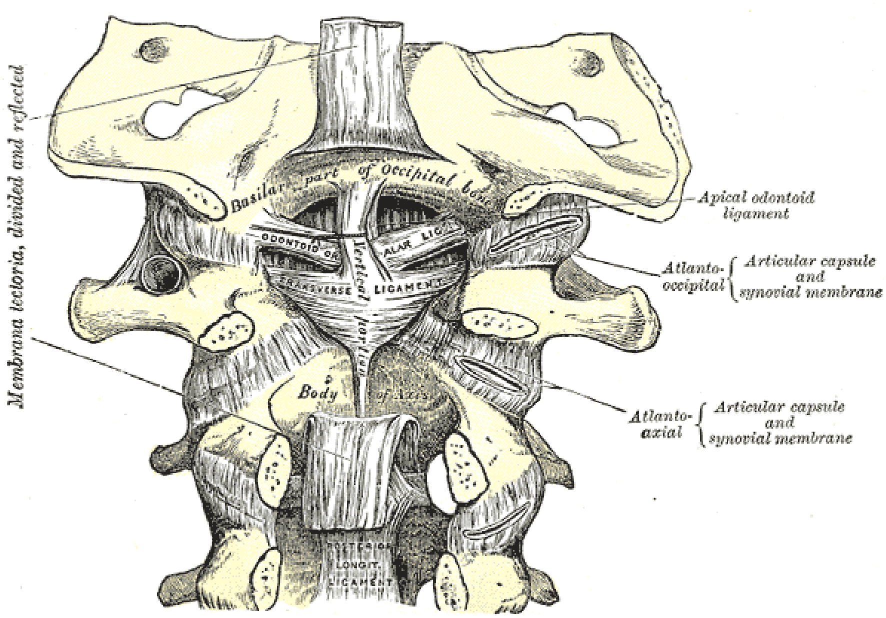

Figure 1.7 Occipitoaxial and atlantoaxial ligaments: posterior view (from 1918 Gray's Anatomy)

Muscles

Some of the neck muscles which are typically considered in ergonomics-focused research studies are as follows: sternocleidomastoid, trapezius, splenius capitis, splenius cervicis, semispinalis capitis, semispinalis cervicis, longissimus capitis, longissimus cervicis, levator scapulae, longus capitis, longus colli, obliquus capitis inferior, rectus capitis posterior major, scalenus anterior, scalenus posterior (Vasavada et al., 2008). Estimating the activity of these muscles is typically accomplished using electromyography (EMG) or optimization methods.

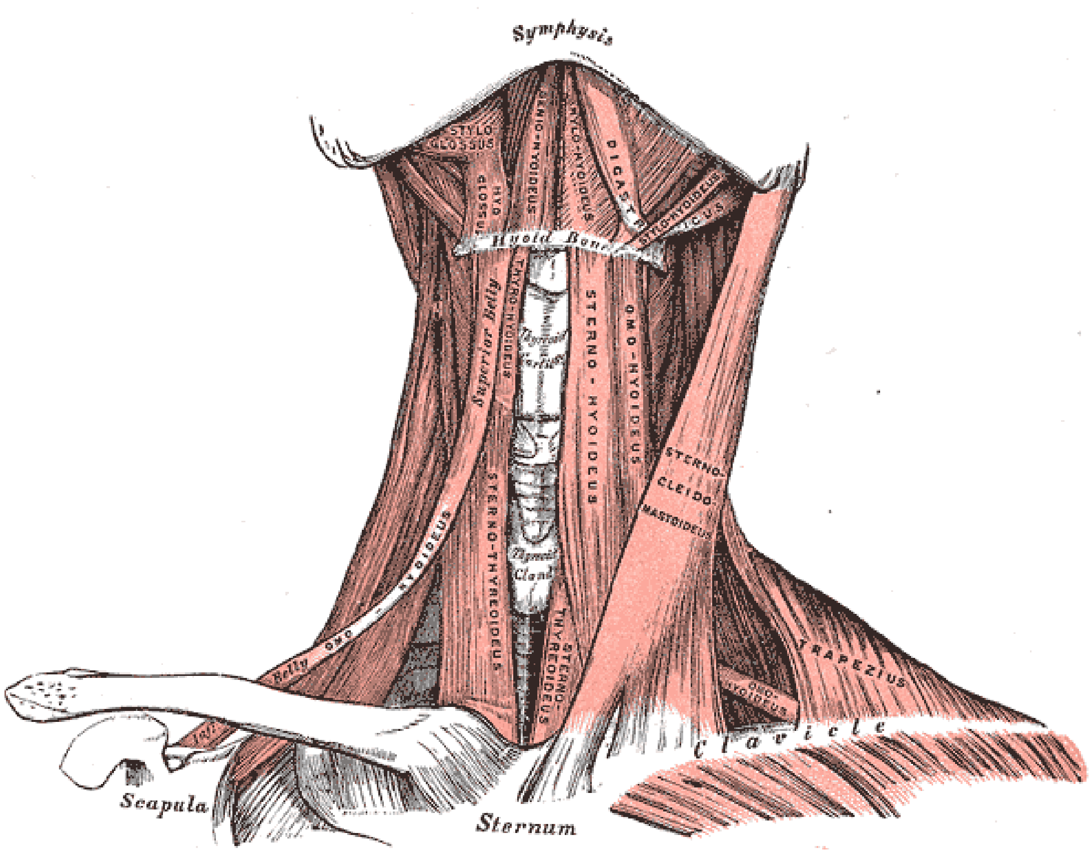

Figure 1.8 Muscles of the neck: Anterior view (from 1918 Gray's Anatomy)

Sometimes two or more muscles are evaluated together as a group of muscles; for example, in EMG-based biomechanical models, this approach may be used to simplify the model. Cervical spine and neck muscles have been illustrated in detail in anatomy books. Figures 1.8 and 1.9 present these muscles.

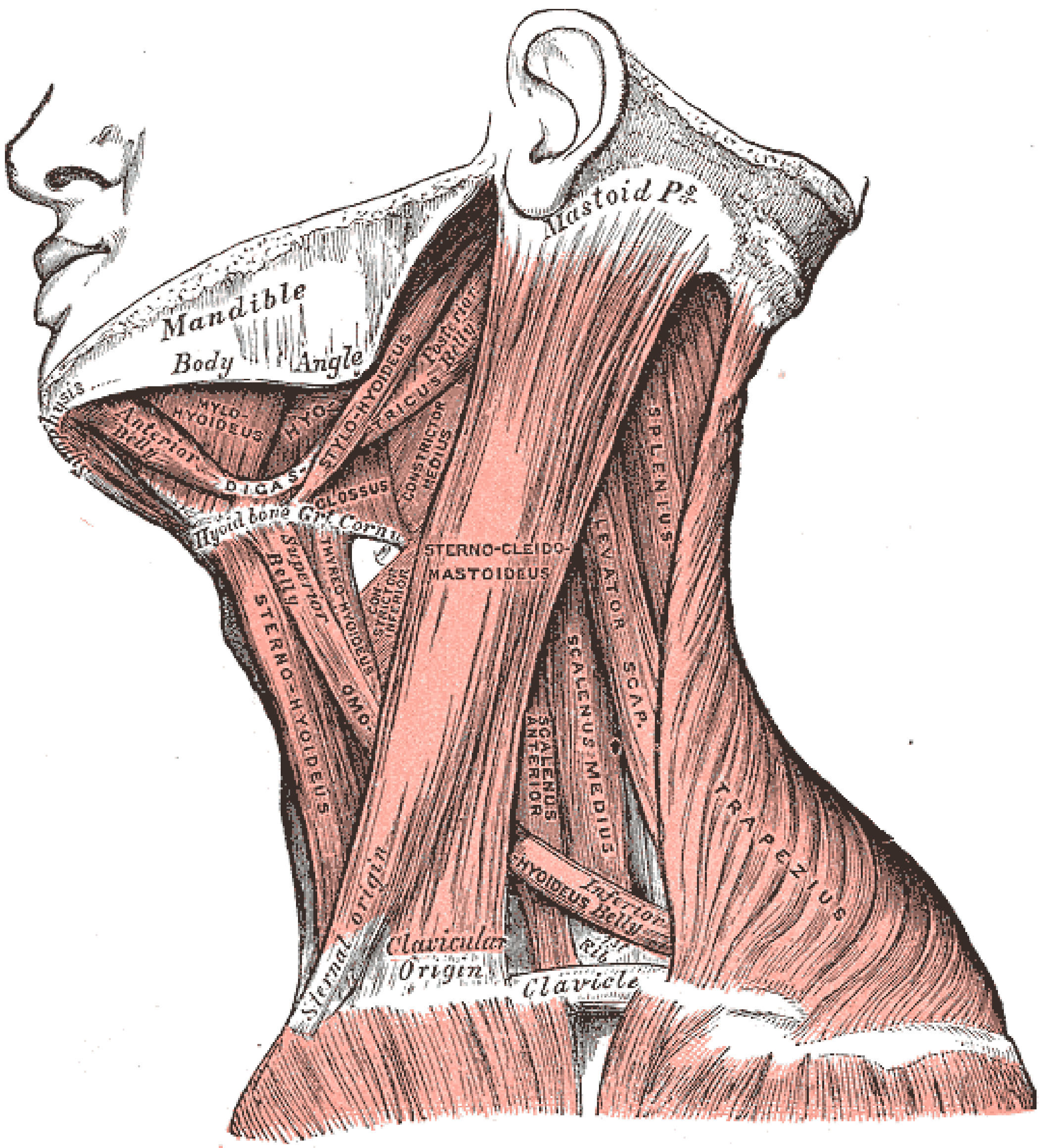

Figure 1.9 The anterior vertebral muscles (from 1918 Gray’s Anatomy)

Cervical Spine Disorders

The diversity in methods employed in epidemiology studies of neck problems makes it complicated to combine their results. Generally, it can be realized from these studies that it is a widespread problem that affects both general and specific occupational populations. This problem not only affects individuals' lives but also impacts their families, society, health care system, economy, and industry (Hogg-Johnson et al., 2008; Hoy et al., 2010). As a part of a study by Hoy et al. (2010), a systematic review on the prevalence of neck pain was conducted, and the mean overall prevalence of neck pain in the general population was found to be 23.1% with a wide range of overall prevalence from 0.4% to 86.8% which shows the variability in the results from different studies. This study revealed that the mean overall prevalence of neck pain was higher in high-income countries in comparison with middle- and low-income countries. Findings also showed that the mean prevalence in urban areas was higher than the prevalence in rural areas (Hoy et al., 2010). In general, the prevalence among females was higher than males. Also, they found that according to the reviewed studies, the prevalence of neck pain increases with age up to the age of 35-49 and then decreases after that (Hogg-Johnson et al., 2008; Hoy et al., 2010). In another study by Strine and Hootman (2007), the data from around 30,000 adults in the United States in 2002 at the age of 18 years or older showed that approximately 31% of U.S. adults had experienced low back and/or neck pain in the last three months including around 34 million with low back pain only (LBPO), 9 million with neck pain only (NPO) and 19 million with both low back and neck pain (LBPNP). The data analyses revealed that, in general, these conditions were higher among females and white non-Hispanics. Another interesting finding was that the prevalence of LBPO and LBPNP decreased by an increase in the educational level while the prevalence of NPO increased with an increase in educational level (Strine and Hootman, 2007). The financial burden for low back and neck pain in the United States in 2013 was estimated as high as $87.6 billion, which showed an increase of $57.2 billion over the previous 18 years (Dieleman et al., 2016).

Risk Factors for Neck Problems

Recent studies on work-related musculoskeletal disorders (WMSDs) demonstrate that a wide range of possible risk factors has been evaluated (Holmstorm et al., 1992; U.S. Department of Health and Human Services, 1997). The possible risk factors include individual and personal factors such as age, and gender, psychosocial factors such as job satisfaction, social support, and stress, and physical factors such as posture, force, and repetition (Holmstorm et al., 1992; U.S. Department of Health and Human Services, 1997; Hogg-Johnson et al., 2008; Hoy et al., 2010). In terms of individual and psychosocial factors for neck problems, as noted previously, it has been found that the prevalence of neck pain is higher among females while regarding age, the prevalence of neck pain increases with age up to the age of 35-49, and then it decreases (Hogg-Johnson et al., 2008; Hoy et al., 2010). Living in urban areas or rural areas, stress, job satisfaction, and social support are among the factors that have been found to be associated with neck and shoulder problems in the literature (Holmstorm et al., 1992; Hoy et al., 2010).

Physical factors

In a 1997 review study by the National Institute for Occupational Safety and Health (NIOSH), different risk factors at the workplace, including posture, force, repetition, and vibration for musculoskeletal disorders, were discussed. The reviewed literature was epidemiologic studies, and they discussed the work-related physical risk factors for neck and neck-shoulder problems. Here, the results of their study are discussed briefly (U.S. Department of Health and Human Services, 1997).

Posture

Strong evidence was found for the association between extreme or static posture and neck and neck-shoulder problems. The results of their review study showed a positive relationship between this risk factor and neck and neck-shoulder MSDs. However, the correlation between different postural exposures and neck problems was not concluded in this study. It implies the need for a new review to include more recent studies. It may add more evidence as well as more details to these findings.

Repetition

The association between repetitive work and neck and neck-shoulder problems was found in their review study, but most of their reviewed studies did not evaluate the neck repetition. They defined repetitive work as a repetitive movement in upper extremities that led to the load on the neck-shoulder area. The fact that in most of the studies, the repetitive movement of the neck was not evaluated casts doubt on the real correlation between neck repetition and neck MSDs.

Force

There was evidence for the association between forceful exertion and neck and neck-shoulder problems. In most of the reviewed studies, forceful work was defined regarding hand and arm activities, which led to loading on the neck-shoulder area. None of the studies evaluated forceful neck movements. It seems impossible to approve or disapprove an actual correlation between forceful neck movements and neck problems from this review study.

Vibration

Because of the lack of literature on the correlation between vibration and neck problems at the time of this review, it was concluded that there was insufficient evidence for an association between this risk factor and neck and neck-shoulder MSDs.

Localized Muscle Fatigue

Muscle fatigue

Fatigue is a complicated term to define (Muscio, 1921). There are different ways to classify fatigue. Fatigue could be categorized as acute fatigue and chronic fatigue regarding the duration. Also, it can be classified as mental fatigue and physical fatigue. Muscle fatigue can be defined as a decrease in muscle ability to generate force or power caused by physical activity (Wan et al., 2017). In a review study by Wan et al. (2017), changes in the nervous, ion, vascular, and energy system, as well as metabolic factors and fatigue reactants, were named as the factors that affect muscle fatigue (Wan et al., 2017). In general, muscular fatigue is a result of changes in muscle regarding its metabolism, energy, and structure. The nutrition and oxygen are supplied by blood circulation. Deficiency in this supply, as well as changes in the performance of the nervous system, can lead to muscular fatigue (Cifrek et al., 2009).

Muscle fatigue evaluation

Perhaps the simplest way to evaluate fatigue is to evaluate the duration that a person can do a certain physically demanding task. Although this method is very simple, it may depend on other factors, such as the participant’s motivation. In this method, only the occurrence of fatigue is recorded, and it does not provide the researcher with the possible biomechanical and physiological changes that may happen during the procedure. Also, if more than one agonist muscle is employed to perform the task, this method would not be appropriate to detect fatigue in a specific muscle among these muscles (Edwards 1981; Cifrek et al., 2009).

The second method is to measure the concentration of lactate in the muscle. For this purpose, the participant’s blood is sampled with intervals while they are performing the physical task. There are two issues regarding this method. First, it is challenging to evaluate fatigue in real-time. Secondly, the results of this method are more general, and they provide information about the global fatigue of the total active musculature, not an individual muscle (Cifrek et al., 2009).

One of the most well-known and easy to use methods to evaluate muscle fatigue continuously for particular muscles while the participant is performing a physical task is surface electromyography (sEMG). In this method, the electrical activity of the muscle is recorded using surface electrodes. The changes in the muscle during fatigue are reflected in the sEMG signals (De Luca 1984). These methods are widely used because it is non-invasive, and it is easy to be used in different places such as inside ergonomics and biomechanics labs. It can detect muscular fatigue in real-time for desired muscles, and these responses are associated with real physiological changes in the muscle during fatigue.

It should be noted that the application of surface EMG is limited to the muscles directly under the skin. Also, the cross talk from neighboring muscles is another challenge regarding surface EMG (Farina et al., 2002a; Cifrek et al., 2009). The changes in the EMG signal because of fatigue were discovered around one hundred years ago. Piper in1912 detected a kind of "slowing" of the surface myoelectric signals for isometric muscle activity (Piper, 1912). Later, in 1923 Cobb and Forbes observed an increase in the amplitude of signals during an isometric contraction of the muscle (Cobb and Forbes, 1932). These studies did not go beyond laboratory efforts because of the lack of appropriate technology. The development of new equipment paved the way for further research on the relation between muscular fatigue and myoelectric signals that began around the 1950s. Knowlton et al. in 1951 found that the amplitude of the signals increase when fatigue occurs, and in 1962 Kogi and Hakamada did a frequency analysis of the signals and they found a shift in the power spectrum of the EMG signal toward lower frequencies during fatigue (Knowlton et al., 1951; Kogi and Hakamada, 1962).

EMG signals and localized muscle fatigue

During fatigue, muscle fiber conduction velocity (CV) decreases due to physiological changes in the muscle tissue, such as an increase in the concentration of lactate and a decrease in the intracellular potential of hydrogen (pH). The muscle tissue acts as a spatial low-pass filter, and the motor unit action potential is affected, and its waveform changes. It is one of the reasons for the shift toward lower frequencies of the surface myoelectric signal power spectrum. It also causes an increase in sEMG signal amplitude (De Luca, 1984; Cifrek, 2009). Besides the decrease in CV, a hypothesis for the changes in sEMG signals is that slow-twitch fibers of the muscle stay active for longer while fast-twitch fibers get fatigued quickly and switch off (Cifrek, 2009).

Time-domain methods and frequency domain methods are two well-known ways to analyze sEMG signals in fatigue studies. In the time-domain method, mean absolute value (MAV) and root-mean-square (RMS) are two representatives of sEMG amplitude. For the frequency-domain method, Fourier based approaches are among well-known methods. In evaluating fatigue, we should consider that both fatigue and force can affect the EMG spectrum and EMG amplitude. In the analyses of EMG, we should consider both methods to distinguish if the changes in EMG signals are the result of force or fatigue. Cifrek et al. (2009) described this concept and considered four different scenarios. “Briefly, four different cases can be distinguished: (1) If the EMG amplitude increases and EMG spectrum shifts to the right, muscle force increase is the probable cause, (2) If the EMG amplitude decreases and EMG spectrum shifts to the left, muscle force decrease is the probable cause, (3) If the EMG amplitude increases and EMG spectrum shifts to the left, this is considered to be result of muscle fatigue, (4) If the EMG amplitude decreases and the EMG spectrum shifts to the right, this is considered to be recovery from previous muscle fatigue.” (Cifrek et al., 2009, p.332). The changes in the spectrum and amplitude of EMG signals due to fatigue were already described in this section. Also, the EMG amplitude increases with an increase in force. It should be noted that the spectral changes of the EMG signal due to force are not well-understood (Farina et al., 2002b). In general, the described procedure by Cifrek et al. (2009) can be used to interpret the changes in EMG signals in different studies. It is specifically important in the studies that investigate the effects of both fatigue and recovery on muscles based on EMG data (Cifrek et al., 2009).

Work-Rest Cycle

Force exertions and awkward postures have been studied as risk factors for MSDs (U.S. Department of Health and Human Services, 1997), but one question is the duration of time that one can exert a specific force or hold a posture without fatigue or the risk of MSDs. What would be the effects of microbreaks during work time? Does the maximum acceptable force or awkward posture depend on the work-rest schedule? What would be the details for such a relationship for each part of the body and different activities such as static tasks, dynamic tasks, and repetitive tasks with low to high frequency? In 1973, Rohmert discussed the definition of fatigue, recovery, and degree of fatigue. He discussed stress and strain and tried to introduce optimal working rhythms for static muscular work. According to his study, force and duration of muscular contraction both affect the recovery time for static muscular works. Also, individual parameters can affect recovery time. For example, different individuals have different maximum strength for a particular muscle, and a similar task could affect them differently. He suggested a rest allowance formula for static muscular works using an exponential relation between rest allowance time and these factors (Rohmert, 1973). An important issue in work activities is the effects of the work-rest cycle, especially the effects of microbreaks on preventing fatigue and musculoskeletal problems. For example, in a study by Vijendren et al., in 2020, the effect of microbreaks on neck and shoulder discomfort during using microscopes for long durations was evaluated. The results showed that the duration of time to the point of the sensation of pain in neck and shoulder increased (i.e., there was a delay in neck and shoulder pain) with microbreaks. Also, based on the recorded surface electromyography (muscle activity of the upper branches of the trapezius descendens muscles), the overall muscle activity decreased with microbreaks (Vijendren et al., 2020).

Flexion-Relaxation Phenomenon in the Cervical Spine

The EMG activity of erector spinae muscles decreases to "silence" during full flexion of the trunk that is defined as the flexion-relaxation phenomenon (FRP). It has been suggested that FRP happens as a result of a transition from active tissues (erector spinae muscles) to passive tissues and articular structures in holding loads and keeping stability in the spine. In other words, during full flexion of the trunk, the tension in passive tissues such as posterior ligaments increase so that there is no need for the same level of active contribution of posterior muscles of the spine (Gupta, 2001; Geisser et al., 2004; Colloca and Hinrichs, 2005). Contributing to this transition is a proposed mechanism that the muscle role in extension moment shifts from superficial muscles to deeper muscles (Andersson et al., 1996; Callaghan and Dunk., 2002). Different aspects of lumbar FRP have been evaluated in previous literature. In 2007, Shin and Mirka investigated the effects of prolonged trunk flexion on the interplay between passive and active tissues in prolonged trunk flexion. The results of this study revealed the viscoelastic responses of the lumbar spine in prolonged flexion. Their findings showed that in prolonged trunk flexion, the full flexion angle, as well as the activity of spine extensor muscles, increased as creep occurred in the system, and the contribution of passive tissues in generating extension moments decreased (Shin and Mirka, 2007). In another study by Ning et al. (2012), the importance of considering FRP in EMG-assisted biomechanical models of the lumbar spine during full trunk flexion was described. As in full trunk flexion the contribution of muscles decreases and the contribution of passive tissues increases, the EMG data of trunk extensor muscles may not be strongly correlated with the trunk extensor moments (Ning et al., 2012).

FRP in the cervical spine has been of interest in several recent studies. In 2009, Burnett et al. investigated FRP in the cervical spine in 20 healthy participants (ten males and ten females). EMG activity of cervical erector spinae, upper trapezius, and thoracic erector spinae and spinal kinematics using an electromagnetic tracking system were recorded simultaneously. The data were collected during four phases of 1) upright posture, 2) neck flexion, 3) full neck flexion, and 4) return to upright while they were in a standard sitting posture. Different methods from previous literature to define FRP in the lumbar spine were utilized in order to define FRP angles in this study. No FRP was observed in upper trapezius or thoracic erector spinae muscles. The presence of FRP in cervical erector spinae changed from 0% to 65% of participants depending on the methods used from previous literature. This study revealed the need for standardized methods to define FRP in the cervical spine (Burnett et al., 2009). In 2010, Pialasse et al. investigated the effects of load and speed on FRP in the cervical spine. The experimental task consisted of three phases: 1. cervical flexion, 2. stay in full flexion, 3. extension to return to initial posture. Two levels of speed were considered. The duration of phases 1 to 3 for the slow condition was 5, 3, and 5 seconds, respectively, while in the fast condition, it was 2, 3, and 2 seconds, respectively. The load had three levels of loaded (700 g), no-load, and counterweighted (-300 g). Neither speed nor interaction between speed and load had a significant effect on the onset and cessation angles of cervical FRP. However, when the load increased, both onset and cessation angles increased, while in the counterweighted condition, both angles decreased. (Pialasse et al., 2010). Maroufi et al., in 2013, studied the difference in cervical FRP between healthy participants and participants with chronic neck pain. The FRP in cervical erector spinae was observed in 85.7% of healthy participants, while only 36.3% of participants with chronic neck pain showed FRP in this muscle. There was a significant difference in observing FRP between healthy and chronic neck pain groups (Maroufi et al., 2013). The effect of neck muscle fatigue on cervical FRP was investigated in a study by Nimbarte et al. in 2014, and the findings showed that fatigue decreased the onset and cessation angles of cervical FRP. It indicates the increased role of passive tissues in stabilizing the cervical spine when muscle fatigue occurs in the neck (Nimbarte et al., 2014). It is interesting that in another study by Zabihhosseinian et al., in 2015, it was found that in pre-fatigue condition, the cervical flexion relaxation ratio (FRR) was significantly higher for healthy participants in comparison to participants with neck pain. For healthy participants, the FRR decreased significantly after fatigue, while for neck pain participants, it slightly increased after fatigue. The onset and cessation angles of FRP decreased significantly after fatigue for both groups (Zabihhosseinian et al., 2015). The effect of static neck flexion on cervical FRP was investigated by Mousavi-Khatir et al. in 2016. In order to evaluate the effects of static neck flexion, the participants were asked to place their head on a device that was designed in a way that the cervical spine was in full flexion and cervical erector spinae muscles were in complete relaxation. Participants were asked to hold this posture for ten minutes. The results showed that after the static neck flexion for ten minutes, the onset angle of cervical FRP increased significantly while the cessation angle did not change. The maximum neck flexion angle and the EMG activity of cervical erector spinae muscles increased significantly after the static neck flexion. They concluded that, in general, the findings might be caused by the occurrence of creep in the cervical spine and a reduction in the stiffness of passive tissues (Mousavi-Khatir et al., 2016).

Biomechanical Models of the Cervical Spine

Introduction

Biomechanical models are used in different research areas such as physical ergonomics, kinesiology, biomedical engineering, and even surgical research. In general, we can divide the biomechanical models into four categories: 1. Physical models: These models are made to simulate the human body parts, such as joints. They are usually inexpensive and simple, but they may not be accurate enough for some research goals. An example application of these models is to test implants or new devices. 2. In vitro biomechanical models using cadaveric specimens: In these studies, either animal or human specimens may be used. For example, the human cadaveric specimens can be used to evaluate the mechanical properties of tissues, their resistance against fatigue, and the kinematic properties of joints. 3. In vivo biomechanical models: these models are important, especially when the study of a phenomenon inside the living body is required, for example, the effects of drugs or the recruitment of muscles in a specific motion. 4. Mathematical models or computer models: These models are important, especially in situations when the other models are not appropriate or feasible to be used. In these models, the anatomical and physical properties of the body are recruited through mathematical equations in order to simulate the body part, such as the human spine (Panjabi, 1998).

The general focus of our study is the effect of neck static flexion on neck problems. A computer model (biomechanical model) will be used to evaluate the effects of neck posture on muscle forces and joint reactions in the cervical spine during static neck flexion. Different biomechanical models have been suggested for the cervical spine. In a recent systematic review by Alizadeh et al., in 2019, the biomechanical models for the cervical spine were reviewed. They classified these models into several groups based on different criteria. For example, cervical biomechanical models can be classified as multibody dynamic, finite element, and hybrid models based on the modeling approach, or in another classification, we have static and dynamic models based on the capability of simulating static or dynamic loads (Alizadeh et al., 2019). Here, four static biomechanical models of the cervical spine have been briefly reviewed.

A biomechanical model of the neck by Moroney et al., 1988

Moroney et al. proposed a biomechanical model for the cervical spine in order to estimate muscle forces at the C4 level and compression and shear forces in the C4-C5 joint. Their model was static and considered 14 pairs of muscles for the neck. Cross-sectional areas, centroids of these areas, and lines of action were scaled for the muscles from a cross-sectional anatomy drawing (Eycleshymer and Schoemaker, 1911). The origin of the coordinate system was located at the center of the C4-C5 disk. It was supposed that there was no resistance in the joint against bending and twisting while the shear and compression forces were calculated after determining the muscle forces. Fourteen participants (ten males and four females) were asked to put on a helmet and do flexion-extension, lateral bending, and twisting tasks in the cervical spine. In some tasks, they were asked to resist external moments generated by external loads exerted to the helmets. Also, EMG data were collected from eight pairs of electrodes attached to the neck. The external moments were calculated according to the weight of the head, the weight of the helmet, and the exerted moments. The force and moment equilibrium equations in three directions (a total of six equations) were extracted to calculate muscle forces. Two optimization methods (minimizing maximum muscle contraction intensity and then minimizing vertebral compression force) were used to solve the equilibrium equations and calculate the muscle forces and C4-C5 shear and compression forces. In order to validate the results, the predicted forces in equivalent muscles and the EMG data were correlated, and the correlation coefficients ranged from 0.29 to 0.85 (Moroney et al., 1988). It is one of the first biomechanical models for the cervical spine. It should be mentioned that one weakness of this model is that they used optimization methods that do not consider the activity of antagonist muscles. It can decrease the accuracy of the calculations.

Cervical biomechanical model by Snijders et al., 1991

Snijders et al. suggested a biomechanical model of the cervical spine in 1991. In this model, C1 and C2 were considered, while C3-C7 was modeled as one link with a variable length. Equations were introduced based on the assumptions of the model, the geometrical parameters, and the findings of the previous studies to define the geometry and the kinematics of the model in flexion, extension, lateral bending, and rotation movements. Another simplification was that the centers of rotation were placed in the middle of the corresponding joints.

Thirteen muscles were considered in this model, and their origin and exertion points were determined based on anatomy and anthropometric references. The joint reactions included only forces in three directions as the joints were supposed to be frictionless. The input of the model was the external load from the weight of the head and, if needed, the weight of the helmet and acceleration forces. Using the force and muscle equilibrium equations and a basic optimization method, the muscle forces and joint reaction forces at C0-C1 were calculated. The solution with the smallest reaction force in this joint was chosen. From the results of this step and through a similar procedure, the reaction forces for the other joints were calculated (Snijders et al., 1991). It should be noted that this model was based on an optimization method. It does not consider the activity of the antagonist muscles, and it can affect the accuracy of the results.

Cervical biomechanical model by Choi and Vanderby, 1999

The cervical musculoskeletal system is statically indeterminant, rendering a situation where it is impossible to calculate all the unknowns of the biomechanical system based on force and moment equilibrium equations alone. One possible solution is the optimization method in which the muscle forces are calculated in order to optimize one or more cost functions. As noted, one weak point of this method is that it does not consider the co-contraction of antagonist muscles. Another possible method to address the challenges of a statically indeterminant biomechanical model of the cervical spine is to use EMG-based models in which the EMG activities of the muscles are recorded and used to estimate muscle forces and consequently, the joint reaction forces. Although this model considers the co-contraction of antagonist muscles, it is not easy to isolate and record cervical muscle activities using EMG. Thus, the muscles may be grouped, and the EMG data for each group of muscles may be the same. Thus, one assumption is that the activity (%MVC) of the muscles in each muscle group is the same. In a study by Choi and Vanderby in 1999, a cervical biomechanical model was developed, and the muscle forces and joint reactions at C4/C5 level were calculated using three different approaches: 1. Double optimization method (DOPT), 2. EMG-based method, and 3. EMG assisted optimization method (EMGAO). In order to calculate the external moment and the EMG activity of the muscles, ten healthy male participants were recruited to do flexion-extension and lateral bending exertions while the participants were wearing a headband connected to a fixed force transducer. Eight pairs of EMG electrodes were used to collect the cervical muscles activities at the C4/C5 level. The biomechanical model was based on the model by Moroney et al. (Moroney et al., 1988). Here we focus on the three approaches they used to calculate the forces and moments. They considered 14 pairs of muscles, which were divided into eight groups corresponding to the eight EMG electrodes. The external forces collected using the transducers, and the weight of the head for each participant was used to calculate the external moments. Only the compression and shear forces were considered as joint reaction forces, and the resistance against bending and twisting moments in the joint was neglected. As mentioned, three different approaches were used to calculate muscle forces and compression and shear forces at C4/C5 level. In the DOPT method, two linear optimization programs were used. First, they minimized maximum muscle force intensity to create a set of feasible solutions. Then, they chose the solution, which minimized the spinal compressive force using a second optimization program. In the EMG-based method, they used the EMG data to calculate the muscle forces. The moments in the three directions were calculated according to the muscle forces, and the results were compared to the external moments in three directions. A common gain (G) was calculated for all muscles based on an error minimization approach between the external and internal moments. This value was multiplied by each muscle force to calculate the final muscle forces. The EMGAO method was a hybrid approach that used the EMG-based method and an optimization approach and calculated individual gains (g values) for each specific muscle separately. It should be mentioned that the muscle forces were used to calculate compression and shear forces at the C4/C5 level. The results revealed that the EMG-based and EMGAO method considered antagonist muscles in the model, while the force for antagonist muscles were zero in the DOPT method. Also, the results from EMG-based and EMGAO approaches showed that the muscle forces were different for participants and different trials of the same participant when the external load was the same. It is because the muscle activities were not the same for each participant (inter-participant variability) or trial (intra-participant variability) even when the external moment was unchanged. The DOPT method could not show these differences, and its results were almost identical for a given external moment (Choi and Vanderby, 1999).

Computer graphical model by Vasavada et al., 1998

In 1998, Vasavada et al. presented a graphics-based biomechanical model for the cervical spine in order to evaluate the effects of neck movements on muscles fascicle length, muscles moment arms, and consequently, the moment-generating capacity of muscles in the cervical spine. A range of flexion-extension, lateral bending, and rotation motions was studied in this model. Bones, muscles, origin, and insertion points for muscles and muscle force-generating parameters, including force-length curves of muscles and tendons, muscles cross-sectional areas, and muscles pennation angles, were defined and modeled using the graphics interface, anatomy references, and previous studies. Insertion and origins of the muscles were defined using the graphical interface. It should be noted that in this model, erector spinae, longus capitis, and longus colli were constrained not to pass through the vertebrae. For those muscles with a broad range of attachment, the muscle was modeled using sub-volumes. In each desired position of the neck, the maximum isometric force of the muscle was multiplied by its moment arm to calculate the moment-generating capacity of the muscle (maximal activation of the muscle was considered), and it was shown that through the range of motion, these parameters would be affected (Vasavada et al., 1998).

Reviewing these biomechanical models for the cervical spine, it is revealed that a direction for future research could be the contribution of passive tissues such as ligaments in cervical biomechanical models. As previously discussed, the contribution of passive tissues such as ligaments affects the activity of neck muscles, especially in neck flexion, when the cervical FRP occurs.

Assessment Tools for Occupational Disorders of the Cervical Spine

Work assessment tools have been developed to evaluate the physical exposure and workload in different occupations and for different work tasks. The goal of these methods includes investigating the risk of MSDs at work, evaluating the ergonomic interventions designed or suggested by experts, and conducting research in these areas (Takala et al., 2010). Many work assessment tools have been developed, but not all of them are well-known. These methods may have been developed to assess the whole body or just a specific part of the body. They may be useful for different occupations, or they may be specifically designed for specific jobs or work tasks such as manual material handling. Thus, there is no single method that is appropriate for all purposes. In other words, for each task and according to some other factors such as cost, time, and availability of experts and ergonomists, a method may match the best with the goal of the project. Sometimes a qualitative estimation may be enough, and in some cases, accurate quantitative calculations of exposure may be required to make appropriate decisions (Takala et al., 2010). In 2010, Takala et al. conducted a systematic review to investigate different observational assessment tools for physical exposures at work. They mentioned four parameters to choose the appropriate method for a specific project: 1. The goals of the project, 2. The characteristics of the occupation and the work tasks to be evaluated, 3. The users who want to perform the project, 4. The resources that are available to conduct the project. On the other hand, the method should be reliable as it would be the foundation for making decisions. Takala et al. (2010) concluded that there is no specific method that is appropriate in all projects. The practitioner may even use different methods in one project. Also, they suggested that subjective evaluations such as interviews should be considered in addition to these methods as it can help consider some important parameters which have not been considered in the assessment tool (Takala et al., 2010).

On the other hand, in a review study, Juul-Kristensen et al. (1997) investigated the criteria used in different work assessment tools to categorize postures and movement intervals for different body parts, including the neck. According to their study, a problem concerning different work assessment tools is that they have used different cut-offs for postures, and this makes it difficult to compare the results of these different methods. For example, they summarized the cut-offs for neck flexion-extension, lateral bending, and axial rotation movements for five different methods, and they showed how the cut-off was different among these methods. Using a similar procedure for different parts of the body, they showed that the classification of postural angles varied considerably. They concluded from their review study that the cut-off angles for postural exposure in most of the reviewed assessment tools were poorly defined (Juul-Kristensen et al., 1997).

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CHAPTER 2. PRELIMINARY STUDY I: EXPLORING THE RELATIONSHIP BETWEEN NECK FLEXION AND NECK PROBLEMS IN OCCUPATIONAL POPULATIONS: A SYSTEMATIC REVIEW OF THE LITERATURE

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Abstract

A systematic review was conducted to evaluate the relationship between occupational neck flexion angles and neck problems. The synthesized findings were used to answer three research questions: 1) Is there a positive/negative relationship between neck flexion and neck problems? 2) What is the appropriate angular threshold for neck flexion as a risk factor for neck problems? 3) What are the gaps in our current knowledge? A review of 21 papers revealed 1) a consistent positive correlation between neck flexion and neck problems, and 2) a neck flexion angle of 20º with the greatest support as the cut-off angle separating high- and low-risk neck flexion postures. Future research should focus on the 1) continuous collection of three-dimensional neck postures to quantify cumulative exposures of neck postures, and 2) development of a standard description of “neck problems” and “neck flexion” to facilitate the development of a dose-response relationship.

Introduction

Neck related musculoskeletal disorders (MSDs) are prevalent in numerous occupations, posing significant health and economic challenges. For example, it has been estimated that between 7% and 74% of surgeons suffer from neck-related pain as a result of their job (Alhusuny et al., 2019). In the textile and garment industry, the 12-month prevalence of neck disorders was estimated to be between 42.3% and 46.3%, with males being at higher risk than females (Tafese et al., 2018, Biadgo et al., 2020). Furthermore, epidemiological studies from other occupations such as construction (Palmer et al., 2001) and sedentary computer usage (Tsauo et al., 2007) have reported work-related neck problems at prevalence rates of 38% and 25%, respectively. Such disorders result in lost workdays, reduced productivity, as well as financial burdens as a result of seeking treatment (Learner et al., 2015), and this can be exacerbated by the fact that one occupational neck injury can lead to episodes of recurrent neck pain (Nolet et al., 2011).

While the etiology of work-related neck problems is multifactorial, including risk factors such as high repetition, exertion force, and awkward posture (Andersen et al. 2002; Côté et al., 2009), awkward posture is often cited as a dominant risk factor for neck pain development. For instance, a Dutch cohort study of 264 computer users reported awkward neck postures as one of the predictors of neck pain (Eltayeb et al., 2009). Another prospective cohort study (Ariëns et al., 2001), with a three-year follow-up, used video recordings of neck posture to determine the relationship between posture and subjective neck pain. After adjusting for work and non-related physical factors, individual and psychosocial factors, they reported a positive relation between neck flexion of 20° or greater for more than 70% of working time with the development of neck pain.

Over the years, risk assessment tools that incorporate neck posture as a risk factor have been developed by researchers. Rapid Upper Limb Assessment (RULA) (McAtamney and

Corlett, 1993), Rapid Entire Body Assessment (REBA) (Hignett and McAtamney, 2000), Loading on Upper Body Assessment (LUBA) (Kee and Karwowski, 2001), and the cumulative trauma disorder (CTD) risk assessment tool (Seth et al., 1999) are some of the work risk assessment tools that include neck postural exposure in their assessment. While these existing postural risk assessment tools are relatively easy to use and can be used to identify jobs for further analysis to reduce neck injury/illness, one certain limitation is that the risk threshold angles are not consistent across different assessment tools. For example, the neck flexion angle of 10º (RULA), 20º (RULA, and REBA), and 30º, 45º, and 60º (CTD) are some of the neck flexion cut-off angles used by the work risk assessment tools (McAtamney and Corlett, 1993; Seth et al., 1999; Hignett and McAtamney, 2000).

In an effort to summarize the literature and establish an understanding of the relationship between awkward neck postures and the risk of work-related neck disorders, a number of review papers have been published. In a literature review by Winkel and Westgaard (1992) the risk factors for shoulder-neck complaints were evaluated. Their results showed that the quantitative relationship between neck-shoulder complaints and head inclination remained unknown as it was not possible to extract a general conclusion based on their reviewed studies (Winkel and Westgaard, 1992). In a 1997 review study by the National Institute for Occupational Safety and Health (NIOSH), strong evidence was found for the association between extreme or static posture involving the neck-shoulder muscles and neck-shoulder problems (U.S. Department of Health and Human Services, 1997). The NIOSH study provided progress in identifying the correlation between neck postural exposure and neck problems. However, the results did not discuss the evidence for the correlation between neck MSDs and neck flexion specifically, grouping neck flexion/extension, right/left lateral bending, and axial rotation together as neck postural exposure. More recently, another review study by Ariëns et al. (2000) sought to explain the relationship between neck postural exposures and neck problems in more detail. The evidence for a relationship between neck pain and neck flexion, neck pain, and neck extension, and neck pain and neck rotations were all found to be inconclusive, although in their study, a sensitivity analysis revealed some evidence for a positive relationship between neck flexion and neck pain (Ariëns et al., 2000). In a systematic review study by Palmer and Smedley (2007), the occupational risk factors for neck-shoulder disorders were investigated with restricted attention to the reports of chronic pain in soft tissues supported by clinical examinations. They found associations between neck flexion and neck-shoulder pain with palpation tenderness but they suggested limited evidence for neck flexion alone as a risk factor for this problem (Palmer and Smedley, 2007).

Due to lack of evidence, none of these studies were able to present strong and conclusive results for the relationship between neck problems and neck postural exposures, including neck flexion/extension, lateral bending, and axial rotation. Unsurprisingly, the other aspects of this possible relationship, such as the angular thresholds for the postural exposures, remained unknown. It must also be noted that these reviews were conducted more than a decade prior to this review, and our increasing understanding of ergonomics has influenced how manual work is designed and executed. New studies have been conducted within recent years with information that might enhance our understanding of the relation between awkward neck postures and neck problems, therefore warranting an updated review. Exploring the literature indicated that evaluating the correlation between neck problems and neck flexion angles in the form of a systematic review is feasible; while for neck extension, neck lateral bending, and neck axial rotations, there are not a sufficient number of studies to enhance our knowledge in this area.

Thus, in this systematic review, the relationship between neck flexion angles and neck problems (broadly defined as neck pain, discomfort, and musculoskeletal symptoms and disorders) among occupational populations was performed. The goal of this study was to examine the correlation between neck problems and neck flexion angles and to see if there is evidence for specific angular cut-offs for neck flexion angles based on the previous literature. This systematic review is intended to answer three questions among occupational populations. Q1. Is there a positive/negative relationship between neck flexion and neck problems? If the answer to Q1 is that there is a relationship between neck flexion and neck problems, then Q2. What is the appropriate angular threshold for neck flexion as a risk factor for neck problems? And finally, overall, Q3. What are the gaps in our current knowledge?

Method

Ovid MEDLINE(R) and Epub Ahead of Print, In-Process and Other Non-Indexed Citations, and Daily, Ovid EMBASE, Ovid Cochrane Central Register of Controlled Trials, Ovid Cochrane Database of Systematic Reviews, CINAHL, and Scopus were the databases used to perform a comprehensive search up to June 28th, 2019. The lead author provided an experienced research librarian with the keywords, and the librarian designed and performed the search process.

Keywords in the title and abstract fields were used to search for risk factors for musculoskeletal disorders associated with neck posture in occupational populations. These keywords included three groups: 1. Keywords related to musculoskeletal disorders and problems, 2. Keywords related to neck and cervical spine, 3. Keywords related to postures and postural exposures. The actual strategy listing all search terms used and how they are combined is available in the appendix. Specific and general musculoskeletal disorders, pain, and discomfort evaluated through physical examination and/or questionnaires were all included. The definition of neck problem(s) covered a wide range, including pain, discomfort, and disorders, while the difference between them was not considered as a factor in addressing the three questions of the study. Neck or head posture evaluated through objective measurements, observation, and questionnaires were all included. These postures were not necessarily collected for the whole duration of the workday, but they represented the workers' neck postural exposures at work. The pattern of the exposure that determines other characteristics of the postural exposure, such as duration, and frequency, were not considered in the inclusion criteria. Thus, all the papers that provided general information about the workers' neck postural exposure at work were included. Also, the inclusion criteria considered language in ‘English,’ and the study population was ‘adult humans among occupational populations.’ The exclusion criteria were: 1. If the MSD symptoms were combined for different parts of the body, such as upper extremity disorders (except for neck-shoulder combination). 2. If the neck postural exposure was combined with the postural exposure of the other body parts, such as the overall risk score using assessment tools for the upper body.

After finding the potential papers through the database search, three independent researchers, working as a team, screened the titles and abstracts of the papers using Covidence software (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia. Available at www.covidence.org). The papers were randomly distributed among three researchers, and each paper was screened by two of them. In cases with a conflict in screening rating, the third researcher resolved the conflict. Then, the same independent researchers assessed the full text of each eligible paper following a similar strategy. The third reviewer resolved the conflicts between the two reviewers. All the references of the selected papers were checked to find additional relevant papers that were not found through the keyword search. The three researchers did individual online searches for relevant papers published in 2019 and 2020 (up to 10/15/2020) so that newly published papers were also included in this systematic review. The findings of each paper with regard to the relationship between neck postural exposure and neck problems were extracted by the first author. The statistical significance of the results was recorded and used in addressing the three research questions of this study. The relevant statistical parameters such as p-value, odds ratio, and relative risk were reported in the form of summary (Tables 2.2-2.5).

Results

The keyword search resulted in 3123 papers after excluding the duplicates. Through title and abstract screening, these were reduced to 134 papers selected for the full review. The full-text review led to 18 papers, and three additional papers were identified from the references of these papers and individual search for synthesis. Figure 2.1 illustrates this procedure. The 21 selected papers were classified into two groups. The first group included case-control studies (three papers). The second group consisted of cross-sectional and longitudinal epidemiologic studies (18 studies). Epidemiologic studies were subsequently classified into three groups: 1. Studies that evaluated neck posture based on questionnaires completed by the participants (five studies), 2. Studies that evaluated neck posture based on direct observation or video recording (eleven studies), and 3. Studies that evaluated neck posture with measuring neck angles using measurement devices (two studies). Tables 2.2-2.5 present details about these studied populations and their results. While all the included studies investigated neck flexion as a risk factor for neck problems, only a very few studies considered other neck postures (i.e., neck extension, lateral bending, and axial rotation) as a variable of interest in their studies. Thus, the main focus of this systematic review will be the relationship between neck flexion and neck problems.

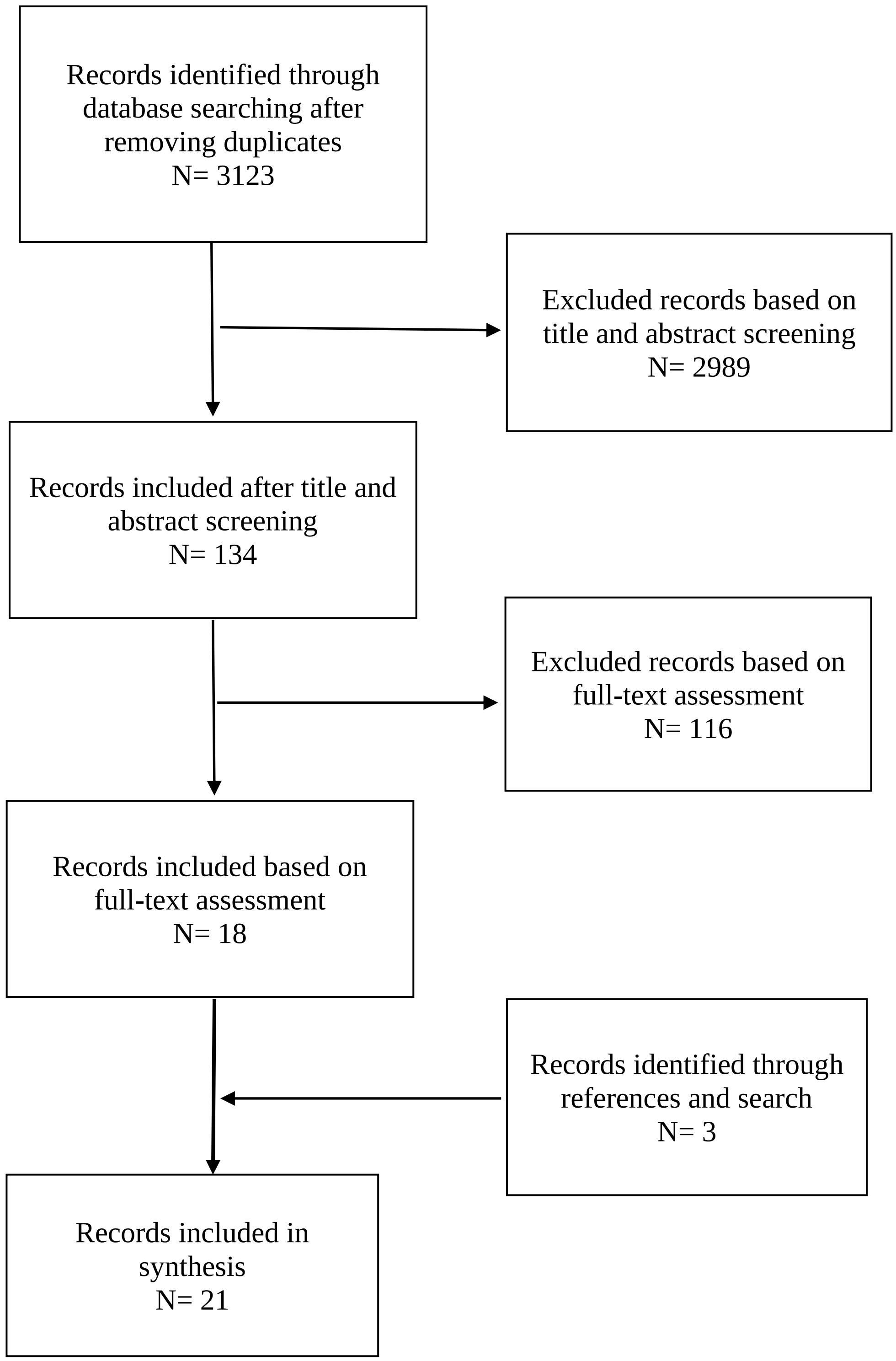

Figure 2.1 The flow diagram of the systematic review

Q1. Is There A Positive/Negative Relationship Between Neck Flexion and Neck Problems?

This is the most fundamental question in our study, and all of the included studies were used to address this question. If there is a positive finding, we will address Q2.

Case-control studies

Three case-control studies evaluated the differences in neck posture between workers with and without neck/neck-shoulder problems (Szeto et al., 2002; Szeto et al., 2005; Baker et al., 2008). The head tilt and neck flexion angle and the upper cervical extension were greater in office workers with neck-shoulder discomfort in comparison with controls during computer use (Szeto et al., 2002), although the results were not statistically significant. During typing in an adjustable workstation, head flexion and head side flexion were positively correlated with right neck pain, while head rotation was negatively correlated with right neck pain. Also, the typists with neck-shoulder discomfort showed larger median flexion angle and larger movements in the head (flexion/extension, side flexion, and axial rotation), although these comparisons were not all statistically significant. The median values for side flexion and rotation angles were greater in the asymptomatic control group (Szeto et al., 2005). Additionally, Baker et al. (2008) found that the neck flexion angle during typing on a computer could distinguish between university faculty and staff with and without MSDs related to the neck. Overall, these case-control studies showed a positive correlation between neck flexion and neck (Szeto et al., 2005; Baker et al., 2008) and neck-shoulder (Szeto et al., 2005) problems.

Epidemiologic studies

Neck posture based on questionnaires completed by the participants

In this section, five epidemiologic studies were found that evaluated the correlation between neck posture and neck/neck-shoulder problems. An association between neck pain and head posture (“poking chin,” also known as forward head posture) during computer use was found among university staff (Chiu et al., 2002). Furthermore, a positive correlation was reported between working in a head/neck downward posture and neck pain among teachers (Chiu and Lam, 2007) and physicians (Mehrdad et al., 2012). Also, a longitudinal study showed that increased and constant exposure to neck flexion was significantly associated with neck-shoulder pain at a three-year follow-up (adjusted for baseline neck-shoulder pain) among the general working population (Sterud et al., 2014). Neck flexion/extension postures at work among electronic assembly workers showed a positive correlation with the risk of cervical MSDs (Maimaiti et al., 2019); however, combining flexion and extension postures of the neck in their postural evaluation questionnaire made it impossible to interpret these results in detail. The epidemiologic studies based on questionnaires confirmed a positive correlation between neck flexion postures and neck (Chiu and Lam, 2007; Mehrdad et al., 2012) as well as neck-shoulder (Sterud et al., 2014) problems.

Neck postures based on direct observation or video recording

Eleven studies out of the 21 selected papers were epidemiologic studies that employed direct observation or video recording to evaluate neck postures. One cross-sectional study showed that with an increase in head forward inclination or rotation, the neck-shoulder MSDs increased among visual display terminal (VDT) jobs, typists, and traditional office workers (Hünting et al., 1981). Also, the other cross-sectional studies revealed a positive correlation between time spent in neck flexion and neck symptoms among assemblers at electronic companies (Kilbom et al. 1986), neck-shoulder symptoms among industrial (electric assembly) workers (Ohlsson et al., 1995), and workers from 19 industrial and service companies (Andersen et al., 2002). The RULA method (McAtamney and Corlett, 1993) showed that neck postures deviated from neutral posture (neck flexion between 0º and 10º without rotation and lateral bending) were positively correlated with neck pain and discomfort among truck drivers

(Massaccesi et al., 2003), and hand-woven carpet industry workers (Choobineh et al., 2004). Employing the REBA method (Hignett and McAtamney, 2000), positive associations between the REBA neck score and neck musculoskeletal pain were found among operating room nurses (Asghari et al., 2019); however, these scores were combinations of neck flexion, extension, lateral bending, and rotation.

Additionally, four three-year longitudinal studies evaluated the correlation between neck posture and neck and neck-shoulder problems. One longitudinal study among workers of 19 industrial and service companies showed an association between the time in neck flexion at work and newly developed neck-shoulder pain (Andersen et al., 2003). Also, studying the work population from 34 industrial and service companies revealed a non-significant positive association between neck flexion and new cases of neck pain (Ariëns et al., 2001), and a positive correlation between neck flexion and neck rotation at work and work absence due to neck pain (Ariëns et al., 2002). Although the results from another longitudinal study among the workers from industrial and service companies revealed a correlation between neck symptoms and neck flexion and rotation using univariate analysis, their multivariate analysis did not find a significant association among these variables (Coenen et al., 2016). The results from the studies based on observation and video recording confirmed a positive correlation between neck flexion and neck (Kilbom et al. 1986; Ariëns et al., 2002) and neck-shoulder (Hünting et al., 1981; Ohlsson et al., 1995; Andersen et al., 2002; Andersen et al., 2003; Sterud et al., 2014) problems.

Neck posture based on measuring neck angles using objective measurement devices

Two studies used objective measurement devices (triaxial accelerometers) to capture head postures during work. Inclinometry (based on triaxial accelerometers) measurement data from a series of cross-sectional epidemiologic studies covering a wide range of occupations and physical workloads (industrial, office, and other works such as dentistry) revealed a positive correlation between neck problems and head inclination (Nordander et al., 2016). However, in another similar study, the results didn't show a positive correlation between the head forward inclination and neck problems (Balogh et al., 2019). Thus, only one of the two studies confirmed a positive correlation between neck flexion and neck problems (Nordander et al., 2016).

Case-control and epidemiologic studies together

Overall, seven papers showed a positive correlation between neck flexion and neck problems (Kilbom et al. 1986; Ariëns et al., 2002; Szeto et al., 2005; Chiu and Lam, 2007; Baker et al., 2008; Mehrdad et al., 2012; Nordander et al., 2016). Additionally, six papers showed a positive correlation between neck flexion and neck-shoulder problems (Hünting et al., 1981; Ohlsson et al., 1995; Andersen et al., 2002; Andersen et al., 2003; Szeto et al., 2005; Sterud et al., 2014).

Q2. What Is the Appropriate Angular Threshold for Neck Flexion as A Risk Factor for Neck Problems?

Once it was determined that there was a relationship between neck flexion and neck problems, a threshold for categorizing risk is needed for further ergonomic studies. However, most of the studies in this systematic review employed only dichotomous divisions to evaluate neck postures, which limits conclusions regarding a dose-response relationship between postural exposure and neck problems. The goal of this section is to investigate possible thresholds for neck flexion regarding neck problems. Table 2.1 summarizes the different angles of neck flexion postures that were used in the reviewed studies and led to evidence of a correlation between the neck flexion and the neck and neck-shoulder problems. A neck flexion angle of greater than 20º as a cut-off for risk is a possible candidate with evidence from case-control studies, cross-sectional epidemiologic, and longitudinal epidemiologic studies for neck problems (Kilbom et al., 1986; Ariëns et al., 2002; Baker et al., 2008; Mehrdad et al., 2012) and neck-shoulder problems (Andersen et al., 2002; Andersen et al., 2003). Neck flexion angles of 15º (Ohlsson et al., 1995) and 56º (Hünting et al., 1981) are other cut-off angles considered but have less evidence compared to 20º flexion.

Table 2.1 Benchmarks for neck flexion and head inclination angles

Study	Measurement	Exposure	Evidence	Task or job group
Baker et al., 2008 (Case-control)	Observation	>20º	Discrimination between participants with and without neck MSDs	Typing on the computer (University faculty/staff)
Mehrdad et al., 2012 (Cross-sectional Epidemiologic)	Questionnaire	>20º	Positive correlation between neck pain and duration of neck flexion >20º	Physicians
Hünting et al., 1981 (Cross-sectional Epidemiologic)	Observation	>56º	Significant increase in neck-shoulder MSDs with head forward inclination of >56º	Data entry terminal workers
Kilbom et al., 1986 (Cross-sectional Epidemiologic)	Observation (Recording)	>20º	Positive correlation between neck symptoms and duration of neck flexion >20º	Assemblers at two electronic companies
Ohlsson et al., 1995 (Cross-sectional Epidemiologic)	Observation (Recording)	>15º	Positive correlation between neck-shoulder symptoms and duration of neck flexion >15º	Workers in repetitive industrial jobs
Ariëns et al. in 2001 (Longitudinal Epidemiologic)	Observation (Recording)	≥20º	Non-significant positive correlation between new cases of neck pain and duration of neck flexion≥20º	Different industrial and service companies
Ariëns et al., 2002 (Longitudinal Epidemiologic)	Observation (Recording)	≥20º	Positive correlation between work absence due to neck pain and duration of neck flexion≥20º	Different industrial and service companies
Andersen et al., 2002 (Cross-sectional Epidemiologic)	Observation (Recording)	>20º	Positive correlation between neck-shoulder problems and duration of neck flexion >20º	Workers in different repetitive jobs
Andersen et al., 2003 (Longitudinal Epidemiologic)	Observation (Recording)	>20º	Positive correlation between newly developed neck-shoulder problems and duration of neck flexion >20º	Workers in different repetitive jobs

Q3. What Are the Gaps in Our Current Knowledge?

In this section, the direction for future research based on the synthesized findings is explored. More epidemiological studies are needed to explore the relationship between the neck axial rotation, neck extension, and neck lateral bending and neck problems. Future studies should also explore the combined effects of different postural exposures (e.g., flexion and axial rotation) on neck problems. Creating a sound dose-response relationship between the neck postural exposure and neck problems can pave the way to establish more reliable and more accurate cut-offs for the neck postural angles, especially for work risk assessment tools and interventions.

The definition of the neck angle and its importance in the relationship between neck postural exposure and neck problems is also a question that has not been adequately addressed in the existing literature. Discrimination between head angle and neck angle and the fact that the head and neck angles could be defined relative to the trunk or relative to the gravitational direction are concepts that need attention in future studies.

Using a questionnaire to evaluate postural exposure is prone to over-estimation or under-estimation of the exposure and doesn't provide the researcher with the pattern of the angles. Also, evaluation of the angles through observation and measurement tools is usually performed for limited durations. This may include postures of the workers at one moment or limited duration of the workday. The pattern of the neck angles during a whole working day should be investigated in more detail. The neck postural exposure such as the neck flexion angle during eight hours of working day could be very variable; for example, if the average flexion angle is 20º, it should not be assumed that 8 hours of 20 has the same risk as 2 hours of 60º, 2 hours of 20º and 4 hours of neutral neck posture (~0º). In fact, this notion introduces other factors to the relationship between neck postural exposure and neck problems, including the pattern of the postural exposure, the duration of a specific postural exposure, and the effects of different work-rest cycles. Also, the pattern of the angles provides information about the repetitive motions of the neck. This information allows us to investigate the effects of neck postural exposure on neck problems from different viewpoints, including the repetition of the neck motions, the duration of static neck postures, and the overall duration of a specific neck posture during a workday.

More longitudinal studies covering a variety of jobs with a wide range of physical workloads using new wearable postural measurement tools such as Inertial Measurement Units (IMU) in combination with the objective and subjective assessment of neck problems would be a useful research direction for the future. Such sensors allow the continuous collection of angles so that the neck postural exposure can be easily recorded for the whole working day for many participants. In other words, we are no longer limited to discrete categorical variables or visual sampling of postures since new technology can provide the opportunity for continuous assessment of postural exposure and the development of a true dose-response relationship. Future research should also include the influences of the pattern of the neck angles during a whole working day and the effects of different work-rest cycles on neck problems.

While these measurements are objective and relatively easy to gather, research studies using new measurement equipment cannot clarify the underlying causal effects of postural exposure on neck problems alone. Measuring muscle activities, muscle fatigue, and muscle blood flow in addition to images of cervical bones and soft tissues could be among the experimental parameters that can be considered in these studies. One aim of these physiology-based research studies could be the investigation of both short-term and long-term anatomical and physiological changes that could happen in the cervical spine system due to postural exposure. These could then be combined with industrial exposure studies to refine the causal relationship between neck postural exposure and neck problems.

Table 2.2 Summary of case-control studies

Study	Population	Findings
Szeto et al., 2002	Sixteen female office workers (eight cases and eight controls according to the records of neck-shoulder discomfort)	The results were not statistically significant, but they showed a trend that both the head tilt and neck flexion, as well as the excursion of these two parameters, were greater for cases than controls. Also, the upper cervical extension angle was greater for cases in comparison to controls.
Szeto et al., 2005 (quasi-experimental)	Thirty-eight experienced female typists (21 cases and 17controls according to the records of neck-shoulder discomfort)	Head flexion ($p=0.048$) and head side flexion ($p=0.015$) were positively correlated with right neck pain while head rotation ($p=0.008$) was negatively correlated with right neck pain. In general, participants under the cases category had movement with larger ranges in flexion/extension ($p=0.036$), side flexion ($p=0.035$), and rotation ($p=0.053$). The median flexion angle was larger in cases ($p=0.325>0.05$), while the median angles for side flexion ($p=0.024$) and rotation ($p=0.004$) were larger in controls.
Baker et al., 2008	Twenty-one cases (18 females) with upper extremity MSDs (six with neck-related MSDs) and 21 controls (18 females) among university faculty and staff.	Neck flexion angle> 20º could distinguish between cases and controls for both upper extremity MSDs and the neck-related MSDs. From all six participants with neck-related MSDs, all had a neck flexion angle> 20º, while from the 21 controls, only two participants had a neck flexion angle> 20º.

Table 2.3 Summary of epidemiologic studies: neck posture based on questionnaires (* C-S= cross-sectional study, **L=longitudinal study)

Study	Population	Findings
Chiu et al., 2002 (C-S*)	One hundred and fifty full-time academic staff (56 females).	The neck pain was significantly associated with head posture during computer processing (p = 0.02). 60.5% of the participants who had neck pain during computer processing were working with poking chin (forward head posture).
Chiu and Lam, 2007 (C-S*)	Three thousand one hundred full-time secondary-school teachers (58% females).	Working in a head-down posture had a significant positive association with neck pain and upper limb pain. The neck pain adjusted odds ratio for working in head-down posture was 1.77 (95% CI 1.14-2.74) for the average length of time > 5.5 hours (<1 hour as reference). The neck pain adjusted odds ratio for working in head-down posture was 2.10 (95% CI 1.38-3.19) for maximal sustained time > 2 hours (<15 minutes as reference).
Mehrdad et al., 2012 (C-S*)	Four hundred five physicians (190 female).	The neck pain was found to be significantly associated with an increased duration of exposure to work with downward neck flexion> 20º. The neck pain adjusted odds ratio for neck flexion>20º was 1.207 (95% CI 1.015-1.435).
Sterud et al., 2014 (L**)	At the baseline, 9961 (4725 females) from the general working population, and at the three-year follow-up, 6745 (3207 females) of those participants.	The results showed that increased and constant exposure to neck flexion was significantly associated with neck-shoulder pain at follow-up (adjusted for baseline neck-shoulder pain). The odds ratios for increased and constant high neck flexion exposure (odds ratio for no exposed was 1) were 1.43 (95% CI 1.05-1.94) and 1.77 (95% CI 1.31-2.39), respectively, for neck/shoulder pain.
Maimaiti et al., 2019 (C-S*)	Seven hundred electronic assembly workers (52.5% females).	Results showed that keep neck flexion/extension for a long time among the workers who replied “always” was associated with a higher risk of cervical MSDs (p-value=0.035) compared to workers who replied “never” to this question (from “never, seldom, sometimes, often, always”).

Table 2.4 Summary of epidemiologic studies: neck postures based on direct observation and video recording (* C-S= cross-sectional study, **L=longitudinal study)

Study	Population	Findings
Hünting et al., 1981. (C-S*) (Observation)	Visual display terminal workers (data entry terminals: 53 workers-50 females, conversational terminals: 109 workers-55 females), typists: 78 workers-74 females.	The head forward inclination of larger than 56º for data entry terminal workers ($p<0.05$) as well as the head rotation angle of larger than 20º among typists ($p<0.05$) showed a statistically significant increase in neck-shoulder MSDs for these workers.
Kilbom et al., 1986. (C-S*) (Observation-Recording)	Ninety-six female workers at assembly departments of two electronic manufacturing companies.	Results showed positive correlations between average time per work cycle in neck flexion >20º and neck symptoms ($p<0.01$). Also, a positive correlation between average time per work cycle in neck flexion >20º and neck-shoulder symptoms ($p<0.05$) was found.
Ohlsson et al., 1995. (C-S*) (Observation-Recording)	Seventy-four industrial (electric assembly) female workers.	A significant association between neck-shoulder symptoms and time spent in neck flexion > 15º was found ($p=0.03$).
Ariëns et al., 2001. (L**) (Observation-Recording)	Nine hundred and seventy-seven workers (240 females) from 34 industrial and service companies.	There was a trend for a positive association between neck flexion and neck pain, although it was not statistically significant.
Ariëns et al., 2002. (L**) (Observation-Recording)	Seven hundred and fifty-eight workers (191 females) from 34 industrial and service companies.	The results showed that neck flexion and neck rotation were positively related to work absence due to neck pain. The adjusted rate ratio for workers with neck flexed ≥20º for at least 40% of work-time was 4.19 (95% CI 1.50 to 11.69). Also, the adjusted rate ratio for workers with neck rotated ≥45º for at least 25% of work-time was 2.81 (95% CI 1.29 to 6.09).
Andersen et al., 2002. (C-S*) (Observation-Recording)	Workers (3123 total, 1823 females) from 19 different workplaces, including different industries and services such as food production companies and, postal-sorting offices.	The adjusted prevalence proportion ratio (PPR) of neck-shoulder symptoms for neck flexion >20º was 1.7 (95% CI 1.1-2.8) for high-level exposures (≥66% of time) while it was not significant for low level (<66% of time). Jobs that didn't include repetitive work were considered as the reference group.

Table 2.4. Continued		
Study	Population	Findings
Andersen et al., 2003. (L**) (Observation-Recording)	From the 3123 participants of Andersen et al., 2002, only 1546 completed all three follow-ups.	The adjusted odds ratios for developing neck-shoulder pain for workers with high-level exposures of neck flexion>20º (≥66% of time) was 1.4 (95% CI 1.1-1.8) while it was not statistically significant for low-level exposure (<66% of work time). The reference group was the jobs that didn't include repetitive work.
Massaccesi et al., 2003. (C-S*) (Observation)	Seventy-seven male truck drivers (38 rubbish-collection vehicle drivers, and 39 street-cleaning vehicle drivers).	In both groups of drivers, a significant positive association between neck RULA score (=1 or >1) (McAtamney and Corlett, 1993) and neck pain were found (P=0.001). Neck RULA score of 1 is neck flexion between 0º and 10º without rotation and lateral bending
Choobineh et al., 2004. (C-S*) (Observation)	The weavers (1439 in total, 98% females) in the hand-woven carpet industry	The association between neck RULA score (=1 or >1) (McAtamney and Corlett, 1993) and neck musculoskeletal symptoms in the adjusted analysis revealed the odds ratio of 1.79 (95% CI 1.25-2.54) (neck RULA score=1 as reference). Neck RULA score of 1 is neck flexion between 0º and 10º without rotation and lateral bending.
Coenen et al., 2016. (L**) (Observation-Recording)	Two hundred and forty-five (41% females) workers from industrial and service companies.	The univariate analyses revealed that some of the postural parameters for both neck flexion and neck rotation were associated with neck symptoms at the baseline and the follow-up of the longitudinal study, while the further adjusted multivariate analysis did not find a significant association between neck postural parameters and neck symptoms.
Asghari et al., 2019. (C-S*) (Observation)	One hundred and forty-four operating room nurses (80.3% females).	The results revealed that the neck REBA score (Hignett and McAtamney, 2000) during table setup (one of their main activities during work) was associated with neck musculoskeletal pain. The multivariate binary logistic regression showed an odds ratio of 1.46 (95% CI 1.03-2.06).

Table 2.5 Summary of epidemiologic studies: neck posture based on measuring neck angles using objective measurement devices

Study	Population	Findings
Nordander et al., 2016 (A series of cross-sectional studies) (Measurement device: triaxial accelerometers)	The pooled data from a series of cross-sectional studies including 2324 females and 817 males from different occupations (industrial, office, and other occupations such as dentistry).	The results revealed that neck complaints and diagnoses were significantly associated with head forward inclination. Also, the exposure-response relationship between the risk factors and the disorders were presented. It was defined as the 95% confidence interval of the slope of the regression line, which indicated the % of the increase in the prevalence of the disorder when there is one unit increase in the exposure. For example, this slope (sex-adjusted) for the 90th percentile of the head forward inclination was 0.2 (95% CI 0.1-0.3) (%/º) for tension neck symptoms.
Balogh et al., 2019 (A series of cross-sectional studies) (Measurement device: triaxial accelerometers)	The pooled data from a series of cross-sectional studies including 4733 females and 1107 males from different occupations. (Similar to the study by Nordander et al., 2016)	The results from adjusted analyses found no significant association between neck-shoulder symptoms and head forward inclination.

Discussion

The aim of this review was to synthesize the existing archival literature to answer research questions related to the potential relationship between neck flexion and neck problems (broadly defined as neck pain, discomfort, and musculoskeletal symptoms and disorders). The findings of the current systematic review study are consistent with previous review studies while they widen our knowledge about the relationship between neck flexion and neck problems. The systematic review by Ariëns et al. (2000) introduced some evidence for a positive correlation between neck pain and neck flexion based on only four cross-sectional studies, and thus, their finding was inconclusive. The more recent systematic review by Palmer and Smedley (2007) investigated the work-relatedness of neck-shoulder disorders and suggested a positive relationship between neck flexion and neck-shoulder problems based on limited evidence from seven papers. From the 21 studies that were included in our review, 18 papers (86%) were published after 1997 (the time inclusion criterion of the Ariëns et al. (2000) study), and nine papers (43%) were published after 2006 (the time inclusion criterion of the Palmer and Smedley (2007) study). With these additional papers, our findings revealed a positive correlation between neck flexion angle and neck problems (Kilbom et al. 1986; Ariëns et al., 2002; Szeto et al., 2005; Chiu and Lam, 2007; Baker et al., 2008; Mehrdad et al., 2012; Nordander et al., 2016), and neck-shoulder problems (Hünting et al., 1981; Ohlsson et al., 1995; Andersen et al., 2002; Andersen et al., 2003; Szeto et al., 2005; Sterud et al., 2014).

Unsurprisingly, none of the previous systematic reviews introduced a cut-off angle for neck flexion regarding neck problems. This was one of the main goals of this systematic review. It was found that a neck flexion angle of 20º has the greatest support as the cut-off angle separating high- and low-risk neck flexion postures regarding neck problems (Kilbom et al., 1986; Ariëns et al., 2002; Baker et al., 2008; Mehrdad et al., 2012) and neck-shoulder problems (Andersen et al., 2002; Andersen et al., 2003). It is important to note that the primary goal of these previous studies synthesized here was not to establish a cut-off for neck flexion angles. These studies have evaluated the correlation between neck flexion and neck problems, and in the current systematic review, their results have been used as evidence to introduce possible cut-off angles for neck postural exposure. Although the neck flexion angle of greater than 20º seems to have more evidence than other possible cut-off angles, it doesn't necessarily prove that it is the best cut-off for the neck flexion angle. In 2016, Nordander et al. used their data from a series of cross-sectional epidemiologic studies to evaluate the exposure-respond relationship between occupational risk factors and MSDs in the neck and shoulder. In the discussion, the authors mention that the “establishment of exposure limits is a political and economic issue, not a scientific one. Still, it may be of some interest to indicate how such a limit may look, e.g., based on a shoulder disorder (infraspinatus tendonitis)” (Nordander et al., 2016, p-81). The authors also mentioned that their findings could be the starting point for introducing cut-offs for physical exposures associated with musculoskeletal disorders (Nordander et al., 2016). The authors of this systematic review are of the opinion that the establishment of cut-off for neck postural exposure associated with neck problems is feasible based on scientific evidence, while considering political and economic aspects could help to make such cut-offs more practical in different occupations. Future studies can establish more accurate and reliable cut-off angles than the available cut-offs and enhance the work assessment tools. Some of the established work assessment tools and how they evaluate neck posture have been summarized in Table 2.6. As it is obvious from Table 2.6, the cut-offs for neck postures are not all the same. This observation is consistent with the findings of a 1997 review study by Juul-Kristensen et al. (1997), who summarized the cut-off angles for neck movements from five different methods and showed how the cut-offs were different among the methods (Juul-Kristensen et al., 1997).

There are some limitations in this systematic review study that require attention. The studies that had reported the correlation between neck flexion and neck-shoulder problems were also included because of the high number of studies that reported the outcome as neck-shoulder symptoms. One reason may be the fact that there are some common muscles between the upper spine and shoulder girdle, such as the trapezius. Conclusions were based on studies that focused on neck problems, while the studies that had considered neck-shoulder problems were used to confirm these conclusions, not as part of the analysis. It’s important to note that in the literature review study by Ariëns et al. (2000), they excluded the studies that had combined the neck-shoulder symptoms, but they questioned the accuracy of their methodology as it may have excluded studies that evaluated the neck region (Ariëns et al., 2000). Additionally, musculoskeletal disorders, pain, and discomfort evaluated through physical examination and/or questionnaires (20 studies) and work absence due to neck pain (one study) were all included in this review. Consistency across studies in what is assessed will provide the ability in the future to make stronger statements regarding the evidence of a relationship between workplace exposures

Table 2.6 Work assessment tools and how they evaluate neck posture

Method	Neck assessment	References
Muscle Fatigue Assessment **(MFA)**	**Light - 1:** Head turned partly to side, back, or slightly forward **Moderate - 2:** Head turned to side; head fully back; head forward about 20º **Heavy - 3:** Same as Moderate but with force or weight; head stretched forward	Rodgers, 2005 (developed in 1987)
Plan for Identifiering av Belastningsfaktorer * **(PLIBEL)**	Is repeated or sustained work performed when the neck is: a) Flexed forward? b) Bent sideways or mildly twisted? c) Severely twisted? d) Extended backward?	Kemmlert, 1995
Quick Exposure Check **(QEC)**	In <u>some guides</u>, 20º has been mentioned	David et al., 2008
Rapid Entire Body Assessment (**REBA**)	Movement: 0º-20º flexion. Score=1 Movement: >20º flexion or in extension. Score=2 In both cases, add +1 if twisting or side flexed	Hignett and McAtamney, 2000
Rapid Upper Limb Assessment (**RULA**)	0º-10º flexion. Score=1 10º-20º flexion. Score=2 ≥20º flexion. Score=3 in extension. Score=4. In all cases, if the neck is twisted, add +1, and if the neck is in side-bending, add +1.	McAtamney and Corlett, 1993
Postural Loading on the Upper-Body Assessment **(LUBA)**	Different cut-offs and risk score even depending on sitting and standing postures	Kee and Karwowski, 2001
Cumulative **T**rauma **D**isorders Risk Index (**CTD Risk Index**)	Level 1: Neck flexion>30º Level 2: Neck flexion>45º Level 3: Neck flexion>60º	Seth et al., 1999
Assessment of Repetitive Tasks of the upper limbs (**ART**)	Does not have specific angles	Ferreira et al., 2009
Strain Index (**SI**), Occupational Repetitive Actions (**OCRA**), **ACGIH-HAL**, and Ovako Working Posture Assessment System (**OWAS**) do not include the neck or do not have specific scores for the neck. * "Method for the identification of musculoskeletal stress factors which may have injurious effects."		

and negative outcomes. Additionally, nomenclature matters; in the reviewed studies, different expressions such as head tilt angle, head inclination, and neck flexion have been used, while detailed definitions have not been described in most of these studies. Thus, these expressions were aggregated into a single grouping to allow for extracting useful interpretations from the reviewed studies. Also, it should be noted that neck pain is considered a multifactorial disease with different risk factors, including individual, psychosocial, and physical risk factors (Ariëns et al., 2000). It is not easy to control all these factors and focus on postural exposure to evaluate the effect of this factor on neck problems separately. As mentioned in our answer to Research Question 3 (Q3), one of the most important outcomes of this study is the direction for future research. It is hoped that the findings of this systematic review can attract the experts' attention for future research focusing on the relationship between elaborately defined neck postural exposure and specifically defined neck problems using the new wearable postural measurement tools that allows continuous assessment of postural exposures.

Conclusion

This study revealed a positive correlation between neck flexion and neck problems among the working population. It also found that a neck flexion angle of 20º has the greatest support as the cut-off angle separating high- and low-risk neck flexion postures regarding neck problems. Future research should focus on the continuous collection of three-dimensional neck postures to quantify cumulative exposures of neck postures and employ a standard description of "neck problems" and "neck flexion" to facilitate the development of a dose-response relationship.

Statement of Authorship

AUTHOR CONTRIBUTIONS

Conception and design: HN, MSH

Abstract screening: HN, ET, PS

Full text review and interpretation: HN

Writing the article: HN, ET, PS, GM, MSH

Critical revision of the article: GM, MSH

Final approval of the article: HN, ET, PS, GM, MSH

Overall responsibility: HN

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Appendix: The Actual Search Strategy Listing All Search Terms Used and How They Are Combined.

Ovid

Database(s): EBM Reviews - Cochrane Central Register of Controlled Trials May 2019, EBM Reviews - Cochrane Database of Systematic Reviews 2005 to June 26, 2019, Embase 1974 to 2019 June 27, Ovid MEDLINE(R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily 1946 to June 27, 2019
Search Strategy:

#	Searches	Results
1	((Arthritis adj3 Neck) or Burners or "cervical disorder*" or "Cervical Dystonia" or "cervical injur*" or "cervical laminectom*" or "cervical muscle*" or "cervical pain" or "cervical problem*" or "Cervical Radiculopathy" or "Cervical Spondylosis" or "Cervical Spondylotic Myelopathy" or "Cervical Stenosis" or CSM or "cumulative trauma disorder*" or "cumulative trauma*" or "Herniated Cervical Disc" or "musculoskeletal disease*" or "Musculoskeletal disorder*" or "musculoskeletal pain" or "musculoskeletal problem*" or Myelopathy or "neck disorder*" or "neck injury" or "neck muscle*" or "neck pain" or "neck problem*" or "neck-shoulder disorder*" or "neck-shoulder injur*" or "neck-shoulder muscle*" or "neck-shoulder pain" or "neck-shoulder problem*" or "occupational disease*" or "Pinched Nerve*" or Radiculopathy or "repetitive strain illness*" or "repetitive strain injur*" or "repetitive stress illness*" or "repetitive stress injur*" or "Stiff Neck" or "work acquired illness*" or "work acquired injur*" or "work-related disease*" or "work-related illness*").ti,ab.	139972
2	(cervical or neck or "neck-shoulder*" or occipital or "upper body" or "upper extremit*" or "upper limb*").ti,ab.	1115113
3	1 and 2	67543
4	(angle or angles or extension or flexion or force or "lateral bending" or "physical load*" or postural or posture or "repetitive motion" or "side-bending" or static or twist or twisting).ti,ab.	1582272
5	3 and 4	11246
6	limit 5 to english language [Limit not valid in CDSR; records were retained]	9997
7	limit 6 to yr="1985 -Current"	9852
8	limit 7 to (letter or conference abstract or editorial or erratum or note or addresses or autobiography or bibliography or biography or blogs or comment or dictionary or directory or interactive tutorial or interview or lectures or legal cases or legislation or news or newspaper article or overall or patient education handout or periodical index or portraits or published erratum or video-audio media or webcasts) [Limit not valid in CCTR,CDSR,Embase,Ovid MEDLINE(R),Ovid MEDLINE(R) Daily Update,Ovid MEDLINE(R) In-Process,Ovid MEDLINE(R) Publisher; records were retained]	1382
9	7 not 8	8470
10	(adult or adulthood or adults or "middle age" or "middle aged").ti,ab,hw,kw.	15044254
11	9 and 10	5757
12	remove duplicates from 11	3167

<u>Scopus</u>

1 TITLE-ABS((Arthritis W/3 Neck) or Burners or "cervical disorder*" or "Cervical Dystonia" or "cervical injur*" or "cervical laminectom*" or "cervical muscle*" or "cervical pain" or "cervical problem*" or "Cervical Radiculopathy" or "Cervical Spondylosis" or "Cervical Spondylotic Myelopathy" or "Cervical Stenosis" or CSM or "cumulative trauma disorder*" or "cumulative trauma*" or "Herniated Cervical Disc" or "musculoskeletal disease*" or "Musculoskeletal disorder*" or "musculoskeletal pain" or "musculoskeletal problem*" or Myelopathy or "neck disorder*" or "neck injury" or "neck muscle*" or "neck pain" or "neck problem*" or "neck-shoulder disorder*" or "neck-shoulder injur*" or "neck-shoulder muscle*" or "neck-shoulder pain" or "neck-shoulder problem*" or "occupational disease*" or "Pinched Nerve*" or Radiculopathy or "repetitive strain illness*" or "repetitive strain injur*" or "repetitive stress illness*" or "repetitive stress injur*" or "Stiff Neck" or "work acquired illness*" or "work acquired injur*" or "work-related disease*" or "work-related illness*")
2 TITLE-ABS(cervical or neck or "neck-shoulder*" or occipital or "upper body" or "upper extremit*" or "upper limb*")
3 TITLE-ABS(angle or angles or extension or flexion or force or "lateral bending" or "physical load*" or postural or posture or "repetitive motion" or "side-bending" or static or twist or twisting)
4 PUBYEAR AFT 1984 AND LANGUAGE(english)
5 TITLE-ABS-KEY(adult or adulthood or adults or "middle age" or "middle aged")
6 1 and 2 and 3 and 4 and 5
7 DOCTYPE(le) OR DOCTYPE(ab) OR DOCTYPE(ed) OR DOCTYPE(bk) OR DOCTYPE(er) OR DOCTYPE(no) OR DOCTYPE(sh)
8 6 and not 7
9 INDEX(embase) OR INDEX(medline) OR PMID(0* OR 1* OR 2* OR 3* OR 4* OR 5* OR 6* OR 7* OR 8* OR 9*)
10 8 and not 9

<u>CINAHL</u>

(TI ((Arthritis N3 Neck) or Burners or "cervical disorder*" or "Cervical Dystonia" or "cervical injur*" or "cervical laminectom*" or "cervical muscle*" or "cervical pain" or "cervical problem*" or "Cervical Radiculopathy" or "Cervical Spondylosis" or "Cervical Spondylotic Myelopathy" or "Cervical Stenosis" or CSM or "cumulative trauma disorder*" or "cumulative trauma*" or "Herniated Cervical Disc" or "musculoskeletal disease*" or "Musculoskeletal disorder*" or "musculoskeletal pain" or "musculoskeletal problem*" or Myelopathy or "neck disorder*" or "neck injury" or "neck muscle*" or "neck pain" or "neck problem*" or "neck-shoulder disorder*" or "neck-shoulder injur*" or "neck-shoulder muscle*" or "neck-shoulder pain" or "neck-shoulder problem*" or "occupational disease*" or "Pinched Nerve*" or Radiculopathy or "repetitive strain illness*" or "repetitive strain injur*" or "repetitive stress illness*" or "repetitive stress injur*" or "Stiff Neck" or "work acquired illness*" or "work acquired injur*" or "work-related disease*" or "work-related illness*") OR AB ((Arthritis N3 Neck) or Burners or "cervical disorder*" or "Cervical Dystonia" or "cervical injur*" or "cervical laminectom*" or "cervical muscle*" or "cervical pain" or "cervical problem*" or "Cervical Radiculopathy" or "Cervical Spondylosis" or "Cervical Spondylotic Myelopathy" or "Cervical Stenosis" or CSM or "cumulative trauma disorder*" or "cumulative trauma*" or "Herniated Cervical Disc" or "musculoskeletal disease*" or "Musculoskeletal disorder*" or "musculoskeletal pain" or "musculoskeletal problem*" or Myelopathy or "neck disorder*" or "neck injury" or "neck muscle*" or "neck pain" or "neck problem*" or "neck-shoulder disorder*" or "neck-shoulder injur*" or "neck-shoulder muscle*" or "neck-shoulder pain" or "neck-shoulder problem*" or "occupational disease*" or "Pinched Nerve*" or Radiculopathy or "repetitive strain illness*" or "repetitive strain injur*" or "repetitive stress illness*" or "repetitive stress injur*" or "Stiff Neck" or "work acquired illness*" or "work acquired injur*" or "work-related disease*" or "work-related illness*"))
AND
(TI (cervical or neck or "neck-shoulder*" or occipital or "upper body" or "upper extremit*" or "upper limb*") OR AB (cervical or neck or "neck-shoulder*" or occipital or "upper body" or "upper extremit*" or "upper limb*"))
AND
(TI (angle or angles or extension or flexion or force or "lateral bending" or "physical load*" or postural or posture or "repetitive motion" or "side-bending" or static or twist or twisting) OR AB (angle or angles or extension or flexion or force or "lateral bending" or "physical load*" or postural or posture or "repetitive motion" or "side-bending" or static or twist or twisting))

AND
(TI (adult or adulthood or adults or "middle age" or "middle aged") OR AB (adult or adulthood or adults or "middle age" or "middle aged"))
Limiters - Published Date: 19850101-20191231; English Language; Exclude MEDLINE records; Publication Type: Journal Article

CHAPTER 3. PRELIMINARY STUDY II: EFFECTS OF BREAK SCHEDULING STRATEGIES ON SUBJECTIVE AND OBJECTIVE MEASURES OF NECK AND SHOULDER MUSCLE FATIGUE IN ASYMPTOMATIC ADULTS PERFORMING A STANDING TASK REQUIRING STATIC NECK FLEXION

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Abstract

Sustained non-neutral postures of the head/neck are related to transient neck discomfort and longer-term disorders of the neck. Periodic breaks can help but the ideal length and frequency of breaks are yet to be determined. The current study aimed to quantify the effects of three work-rest strategies on fatigue development. Participants maintained a 45-degree neck flexion posture for a total of 60 minutes and were provided three minutes of rest distributed in different ways throughout the experiment [LONG (one, three-minute break), MEDIUM (two, 1.5-minute breaks), or SHORT (five, 36-second breaks)]. Surface electromyography data were collected from the bilateral neck extensors and trapezius. Subjective discomfort/fatigue ratings were also gathered. Results of the analysis of the EMG data revealed that the SHORT condition did not show increased EMG activity, while LONG [21%] and MEDIUM [10%] did ($p<0.05$), providing objective data supporting the guidance of short, frequent breaks to alleviate fatigue.

Introduction

Neck pain is prevalent in both the general and working populations (Bovim et al., 1994; Côté et al., 1998). In a cross-sectional study by Côté et al. (1998), the lifetime prevalence of neck pain was found to be 66.7% in adults between the ages of 20 and 69 years. The annual incidence rate of neck pain in a similar study by the same author was found to be 14.6% (Côté et al., 2004). In another cross-sectional study by Genebra et al., (2017), among adults aged 20 and over, 20.3% of the interviewed participants had experienced neck pain once or more in the last 12 months. It has been estimated that health care spending on low back and neck pain in the United States was $87.6 billion in 2013, making it the third most costly condition for personal health care spending in 2013 (Dieleman et al., 2016). Neck pain can be transient, such as that from muscular fatigue during extended bouts of work with non-neutral neck postures; or chronic, indicating the potential for an underlying musculoskeletal disorder. Work that requires sustained non-neutral postures of the head and neck have been shown to be related to transient neck discomfort as well as longer-term disorders of the tissues of the neck (Vijendren et al., 2018; Davila et al., 2019).

Neck pain/discomfort is seen across a wide variety of working populations. It can be a burdensome problem causing disabling conditions and work absenteeism (Côté et al., 2008; Côté et al., 2009; Palmer et al., 2001). A high prevalence of neck discomfort has been reported in scissor makers, shop assistants, factory workers and surgeons (Kuorinka and Koskinen 1979; Luopajarvi et al., 1979; Howarth et al., 2019; Coleman et al., 2019; Davila et al., 2019; Wells et al., 2019). Similarly, recent surveys of surgeons have shown that they experience high levels of work-related pain in the neck (Howarth et al., 2019; Coleman et al., 2019; Davila et al., 2019; Wells et al., 2019; Szeto et al., 2009) and these surgeons are concerned that this pain will influence their ability to perform surgical procedures in the future (Park et al., 2017; Howarth et al., 2019; Coleman; et al., 2019; Davila et al., 2019; Wells et al., 2019). Extended time on computers (desktops, laptops or tablets) for work or home use is also associated with neck fatigue and discomfort symptoms (Jensen et al., 2002; Brandt et al., 2004). One study reported that over 61% of visual display terminal users experienced neck/shoulder discomfort determined through questionnaires and a physiotherapist's examination (Bergqvist et al., 1995).

Prolonged static posture due to high work demand can generate negative muscular responses such as ischemia/hypoxia (Merletti, 1984) and lead to neck muscle fatigue. In the presence of ischemia, oxygen supply to blood is hindered (Griffin et al., 2001) and in the absence of adequate oxygen supply, anaerobic muscle metabolism occurs with the inevitable accumulation of lactate in the muscle (Di Prampero et al., 1999) resulting in transient discomfort in the muscle tissue. Lactate accumulation results in reduced production of ATP, thereby accelerating fatigue (Westerblad et al., 2010). These physiological responses result in changes in the electrical activity of the muscles measured through electromyography. As the muscle fatigues, there is a loss in the force-generating capacity of individual motor units and to maintain the posture, the central nervous system (CNS) gradually recruits new motor units, thereby increasing the measured magnitude (integrated EMG) of the signal (Bosch et al., 2007; Straker et al., 1997; Vijendren et al., 2018). In some muscles, shifting from the engagement of fast-twitch muscle fibers to slow-twitch fibers can lead to a decrease in median frequency, but that has not been seen consistently in the muscles of the neck (Szeto et al., 2005).

Previous studies have demonstrated the positive effects of periodic breaks on fatigue development (Mclean et al., 2001; Sjøgaard et al., 1988; Griffin et al., 2001). Studies exploring the effect of breaks during surgical tasks (Engelmann et al., 2011; Hallbeck et al., 2017; Vijendren et al., 2018), and computer terminal work (Galinsky et al., 2000; Galinsky et al., 2007; Mclean et al., 2001) have shown that incorporating breaks between bouts of static posture can reduce participants' subjective discomfort and fatigue. Several previous studies have considered varied break durations and frequencies, but there is no consensus on the frequency or duration of the breaks (Galinsky et al., 2000; Galinsky et al., 2007; McLean et al., 2001; von Thiele Schwarz et al., 2008). To successfully incorporate work breaks into practice, further quantitative research using objective measures of fatigue (EMG) may be needed to identify the optimal frequency and duration of breaks to reduce muscle fatigue.

The current study aims to explore the impact of varied work-rest intervals and how they can affect the development of neck and shoulder muscular fatigue during a simple standing task that requires static neck flexion. We hypothesize that the fatigue response of the neck and shoulder muscle will vary across the three different work-rest scheduling models.

Method

Participants

Fourteen participants (seven men, seven women) from Iowa State University student community completed data collection for all conditions in this study. Sixteen participants consented, but two participants were unable to complete the study. Participants were all adults between 18 and 65 years of age with no history of chronic problems in the neck, shoulders, back, legs, or neck, and all were right-handed. Mean (standard deviation) of anthropometric variables were as follows: age was 24 (4.2) years; whole body mass was 70.1(12.0) kg; stature was 172.2 (8.4) cm; standing elbow height was 112.3 (5.3) cm. Participants were all college students, so their experience in performing tasks similar to those in this study were comparable. Participants provided written informed consent prior to each day of participation.

Apparatus

Surface electromyography was used to collect muscle activity of the cervical extensor musculature and trapezius muscles using DELSYS® Bagnoli-16 EMG system and DE-2.1

sensors (Delsys Inc., MA). Eight surface electrodes were used to record the activity of the right and left pairs of the neck extensors at the C2/C3 level (SC2/3), the neck extensors at the C3/C4 level (SC3/4), and the right and left pairs of the trapezius at two locations of the upper trapezius (UT1 and UT2). The SC2/3 electrodes were placed bilaterally at the C2-C3 levels 1.5 cm from the midline of the spine (shaving as necessary). The SC3/4 electrodes were placed bilaterally at the C3-C4 level at a distance of 2.5 cm from the midline of the spine. These horizontal locations varied slightly from participant to participant, depending on the anthropometry of the neck so that the electrodes were placed over the belly of the most superficial muscle. Prior to electrode placement the skin was cleaned thoroughly with rubbing alcohol. While it is recognized that there are other neck extensor muscles within the pickup area of the surface electrodes for the neck extensors (SC2/3 and SC3/4), we will refer to these dependent variables as the SC2/3 and SC3/4 emphasizing the significant contributions of the semispinalis capitis and splenius capitis muscles to the captured signal. The location of the UT1 electrodes were on the superior surface of the trapezius over the belly of the muscle at that location, while the UT2 electrodes were 4cm inferior to that position. Surface EMG data collection was initiated every 30 seconds throughout the experiment and data were collected for four seconds at a frequency of 1024 Hz.

To capture the participants' subjective level of discomfort and fatigue, a simple visual analog scale (VAS) was used. Participants were asked to evaluate on a scale of 0 ("no discomfort") to 10 ("significant discomfort") their level of discomfort in the neck, shoulder, upper back, lower back, wrists/hands, knees, and ankles, as well as their overall fatigue (on a scale of 0 ("no fatigue") to 10 ("extremely fatigued")) (Hallbeck et al., 2017). Participants provided these data immediately before and immediately after the 63-minute experimental task.

Experimental Procedures

Participants came to the lab on three separate days, once for each work-rest condition. Participation sessions were separated by at least 48 hours to allow for recovery and reduce potential carry over effects. Each day participants provided written informed consent. On the first day, basic anthropometric data including age, stature, body weight, standing elbow height, standing knee height, and hand dominance were collected.

The protocol for this study was approved by the Iowa state University IRB (Approval memo found in Appendix). Upon arrival each day, participants provided written informed consent to participate, and then they were led through a series of non-strenuous warm-up/stretch exercises that focused on the neck and shoulder region (flexion/extension, rolling and lateral motions of the neck). Surface electrodes were then affixed to the skin over the muscles to be sampled. The participants then provided baseline discomfort and fatigue level using the VAS to provide these baseline discomfort and fatigue scores. Participants were then asked to stand next to a table and perform a simple distractor task on a tablet computer for a total of 60 minutes with a total of 3 minutes of rest. While performing the distractor task (a simple computer game called "2048"), participants were required to flex their neck at a 45-degree angle. In pilot studies, this flexion angle was shown to generate muscular fatigue without engaging the flexion- relaxation phenomenon. At specified times, participants were given a short rest break - variable frequency and duration depending on the condition (Figure 1). The rest break schedule varied between conditions, but the total work time was 60 minutes and total rest time was three minutes for all conditions. The order in which the work- rest (W-R) conditions were presented was randomized across the three days. The experiment consisted of three work-rest conditions shown graphically in Figure 3.1.

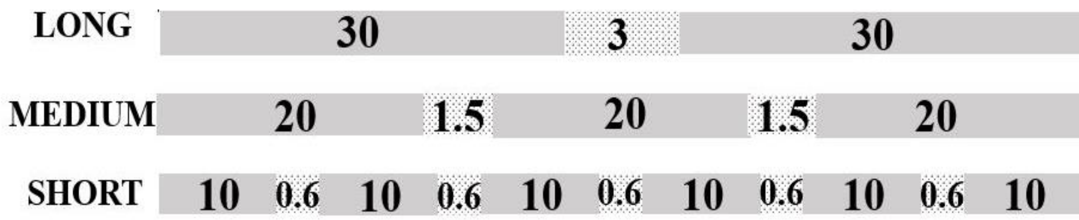


Figure 3.1 Graphical presentation of the three work-rest conditions - all times in minutes. Darker regions represent time when neck is flexed at a 45-degree angle (work) and lighter regions represent time when the head is in an upright neutral posture (rest).

The work surface was set at the height of 5 cm below the participant's standing elbow height, and the participant selected a comfortable (but not staggered) stance. This foot position was marked with tape so that the participant could return to this same foot position for every experimental condition across days. The 45-degree flexed neck position was then identified. Participants wore a baseball cap (secure fit) with a lightweight laser light attached to the bill. The participants were asked to flex their head-neck until a 45-degree angle was reached and tape was placed on the table marking the laser pointer location when the head was flexed to 45 degrees (Figure 3.2). During the neck flexion phases of the experiment, participants were required to keep the laser beam on the tape to ensure they maintained a continuous 45-degree head flexion posture. Once the participant was in position, the tablet computer was placed on the tabletop surface in front of them. The tablet was set at an angle of around 30 degrees, so the screen was slightly tilted towards the participant. The participants placed the tablet in a position that was within their comfortable line of vision and within a comfortable hand/arm reach. The distance from the tablet to the table edge was recorded and the tablet was placed in the same location for every experimental condition.

During the work task, participants played a simple game on the tablet computer. They were required to keep both hands just above the tablet, even if only one hand was being used in

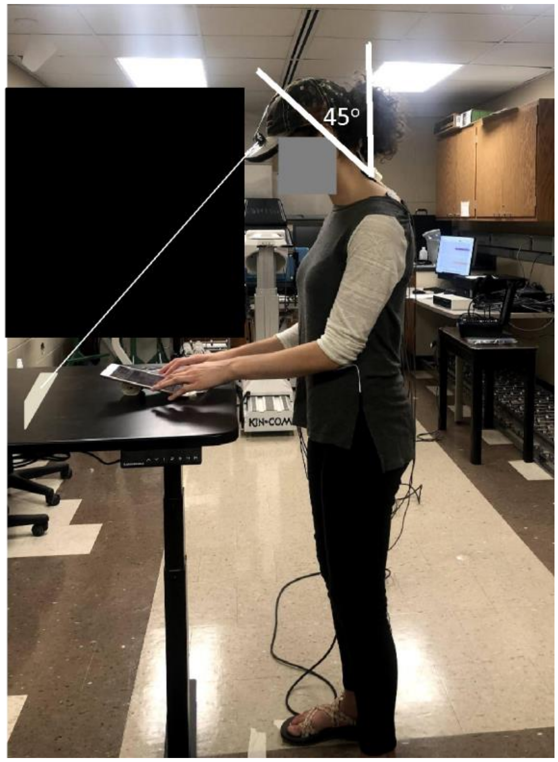


Figure 3.2 Experimental apparatus showing how the laser pointer secured to the bill of the ballcap and the masking tape on the table were used to control 45-degree head-neck flexion during the experimental procedure. Also shown is the upper extremity posture while interacting with the tablet.

playing the game. At thirty-second intervals, the participants were asked to pause in their game playing for a static (no motion to control for motion artefacts) EMG data collection. During this “pause”, participants maintained the 45-degree head-neck flexion angle but placed the tips of their index fingers lightly against marked positions on the sides of the tablet (Figure 2). Once the participant achieved the required position, data were collected for four seconds and then the participants were instructed to resume the game-playing task. During the experimental task an experimenter watched closely as the participant performed the task to ensure that the trunk remained in an upright posture.

At the designated time and for the designated duration as determined by the W-R condition assigned for that day and participant took a break. At the designated time, the experimenter said “rest” and the participant raised their head-neck to an upright neutral posture. They were allowed to move around, but they were asked to keep their head in the upright posture. At the completion of the break period, the experimenter said “return” and that was the signal for the participant to flex the head-neck so that the laser was focused on the tape target and they were to resume the game on the tablet. This continued until the 63-minute total experiment duration was completed. At that time the participant again completed the VAS form for body part discomfort and overall fatigue.

Data Processing

The first step in the processing of the EMG data was to apply a simple band-pass filter eliminating signal frequencies less than 10 Hz and greater than 400 Hz as well as 60 Hz and its aliases. These filtered data were then processed in two different ways – one in the time domain and one in the frequency domain. In the time domain, these data were demeaned, rectified, and then averaged over the full four-second data collection period creating the average value of the rectified amplitude (AVRA). Since the task was symmetric in the sagittal plane, the average of the right and left of each muscle was calculated. In the frequency domain, a Fast Fourier Transform was applied to these data to calculate the median frequency (MDF) for each trial, and then the average of the right and left of each muscle was calculated. For each participant, there were 120 data points (two data collections/minute for 60 minutes (no data collected during the rest intervals)) of AVRA and MDF per condition. To control for day-to-day and person-to-person variability, the AVRA data were normalized with respect to the muscle-specific average of these 120 data points. It is noteworthy that as the participants “settled in” to the experiment each day, there was often transient noise observed in the EMG signals early in the trial, so the first two minutes of data collection (four data points) were not considered in this analysis nominally rendering a total of 116 data points per participant per condition. For the AVRA and MDF variables, the difference between the average of the values in the first five minutes and the average of the values in the last five minutes of the 63-minute period (omitting the first two minutes from the analysis) were calculated. This difference in the values from the beginning to the end are simply noted by the variable names SC2/3, SC3/4, UT1 and UT2 and are considered in both the time and frequency domain. The processing of the subjective responses of the participants (discomfort and fatigue from the VAS) was simply to calculate the difference in these integer (0-10) values (the post-experiment value minus the pre-experiment value).

Experimental Design

The independent variable in this study was the work-rest cycle strategy (W-R), which had three levels of LONG, MEDIUM, and SHORT, and these profiles are shown in Figure 1.

The dependent variables considered in this study included both objective and subjective measures. The objective measures of fatigue were the changes in the AVRA (variable names: SC2/3, SC3/4, UT1 and UT2), and MDF (mfSC2/3, mfSC3/4, mfUT1 and mfUT2) from the beginning of the experiment to the end of the experiment of the right-left average of the sampled muscles (calculations and normalization described above in Section 2.4). The subjective measures were the change (end - beginning) in the discomfort of the neck, shoulders, upper back, lower back, wrists/hands, knees, and ankles/feet, as well as overall fatigue.

Statistical Analyses

A randomized block design was employed, with participants acting as a random-effects blocking variable, and W-R cycle strategy was considered as the treatment. Statistical software JMP Pro 15 was used to perform all the statistical analyses. Prior to conducting the statistical analysis, the assumptions of the ANOVA procedure were assessed. The normality of residuals and the equality of variances were tested for all dependent variables using Shapiro-Wilk test and O'Brien test, respectively. For those dependent variables that passed these tests, the one-way ANOVA was conducted. For those dependent variables that violated these assumptions, the non-parametric Kruskal-Wallis test was employed, as were the non-parametric Wilcoxon Signed-Rank tests for the post-hoc pairwise comparisons. A significance level of 0.05 was used as the criteria value for statistical significance in all tests. In order to maintain an overall significance level of 0.05, the Bonferroni correction was applied for the pairwise comparisons (0.05/3=0.0167). A Kruskal-Wallis test was used to evaluate the effects of different conditions on the change in the subjective discomfort and fatigue scores. A criterion significance level of 0.05 was again used.

Results

An analysis of the subjective measures of body part discomfort and overall fatigue showed statistically significant increases in all measures over the 63-minute task, with a particularly strong response of the neck and shoulder discomfort as well as the overall fatigue. This was true for all three W-R strategies (Table 3.1). The statistical analysis of the independent variable W-R, however, did not reveal any statistically significant differences in the increase in the discomfort or overall fatigue scores among the three different work-rest conditions tested (all p-values >0.05) indicating that while the participants were subjectively fatigued, there were no statistically significant differences as a function of work-rest schedule strategy.

With respect to the more objective EMG data, a comparison of the AVRA values collected at the beginning and the ending of the 63-minute task did show evidence of muscle fatigue development. Figures 3.3 and 3.4 show the responses of the AVRA for SC3/4, SC2/3, respectively. For both the SC2/3 and the SC3/4 sampling locations, there was a statistically significant increase in the average rectified value of the amplitude for medium and long condition – an indicator of muscle fatigue development. This response was not seen in the upper trapezius sampling locations and, consistent with the results of Szeto et al. (2005), none of the muscle sampled showed a statistically significant decrease in median frequency of the EMG signal.

In terms of testing the effects of work-rest scheduling strategies, the response of the SC3/4 at different levels of W-R was statistically significant (Kruskal-Wallis Test: p=0.0009), while the response of the SC2/3 - while demonstrating a similar trend - was not statistically significant. The pairwise comparison using the Wilcoxon Signed-Rank Test for the response of the SC3/4 showed that there is a significant difference between LONG and SHORT conditions (p=0.0004) and MEDIUM and SHORT conditions (p=0.0063) while LONG and MEDIUM conditions were not significantly different. The statistical analysis of the AVRA of the two levels of the trapezius did not show a statistically significant difference across levels of W-R. The analysis of the median frequency of all sampled muscles revealed small, inconsistent and non-significant differences.

Table 3.1 The mean (standard deviation) of the increase in discomfort scores and overall fatigue for three different conditions (LONG, MEDIUM, and SHORT). * indicates that the increase over the 63-minute task was statistically significant (*** p<0.0001; ** p<0.001; * p<0.05). There were no statistically significant differences in these values as a function of the W-R condition.

	LONG	MEDIUM	SHORT
Neck	5.14 (2.63) ***	4.64 (2.71) ***	5.36 (2.56) ***
Shoulder	4.14 (2.54) **	3.68 (3.12) ***	3.79 (2.42) ***
Upper back	2.93 (2.16) **	2.93 (2.87) **	3.07 (2.70) **
Lower back	2.71 (2.67) **	2.14 (2.28) **	2.29 (2.55) *
Wrist/ hand	2.43 (2.56) *	1.93 (2.37) *	1.29 (1.90) **
Knee	3.14 (2.71) *	2.43 (2.68) **	2.79 (3.29) **
Ankle/ feet	5.00 (2.69) ***	4.43 (2.10) ***	4.57 (2.31) ***
Overall fatigue	5.07 (2.34) ***	4.71 (2.43) ***	4.43 (2.06) ***

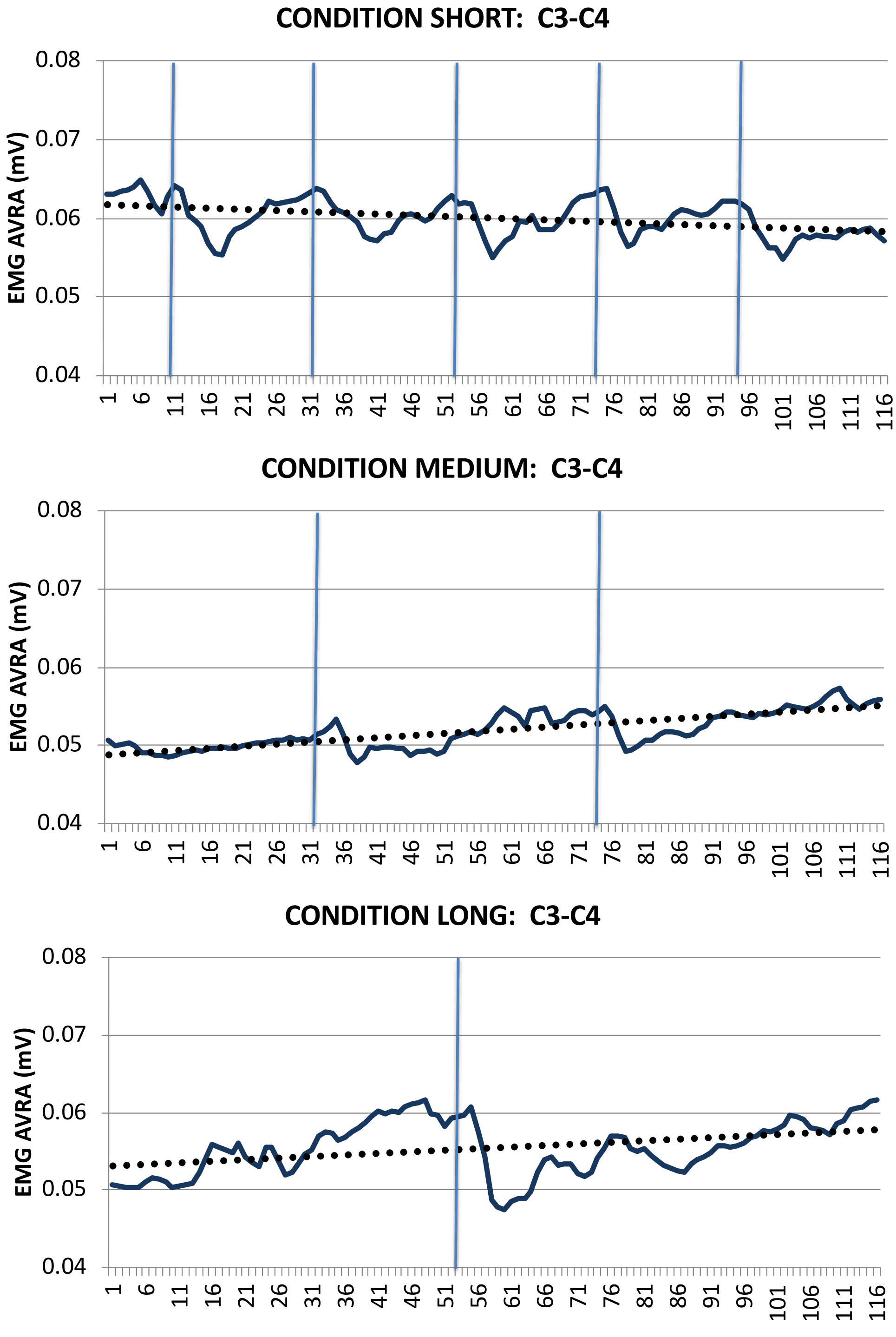
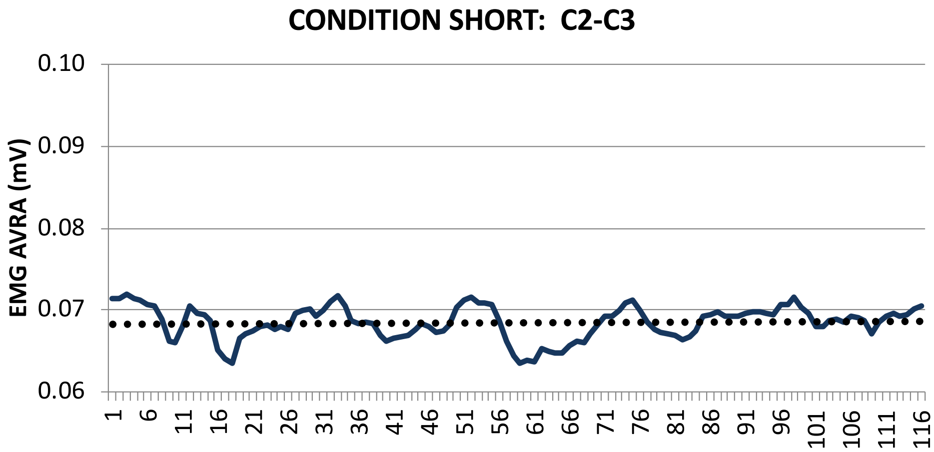
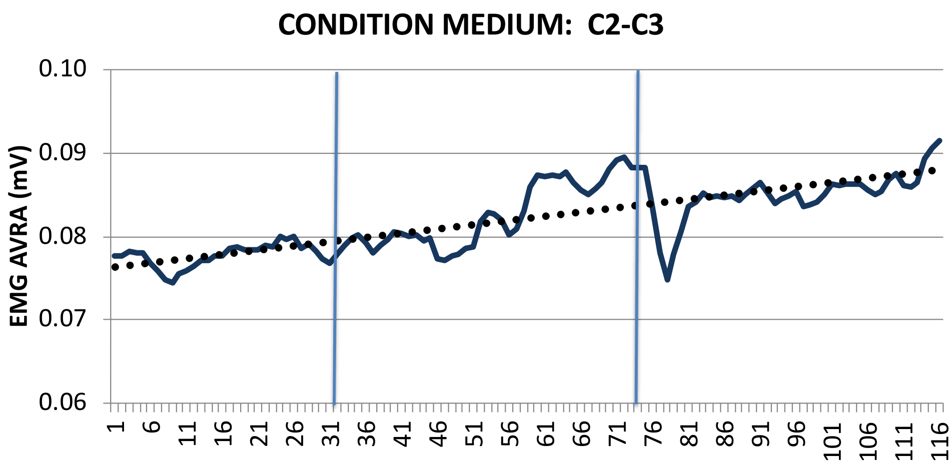


Figure 3.3 Average AVRA values for SC3/4 (averaged for left and right muscles in mV) of all the subjects over the duration of the 116 data collections (one collection every 30 seconds). The post-hoc analyses showed that the response in the SHORT condition was significantly different than that of the MEDIUM and LONG conditions.





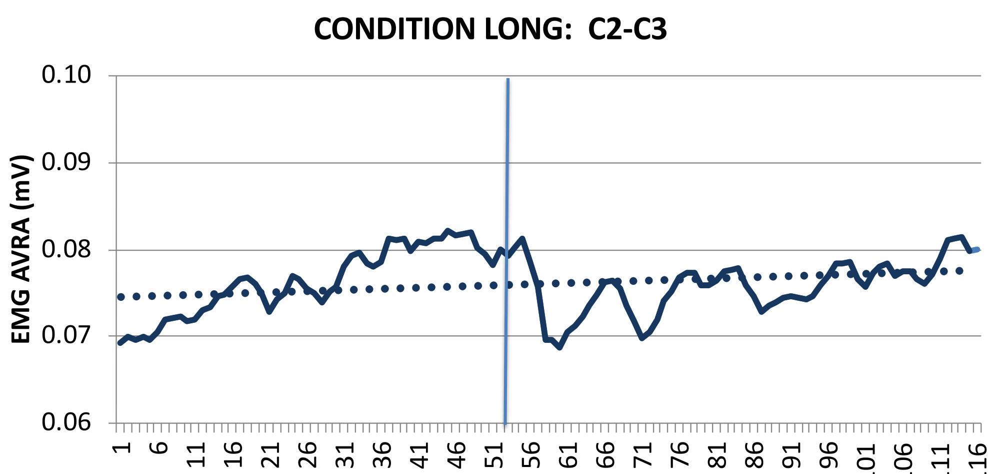


Figure 3.4 Average AVRA values for SC2/3 (averaged for left and right muscles in mV) of all the subjects over the duration of the 116 data collections (one collection every 30 seconds). While there were trends that were consistent with the response of SC3/4, these responses were not statistically significant as they were for SC3/4.

Discussion

Physical fatigue is a highly subjective and challenging-to-measure human response to work. There are established objective physical responses of skeletal muscle that have been used extensively in ergonomics and work physiology literature and most of these have involved the capture and interpretation of the electrical activity of the muscles through surface electromyography. In the current study, both time-domain and frequency-domain electromyography measures of neck muscle fatigue were considered and, interestingly, the time-domain measures were responsive while the frequency domain measures were not. This result is consistent with the results of previous studies (e.g. Szeto et al., 2005; Vijendren et al., 2018) and may be the result of complex neural strategies that involve the increased recruitment of Type II muscle fibers that may be somewhat unique in the cervical muscles.

It is well established that the introduction of breaks during prolonged static neck flexion can delay the onset of neck and shoulder fatigue/pain (e.g. Genaidy et. al., 1995; Vijendren et al., 2018). The aim of the current study was to explore the effects of different work-rest cycles on neck muscle fatigue development, while keeping the total work time and total rest time constant. The results support our hypothesis that different work-rest strategies will impact the development of muscular fatigue. The LONG and MEDIUM conditions showed significantly higher muscle fatigue (as demonstrated by an increase in the AVRA value for the C3-C4 cervical erector spinae) than the SHORT condition. However, following that trend, our hypothesis might have predicted that the LONG condition would have created even more muscular fatigue that the MEDIUM condition which was not the case. It appears that there may be thresholds/discontinuities in this response that may be important in the development of work-rest cycles for the attenuation of fatigue in the cervical musculature. Our results would indicate that the threshold is somewhere in between what we have called the MEDIUM and SHORT conditions. Future research may seek to elucidate more precisely this threshold value.

While these results demonstrated a significant effect of W-R on the SC3/4, there were no significant effects of W-R on the trapezius muscles or the SC2/3. To explore the non-response of the trapezius, it is important to remember that the upper extremities were not supported in the task. Some participants may have chosen to utilize a posture wherein the shoulders would be elevated, while others could choose to abduct the shoulders during the task, resulting in differing levels of trapezius muscle utilization. This variability in strategy would have a direct impact on the fatigue development in the trapezius muscles – creating variability that would make it difficult to find statistically significant trends. The case for SC2/3 is a bit more challenging to interpret but may again focus on different strategies for accomplishing the experimental task. The SC2/3 muscles may be a bit more focused on maintaining head tilt angle and therefore may be performing a slightly different role during the experimental task. Tracking the sagittal plane angle at multiple levels in the cervical spine in future research might provide some insights to this slightly differential response.

The result of the current study showed that more frequent and shorter breaks reduces muscle fatigue – a result consistent with several field studies that have focused the subjective assessment of muscular fatigue and the effects of break duration and break activity. For example, Balci & Aghazadeh (2003) studied video display terminal workers. In this study the total work time was 120 minutes and the total rest period was 30 minutes, but the distribution and duration of the resting bouts varied. The results of the body part discomfort analysis from this previous study showed that the more frequent/short duration breaks resulted in lowered levels of body part discomfort. A study by McLean et al. (2001) on computer terminal workers also suggested that microbreak can reduce discomfort significantly when applied every 20 minutes. Participants were assigned with no breaks, microbreaks at their wish, breaks at every 20 minutes and breaks every 40 minutes. The results obtained from this study based on a discomfort survey, showed that taking a break every 20 minutes reduced muscle discomfort significantly. The EMG-based results in the current study do support the results of these studies that have focused on the subjective assessments. Interestingly, our participants' subjective ratings did not show a clear advantage of one work-rest strategy over another. Finally, a study by Hallbeck and colleagues (2017) with surgeons as the occupational group, explored the effects of breaks, but this time by adding simple exercise. In this multi-site cohort study, the authors did a pre- post- survey of 56 attending surgeons – one day without microbreaks and one day with microbreaks. At intervals of 20-40 minutes, the surgeons were provided breaks lasting 1.5-2 minutes. The results showed that shoulder discomfort was significantly reduced and almost 60% of the surgeons reported improved physical performance (none noted decreased physical performance). Eighty-seven percent of the surgeons studies said that they would like to incorporate the microbreaks with exercises into their regular operating room routine. The break frequency and duration is similar to the MEDIUM and LONG conditions in the current study, indicating that the use of exercise during a break may further enhance the effectiveness of the breaks.

There are some limitations to the generalizability of these results that should be noted. First, the duration of our study is quite a bit shorter than the duration of tasks requiring static work postures experienced by workers in many occupations. In this controlled laboratory study, the allocated time proved to be enough to objectively develop muscle fatigue without creating any strain from prolonged neck flexion (Kromberg et al., 2020), but to achieve this muscular fatigue artificial constraints on participant mobility during this standing task was required to avoid small periods of recovery. More realistic scenarios (longer task duration, allowing participants to self-select break periods, neck stretching/motions during breaks) may prove to be a valuable next step in this line of research. Second, the sample of fourteen participants were relatively inexperienced in performing work requiring this posture. If our sample was larger and included workers experienced in work requiring these postures, different work strategies of this type of standing task might emerge. Finally, the participants were all healthy, pain-free individuals with no history of chronic neck problems. Future studies can examine the effect of breaks on the responses of those with chronic neck pain.

Conclusion

Overall, it appears that, of the work-rest strategies tested, the best W-R period strategy for preventing neck muscle fatigue for flexion of 45 degrees is the shortest one tested with a 10-minute static work posture and 36 second relaxation period. This is shorter than most of the recommendations in the literature, which may balance the physiologic data with the acceptability of task interruption. Determining the best work-rest cycle strategy for performing work requiring neck flexion is important as more and more office work is performed on laptops and tablets. Other types of work may also require long periods of neck flexion to complete tasks. Future work can be done considering the effects of different strategies on the other aspects of an occupation including physical and cognitive performance (such as productivity and accuracy). It could help to determine the appropriate strategy for each specific occupation.

Statement of Authorship

AUTHOR CONTRIBUTIONS

Conception and design: PS, GM, HN, MSH

Analysis and interpretation: PS, HN, JK, GM, MSH

Data collection: PS, JK, HN

Writing the article: PS, HN, JK, GM, MSH

Critical revision of the article: GM, MSH

Final approval of the article: PS, HN, JK, GM, MSH

Statistical analysis: HN, PS

Overall responsibility: PS

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Appendix: IRB approval memo

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 09/24/2019

To: Gary Mirka

From: Office for Responsible Research

Title: **Effects of Break Schedule on Neck Muscle Fatigue**

IRB ID: **19-392**

Submission Type: Initial Submission   **Review Type:** Expedited

Approval Date: 09/24/2019   **Approval Expiration Date: N/A**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- Retain signed informed consent documents **for 3 years after the close of the study**, when documented consent is required.

- **Obtain IRB approval prior to implementing any changes** to the study or study materials.

- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.

- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.

- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks** to subjects or others.

- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of

those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to **post-approval monitoring by Iowa State University's Office for Responsible Research**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.

- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.

- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

CHAPTER 4. PRELIMINARY STUDY III: A MAXIMUM VOLUNTARY CONTRACTION (MVC) PREDICTION METHOD BASED ON SUBMAXIMAL VOLUNTARY CONTRACTION (SVC)

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Modified from a manuscript to be submitted to Journal of Electromyography and Kinesiology

Abstract

The motivation for developing this model was to decrease muscle fatigue and the risk of injury due to exerting MVC in the experiments that require participation on multiple days. The main goal of this study was to develop a regression model that calculates the muscle MVC for a test day based on the MVC and SVCs of that muscle during a reference day and the SVCs of that muscle during that test day. The MVC and SVC of biceps brachii, rectus femoris, and neck flexor and extensor muscles were collected from ten participants on two days. On the first day of participation, the muscles MVC, and 20%, 40%, and 60% of the maximum generated moment during MVC were collected (SVC-20%, SVC-40%, and SVC60%, respectively). On the second day of participation, the participant's SVCs from the first day and their new MVC were collected. The best SVC as a predictor for the MVC was found using stepwise multiple linear regression. The best fit linear regression between the best SVC and MVC was found for the first day of participation. The same regression equation was used to predict MVC based on SVC on the second day of participation. In all the regression models, the intercept was set to zero. The absolute percentage error (AE%) was used to evaluate the accuracy of the MVC estimations. The results suggest that in this predictive model, SVC-60% was the best linear predictor of MVC for biceps brachii, rectus femoris, and neck flexors, while SVC-20% was the best predictor of MVC

for neck extensors. Using the MVC and SVCs of a reference day and the SVCs of the test day to estimate the MVC on the test day led to a mean absolute percentage error between 23.54%-29.36% depending on the muscle. Thus, there will be a compromise between the required accuracy of the MVC and the risk of fatigue and injury due to exerting actual MVC.

Introduction

Electromyography (EMG) is a tool that is widely used to collect information on muscle activity in the fields of ergonomics and biomechanics. Applications range from measurements of muscle fatigue (Cifrek et al., 2009) to developing biomechanical models (Granata and Marras, 1995; Nikooyan et al., 2012). EMG is influenced by a number of extrinsic and intrinsic factors. De Luca (1997) discussed several of the causative factors that influence EMG signal, including electrode configuration and orientation, blood flow in the muscle, and the amount of tissue between the electrode and muscle of interest. Other researchers have further identified perspiration and temperature (Winkle and Jørgensen, 1991) and cross-talk of surrounding muscles (Koh and Grabiner, 1993) as factors that influence EMG signal. These factors can vary day-to-day in a single participant and across multiple participants, making it difficult to accurately compare EMG signals across days. To overcome the challenges associated with the EMG signal variability, researchers often normalize the EMG data.

In general, the EMG data is divided by a reference EMG value, also known as the normalization factor. This ratio will be used as the normalized EMG (Burden, 2010). Different EMG reference values have been used in the literature. Some of these reference values include the EMG from the maximum voluntary contraction (MVC) that can be divided to isometric and non-isometric contractions (e.g. Mirka, 1991; Knutson et al., 1994; Burden and Bartlett, 1999; Burden, 2010), the EMG from a submaximal voluntary contraction (SVC) that can be divided to isometric or non-isometric contractions (e.g. Yang and Winter, 1983; De Luca, 1997; Burden, 2010), and the mean or maximum value of the EMG from the specific task that is evaluated (e.g. Allison et al., 1993; Knutson et al., 1994; Burden and Bartlett, 1999; Burden, 2010). There is no consensus on the best method for EMG normalization that would be effective in all research studies (Perry 1992; Bolgla and Uhl, 2007; Albertus-Kajee et al., 2010; Ball and Scurr, 2013). An MVC during an isometric contraction (MIVC) is the most common reference value to normalize the EMG data (Sinclair et al., 2015) and is widely used for normalization in EMG-assisted biomechanical models. For example, MVC has been used to normalize the EMG data in most of the EMG-assisted biomechanical models of the trunk (Dufour et al., 2013). While MVC is widely used to normalize EMG data, it has faced criticism from different researchers (Burden, 2010), such as normalized EMG values greater than 100% (Clarys, 2000), and injury and fatigue risk to participants.

It is often not easy to obtain a true and reliable MVC for EMG normalization (Dufuor et al., 2013). Additionally, it’s not possible to ensure that the true MVC has been obtained as it can be impacted by participants’ motivation and sincerity (Marras and Davis, 2001; McNair et al., 1996). Furthermore, utilization of the MVC method can be restricted or impossible for symptomatic participants (Zellers et al., 2019), and it can also be uncomfortable or cause injuries in healthy participants in regions vulnerable to injury (Zeh et al., 1986; Battie et al., 1989; Dufour et al., 2013). One example is collecting MVC values of the neck muscles. Forces applied by the neck muscles can cause injury, particularly when the neck is in a non-neutral position (Huelke and Nusholtz, 1986). It may place participants at a higher risk for injury if they are regularly attempting MVCs of different neck muscles through flexion, extension, lateral bending, and axial rotation. To further add to this challenge, neck MVC can be affected by the pain or the fear of pain in participants with a history of neck pain (Lindstroem et al., 2012).

If we consider an experiment that requires participants to participate over several days, collecting MVC during all participations can be challenging. In some studies, particularly those involving fatigue, where the participant is required on multiple days, MVC is measured at each data collection and used to normalize the EMG data on that particular day. Developing a method that requires the MVC data collection only during the first participation will be practically favorable in such experiments. Previous studies have investigated other methods in order to address the problems regarding MVC (Marras and Davis, 2001; Burden, 2010), but a procedure for multi-trial experiments that requires MVC data collection during a reference participation has not been established.

Marras and Davis (2001) proposed a normalization method for the lumbar muscles that did not require an MVC. Their method involved developing regression equations to predict maximum contraction moments based on anthropometric measurements. These equations were developed from a database constructed of participant anthropometry and moment data from previous studies conducted in the laboratory. In their study, a regression equation based on the anthropometric measurements data from 120 participants was developed to predict maximum trunk moments. Also, EMG data was recorded on a new set of participants as they performed a series of sub-maximal and maximal exertions. This EMG data was used to develop a linear regression model to determine the EMG- moment relationship for each of the lumbar muscles under study. This relationship was extrapolated to the previously predicted maximum contraction moment to get an EMG normalization reference point. One strength of this method is its ability to provide a reference point for EMG normalization when a participant is unable or unwilling to exert an MVC, which could be especially useful in injured populations. However, this method assumed there was a relationship between anthropometry and trunk moments. The authors reported a large portion of unexplained variability in this model, which indicates that the anthropometry-trunk moment model is not always accurate. To overcome this issue, it may be useful to use a participant-specific MVC rather than a predicted maximum contraction value. A participant could perform an MVC and SVC once to create a regression model; then, in subsequent data collection sessions, the regression equation could be used to predict the MVC on that day. Following the example of Marras and Davis (2001), we propose a linear regression model developed from EMG values of sub-maximal exertions (SVC) that can be used across multiple experimental days. Regression equations will be based on the participant's own sub-maximal and maximal exertions. The data collected from the first data collection will be used to develop the regression equations, and the model will be tested on the subsequent data collection days for each participant.

The main goal of this study was to develop a regression model that calculates the muscle MVC for a test day based on the MVC and SVCs of that muscle during a reference day and the SVCs of that muscle during that test day. We hypothesized that the relationship between SVCs and MVC on a reference day could be used to calculate MVC on an arbitrary day based on SVCs on that arbitrary day. Such a model can be used in different studies where the participant needs to perform the experimental tasks on several days, and it can vary from the evaluation of muscle fatigue to the EMG-based biomechanical models.

Method

Participants

Ten healthy adults (nine males, one female, all right-handed) were recruited for this study. The participants reported no history of problems or chronic pain in the neck, shoulders, back, and knees. They also reported not experiencing pain nor discomfort in these joints on data collection days. The mean and standard deviation (SD) of their age and anthropometric measurements were as follows: age 34 (9) years, stature 175.3 (9.2) cm, body weight 77.5 (23.2) kg, standing elbow height 111.6 (6.2) cm, knee height 50.7 (2.5) cm, neck width (left to right) 12.1 (0.6) cm, and neck circumference 36.4 (3.9) cm.

Data Collection Instrumentation

The experimental apparatus consisted of two main instruments. A Kin-Com Isokinetic Dynamometer (125E, Chattanooga TN, USA) was used to provide resistance against and measure joint moments generated by the muscles during maximum muscle contractions (MVCs) and submaximal muscle contractions (SVCs). The dynamometer also provided visual feedback so that the participant could observe the real-time generated moment. This visual feedback was necessary to exert specific percentages of SVCs. Also, the posture of the joints during muscle exertions was standardized and fixed using the dynamometer. Surface electromyography (EMG) was employed to collect the desired muscles activities using DELSYS Trigno Wireless Biofeedback System (Delsys Inc., MA). The surface EMG data were collected at a frequency of 2148 Hz.

Experimental Procedure

The protocol for this study was approved by the Iowa state University IRB (Approval memo found in Appendix). Each participant attended two times (different days) with at least a 48-hour interval between the two data collections to control for fatigue and carryover effects. The experimental procedure was the same for both participations. On each day of data collection, the experiment was explained to the participant, and an informed consent document was completed. The basic demographic and anthropometric data were collected on the first day of participation. After a short warmup, the participant’s skin at the location of the EMG electrodes was cleaned using alcohol. One EMG electrode was attached to the biceps brachii on the participant’s dominant side, and one electrode was attached to their rectus femoris on the same side. The SENIAM recommendations for sensor locations (Seniam, 2006) were followed for these two EMG electrodes. Four EMG electrodes were attached to the participant's neck at right and left anterior locations and posterior locations at the C4/C5 level of the cervical spine. The neck sensors were bilaterally symmetrical and inferiorly-superiorly oriented. The offset from the midline was 3.0-3.5 cm for the anterior sensors and 2.0-2.5 cm for the posterior sensors depending on the participant's neck width. In order to ensure appropriate attachment of the sensors to the skin and for participant's convenience, the required sensors were attached at the time of data collection for the corresponding muscle and were detached afterward.

The MVC and SVC of these muscles were recorded through three different trials with five-minute rest between each of the two trials. These three trials studied elbow flexion (biceps brachii electrode), knee extension (rectus femoris electrode), and neck flexion and extension (neck electrodes), respectively. For the biceps brachii, the participant was standing beside the dynamometer while the elbow joint was at 90º of flexion and the forearm was horizontal. The participant held the handle of the dynamometer, and a wrist strap helped this grasping posture. An imaginary line between the rotation axis of the dynamometer and the handle of the dynamometer was parallel to the ground so that this line and the participant's forearm were in the same direction (Figure 4.1). Then the participant was asked to flex their elbow, exerting their maximum voluntary contraction in biceps brachii for two seconds in two different trials with 1-minute rest between two exertions. In this experiment, verbal encouragement was used during all MVC data collections. The generated moment was captured and observed using the visual feedback of the dynamometer, and the EMG electrodes were collecting the biceps brachii activities. The greatest value of the generated moment during the two trials was selected as the maximum moment of biceps brachii. The participants were then asked to generate 20%, 40%, and 60% of this value. The EMG data were collected and noted as 20%, 40%, and 60% of biceps brachii MVC. These values were used to record the submaximal voluntary contractions for this muscle. For example, the participant was asked to exert biceps brachii flexion at 20% MVC, while the visual feedback of the dynamometer allowed the participant to generate that specific moment. The participant held that exertion level for two seconds, and the muscle activities were collected using the EMG electrode. The order of the three different levels of SVCs was randomized for each participant, muscle, and day of data collection independently. The MVC and SVCs of rectus femoris and neck flexor and extensor muscles were recorded following a very similar procedure. The only difference was the position of the participants and the arrangement of the dynamometer. For rectus femoris, the participant sat on the dynamometer seating system, and their trunk was fixed to the back of the seating system using shoulder straps. Their trunk and thighs made a 90º angle, and their thighs were parallel to the ground. The knee was at 90º of flexion so that their shin was perpendicular to the ground. Also, an imaginary line between the rotation axis of the dynamometer and the handle of the dynamometer was perpendicular to the ground, parallel to the participant's shin (Figure 4.2). The participant was asked to extend their knee, exerting their MVCs and SVCs of the rectus femoris.

Figure 4.1 Apparatus and participant's position for biceps brachii exertions

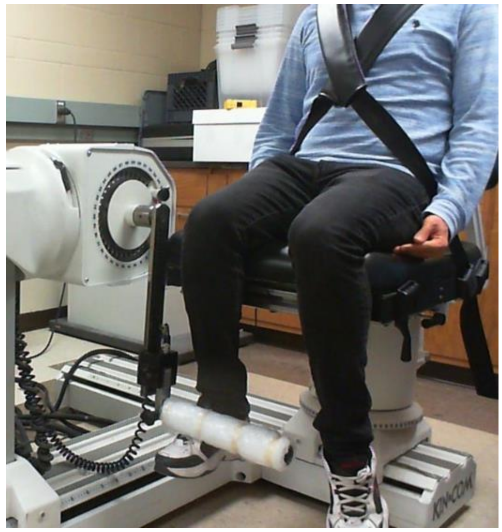

Figure 4.2 Apparatus and participant’s position for rectus femoris exertions

For neck flexor muscles, the participant sat on the dynamometer seating system, and their trunk was fixed to the back of the seating system using shoulder straps. Their trunk and thighs made a 90^{o} angle, and their thighs were parallel to the ground. The handle arm of the dynamometer was adjusted so that it was at the participant’s forehead height on the seating system while their neck was at a neutral posture with no flexion, extension, lateral bending, or axial rotation. The height of the rotation axis of the dynamometer was adjusted at participant’s seventh cervical vertebrae (C7) level when they were sitting on the dynamometer seating system. An imaginary line between the rotation axis of the dynamometer and the intersection of the head and handle arm of the dynamometer was perpendicular to the ground. The participant was asked to exert their neck flexion MVCs and SVCs (Figure 4.3.a), and neck extension MVCs and SVCs (Figure 4.3.b).

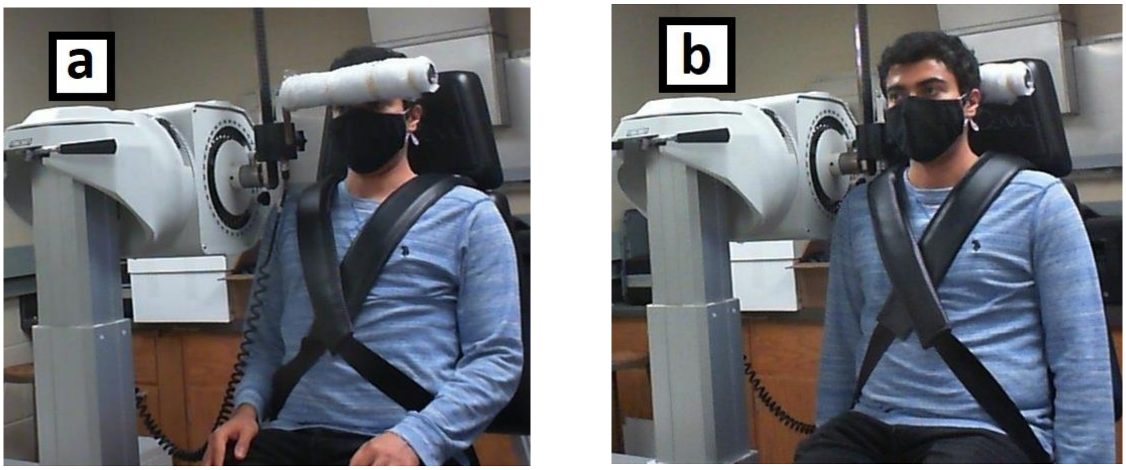

Figure 4.3 Apparatus and participant’s position for (a) neck flexion and (b) neck extension exertions

At the completion of the last trial, the participant performed a five-minute cool-down exercise and were free to go. On the second day of the data collection, the exact same procedure was repeated except that the SVCs moments to be generated were calculated based on the MVC values of the first day of participation. For example, the SVCs of the biceps brachii on the second day were 20%, 40%, and 60% of the MVC value of biceps brachii on the first day of data collection.

Data Processing

The demeaned EMG data were filtered using bandpass Butterworth filter (high pass=10Hz, low pass=400Hz) and band-stop Butterworth filter (60 Hz and 120 Hz). Then, the EMG data in time domain were rectified. The rectified MVC data were smoothed using a 10 Hz lowpass Butterworth filter. Moving average filter with a 500-millisecond window size was used on the MVC data, and the maximum of the processed MVC data was found. For each muscle and day of data collection, two MVC trials were performed. The greater calculated MVC from these two trials was chosen as the MVC value for that muscle and day of data collection. Also, the mean value of the rectified SVCs data for two seconds of data collection was calculated for each muscle and day of data collection. This procedure was performed for 20%, 40%, and 60% SVCs, and the calculated values were denoted as SVC-20%, SVC-40%, and SVC-60%. The MVC and SVCs values were averaged for right and left neck flexor muscles as well as for right and left neck extensor muscles.

Data Analysis and the Dependent Variable

For each muscle, backward stepwise multiple linear regression was used to predict MVC based on SVC-20%, SVC-40%, SVC-60%, and their combinations. The data from both days (D1 and D2) were included in the analysis to find the best SVC EMG that can predict the MVC for that muscle on D2. The model intercept was set to zero. Both penalized-likelihood criteria of Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to select the best model. A linear regression model was used to describe MVC-D1 based on the selected SVCs-D1 while the intercept was set to zero. This was the predictive equation for the corresponding muscle. Thus, the SVC-20%-D2, SVC-40%-D2, SVC-60%-D2 were used as the inputs of the predictive model to predict MVC-D2. The absolute percentage error (AE%) was calculated for the muscle as the dependent variable of this study according to Equation (4.1)

$$\text{AE\%}_i = \left| \frac{(Actual\text{-}MVC_i) - (Predicted\text{-}MVC_i)}{(Actual\text{-}MVC_i)} \right| *100\% \quad (4.1)$$

where i represents the number of participants. The best fit regression equations developed on D1 were used to predict the MVC on D2, herein called (ANALYSIS-1), and the best fit regression equations developed on D2 were used to predict the MVC on D1, herein called (ANALYSIS-2).

Results

The results of the backward stepwise analyses revealed that the best model for predicting MVC for biceps brachii (R-squared=0.93), rectus femoris (R-squared=0.88), and neck flexor (R-squared=0.96) consisted of only SVC-60%. These findings were consistent using both AIC and BIC. Surprisingly, for neck extensors, the best model included only SVC-20% (R-squared=0.95). Thus, in the predictive model for biceps brachii, rectus femoris, and neck flexor muscles, only SVC-60% was used, while for neck extensor muscles, only SVC-20% was used. Figures 4.4 illustrates how the regression model based on MVC-D1 and SVC-20%-D1 predicts MVC-D2 using SVC-20%-D2 for neck extensor muscles (ANALYSIS-1). Figure 4.5 shows how the regression model based on MVC-D2 and SVC-20%-D2 predicts MVC-D1 using SVC-20%-D1 for neck extensor muscles (ANALYSIS-2). Table 4.1 presents the SVC level and the slope (R-squared) of the linear regression model that were used in ANALYSIS-1 and ANALYSIS-2 to predict MVC values of the studied muscles (all intercepts were set to zero). Also, the mean (SD) of AE% for all the studied muscles using both ANALYSIS-1 and ANALYSIS-2 have been shown in Table 4.2.

Table 4.1 The SVC level and the slope (R-squared) of the linear regression model that were used in ANALYSIS-1 and ANALYSIS-2 to predict MVC values (all intercepts were set to zero)

Muscle	SVC level	Slope (ANALYSIS-1)	Slope (ANALYSIS-2)
Biceps brachii	SVC-60%	2.53 (0.90)	2.27 (0.97)
Rectus femoris	SVC-60%	2.03 (0.91)	2.21 (0.85)
Neck flexor	SVC-60%	2.22 (0.97)	1.82 (0.98)
Neck extensor	SVC-20%	8.51 (0.98)	10.15 (0.95)

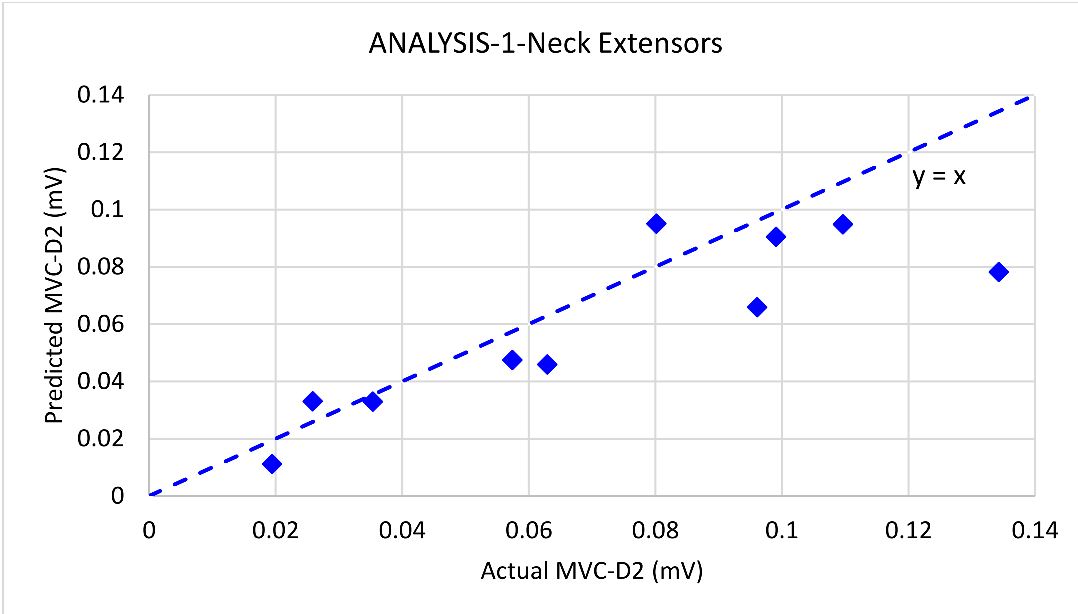

Figure 4.4 The predicted and actual MVC-D2 values (ANALYSIS-1)

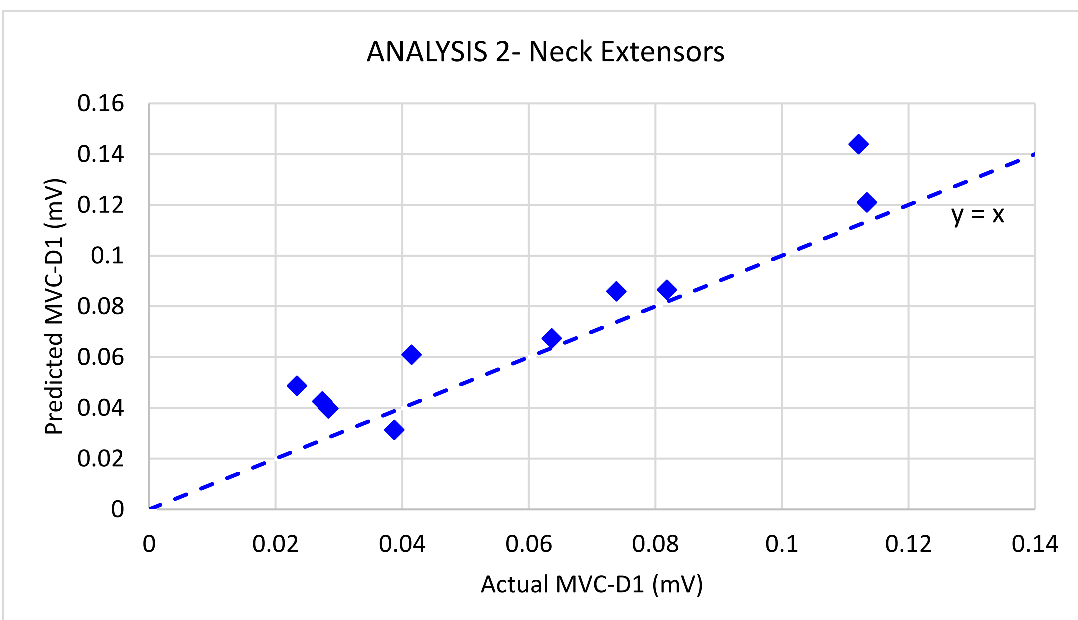

Figure 4.5 The predicted and actual MVC-D1 (ANALYSIS-2)

Table 4.2 The mean (SD) of AE% for ANALYSIS-1 and ANALYSIS-2

Muscle	ANALYSIS-1	ANALYSIS-2
Biceps brachii	28.92 (23.22)	22.40 (17.69)
Rectus femoris	29.36 (21.57)	24.80 (17.66)
Neck flexor	28.39 (18.13)	17.84 (13.73)
Neck extensor	23.54 (12.70)	33.40 (31.84)

Discussion

The main purpose of this study was to develop a method that predicts a muscle's MVC EMG based on a regression equation relating SVC and MVC on a reference day. In addition to muscle MVC on a reference day, muscle SVC on the reference day and the test day will be required. In this study, a linear relationship between muscle MVC and submaximal exertions was considered. The results revealed that this model was able to predict muscle MVC with a mean absolute percentage error between 23.54%-29.36% depending on the muscle. Also, the absolute percentage error was variable, and the SD of this error was 12.70%-23.22% for different muscles (Figures 4.4-4.5 and Table 4.2). The motivation for developing this model was to decrease muscle fatigue and the risk of injury due to exerting MVC in the experiments that require different participations on different days. Thus, there will be a compromise between the required accuracy of the MVC and the risk of fatigue and injury due to exerting actual MVC.

Using isometric MVC to normalize task EMG data is a very established technique (Sinclair et al., 2015); however, other methods have been introduced and studied. These methods use other levels of muscle activity such as SVCs (Yang and Winter, 1983; De Luca, 1997; Burden, 2010) or predict MVC based on participants anthropometrics and their SVCs (Marras and Davis, 2001). These methods are not using actual MVC, and they could be useful, especially in the cases that the participant is not able to exert MVC. Our developed method is based on actual MVC and would be suitable in studies that the participant is able to exert muscle MVC, but they are required to attend on several days, or they are recruited for different studies. In these studies, muscle MVC could be collected once and be used to predict muscle MVC on other days.

Among the three levels of SVCs, SVC-60% was the best predictor of MVC for biceps brachii, rectus femoris, and neck flexors, and SVC-20% was the best predictor of MVC for neck extensors. These results revealed that adding different levels of SVC to the model will not improve the model in predicting MVC. This implies that a linear relationship between different levels of SVCs (including MVC) was an acceptable assumption in our model. Our results introduced SVC-60% (three muscles) and SVC-20% (one muscle) as the best predictors compared to other levels of SVCs, while the reason for this finding is not completely clear to the authors. SVC-60% was the closest exertion to MVC in our study, and this would make it the best predictor of MVC if the relationship between different levels of SVC is not perfectly linear. Also, it should be noted that the participants were using visual feedback to exert SVC-s, and they were required to hold this exertion for two seconds steadily. Exerting SVC-60% and SVC-40% steadily during neck extension could have been more challenging compared to SVC-20%, so that SVC-20% became the best predictor for neck extensor muscle.

In the study by Marras and Davis (2001), the error between the real maximum contraction moments and the predicted maximum contraction moments based on participants' anthropometrics was about 35.6%. In our study, the AE% between the predicted MVC and the actual MVC was used to evaluate the model. There was a mean absolute percentage error between 17.84%-33.40% depending on the muscle (Table 4.2). The consistency in the value of this error among different muscles as well as between ANALYSIS-1 and ANALYSIS-2 shows the overall validity of the model; however, it implies common sources for this error. It is interesting that ANALYSIS-2 led to similar results; however, all the SVCs were based on the MVC of the first day of data collection.

Collecting real MVC depends on the participant's motivation and sincerity (Marras and Davis, 2001; McNair 1996). In this study, the experimental procedure was explained to the participants, and verbal encouragement was used during MVC exertions to ensure that real MVC was collected. However, inconsistency in exerting real MVC on the two days of data collection could be a source of error in our predictive model. Additionally, the EMG signal of the same muscle could be different on different days because different factors such as electrode orientation, perspiration, and temperature (De Luca, 1997; Winkle and Jørgensen, 1991) could affect EMG signals. In this study, standardized procedures were used in an experimental environment to reduce such possible errors, but these could be another source of error in the model. It should be noted that participants with different backgrounds, including more females, could help enhance the generalizability of these findings. Also, the next step should be evaluating the application of this method for normalizing EMG data in biomechanical models and other EMG studies and comparing the results from different methods of EMG normalization.

Conclusion

The results suggest that in this predictive model, 60% of MVC denoted SVC-60% was the best linear predictor of MVC for biceps brachii, rectus femoris, and neck flexors, while SVC-20% was the best predictor of MVC for neck extensors. Using the MVC and SVCs of a reference day and the SVCs of the test day led to a mean AE% between 23.54%-29.36% depending on the muscle. Also, the AE% was variable, and the standard deviation of this error was 12.70%-23.22% for different muscles. Thus, there will be a compromise between the required accuracy of the MVC and the risk of fatigue and injury due to exerting actual MVC. The next step should be evaluating the application of this method for normalizing EMG data (e.g., biomechanical models) and comparing the results from different methods of EMG normalization.

Statement of Authorship

AUTHOR CONTRIBUTIONS

Conception and design: HN, GM, JK

Analysis and interpretation: HN, GM

Data collection: HN

Writing the article: HN, JK, GM

Critical revision of the article: GM

Final approval of the article: HN, GM, JK

Statistical analysis: HN

Overall responsibility: HN

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Appendix: IRB approval memo

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 06/08/2020

To: Gary Mirka

From: Office for Responsible Research

Title: **Normalization of electromyography based on maximal and submaximal voluntary contractions**

IRB ID: **20-203**

Submission Type: Initial Submission **Review Type:** Expedited

Approval Date: 06/08/2020 **Approval Expiration Date: N/A**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp.**
- Retain signed informed consent documents **for 3 years after the close of the study,** when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks** to subjects or others.
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are

protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to post-approval monitoring **by Iowa State University's Office for Responsible Research.** In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.
- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses,** unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.
- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

CHAPTER 5. A SYSTEMS-LEVEL EVALUATION OF THE BIOMECHANICAL RESPONSE OF THE CERVICAL SPINE TO SAGITTAL PLANE FLEXION

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Abstract

The focus of this study was to perform a system-level evaluation of the biomechanical difference between neck flexion relative to trunk and neck flexion relative to gravity, considering both active and passive tissues. Ten males participated in this research on two different days. The EMG/IMU sensors were used to collect participant's neck muscle activity as well as the orientation of their neck, head, and upper back. On each day of participation, the participant completed two parts of this experiment. First, the neck flexion-relaxation phenomenon (FRP) was investigated with or without a trunk flexion of 45º (one condition per day). The results of this part of the experiment showed that the onset and offset angles of the FRP were not affected by trunk flexion. In the second part of the experiment, the participant was asked to hold a static neck flexion posture for 30 minutes. On each day of the participations, one of these two conditions was performed: 1) Condition HN-45 where head and neck were flexed 45º relative to trunk while the participant was standing straight, and 2) Condition T-45 where head and neck were not flexed relative to trunk, but trunk was flexed 45º. The findings revealed that T-45 caused higher neck muscle fatigue and neck subjective discomfort compared to HN-45 during

static neck flexion posture, but the long-term effects of these two conditions are not clear because of the difference in the role of passive tissues in holding these postures. Also, the EMG data during the first three minutes of the 30-minute static neck flexion posture were implemented in a biomechanical model of the cervical spine to investigate joint reaction forces at C4/C5 level. The estimated neck C4/C5 joint reaction compression force from the biomechanical model was the same for conditions HN-45 and T-45. The estimated neck C4/C5 joint reaction shear force was significantly higher in condition T-45 compared to condition HN-45. This study presented the importance of a system-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion. These findings could help to enhance the work assessment tools and ergonomic interventions.

Introduction

Neck pain is a widespread problem that affects both general and occupational populations (Bovim et al., 1994; Côté et al., 1998; Hoy et al., 2010). This problem not only affects individuals' lives but also impacts their families, society, health care system, economy, and industry (Hogg-Johnson et al., 2008; Hoy et al., 2010). As a part of a study by Hoy et al. (2010), a systematic review on the prevalence of neck pain was conducted, and the mean overall prevalence of neck pain in the general population was found to be 23.1% with a wide range of overall prevalence from 0.4% to 86.8% (Hoy et al., 2010). In another study by Strine and Hootman (2007), the data from around 30,000 adults in the United States in 2002 at the age of 18 years or older showed that approximately 31% of U.S. adults had experienced low back and/or neck pain in the last three months including around nine million with neck pain only and 19 million with both low back and neck pain (Strine and Hootman, 2007). The financial burden for low back and neck pain in the United States in 2013 was estimated as high as $87.6 billion, which showed an increase of $57.2 billion over the previous 18 years (Dieleman et al., 2016).

The risk factors for neck pain and neck musculoskeletal disorders (MSD) include individual and personal factors, psychosocial factors, and physical factors (Holmstorm et al., 1992; U.S. Department of Health and Human Services, 1997; Hogg-Johnson et al., 2008; Hoy et al., 2010). Previous studies have found a positive relationship between neck postural exposure and neck problems among different working populations (Ariëns et al., 2002; Chiu and Lam, 2007; Baker et al., 2008; Mehrdad et al., 2012; Nordander et al., 2016; Maimaiti et al., 2019). Neck flexion is a postural exposure that has been found to be positively correlated with neck problems among female typists (Szeto et al., 2005), teachers (Chiu and Lam, 2007), physicians (Mehrdad et al., 2012), and assemblers at electronic companies (Kilbom et al. 1986). These previous studies have evaluated the correlation between neck flexion and neck problems; however, their definition of neck flexion is not always clear. For example, it is not often possible to describe if the neck flexion angle is relative to the trunk or the neck flexion angle is relative to gravitation. This factor could be important in the application as the results of work assessment tools would be affected by the definition of neck flexion.

Different work assessment tools have developed methods to quantify neck postural exposure as a part of their evaluation (McAtamney and Corlett, 1993; Kemmlert, 1995; Seth et al., 1999; Hignett and McAtamney, 2000; Kee and Karwowski, 2001; Rodgers, 2005). The goal of these methods includes investigating the risk of MSDs at work, evaluating the ergonomic interventions, and conducting research in these areas (Takala et al., 2010). Neck flexion is a postural exposure that has been described in detail in most of these assessment tools (McAtamney and Corlett, 1993; Seth et al., 1999; Hignett and McAtamney, 2000; Kee and Karwowski, 2001). However, the distinction between the neck flexion angle relative to the trunk and the neck flexion angle relative to the gravitational direction has not been considered in these methods. This could be important, especially in the extreme cases of trunk flexion. For example, in a situation where the lower back is flexed forward, the weight of the head is exerted to the cervical spine, while the neck may not be flexed relative to the trunk.

Studying the effects of the neck flexion angle relative to the trunk and the neck flexion angle relative to the gravitational direction on the biomechanics of the cervical spine could clarify the difference between these two neck postural exposures. It is believed that both active (muscles) and passive (e.g., ligaments and intervertebral discs) tissues are important in studying cervical spine biomechanics as neck problems could involve active tissues (e.g., neck muscle fatigue), passive tissues (e.g., ligamentous sprains), and both active and passive tissues (e.g., strains of muscles and tendons) (Chaffin 1973; Meleger and Krivickas, 2007). In order to describe the neck flexion relative to trunk and the neck flexion relative to gravity, both active and passive tissues should be considered. Thus, the goal of this research is to investigate these two neck postural exposures through an experimental procedure that considers both active and passive tissues.

A well-known method to explore active tissues (e.g., muscle fatigue) is surface electromyography (sEMG) (Knowlton et al., 1951; Kogi and Hakamada, 1962). During fatigue, muscle fiber conduction velocity (CV) decreases due to physiological changes in the muscle tissue, such as an increase in the concentration of lactate and a decrease in the intracellular potential of hydrogen (pH). The muscle tissue acts as a spatial low-pass filter, and the motor unit action potential is affected, and its waveform changes (Basmajian and De Luca, 1985; Brody et al., 1991). This leads to a shift toward lower frequencies of the surface myoelectric signal power spectrum and an increase in EMG signal amplitude (De Luca, 1984; Brody et al., 1991; Cifrek, 2009). Another hypothesis for the changes in EMG signals is that slow-twitch fibers of the muscle stay active for longer while fast-twitch fibers get fatigued quickly and switch off (Cifrek, 2009). EMG has been used in previous studies to evaluate neck muscle fatigue during static postures (Chaffin 1973; Szeto et al., 2005; Vijendren et al., 2020; Sarker et al., In Press); however, the neck muscle fatigue for static neck flexion relative to trunk compared to static neck flexion relative to gravity has not been investigated.

EMG can also be used to study how active and passive tissues cooperate in the cervical spine. For example, cervical flexion-relaxation phenomenon (FRP) studies have investigated the cooperation between active and passive tissues in the cervical spine (Burnett et al., 2009; Pialasse et al., 2010; Maroufi et al., 2013; Nimbarte et al., 2014; Zabihhosseinian et al., 2015; Mousavi-Khatir et al., 2016). Different aspects of cervical spine FRP have been evaluated, such as the effects of load and speed on cervical FRP (Pialasse et al., 2010), the difference in cervical FRP between healthy participants and participants with chronic neck pain (Maroufi et al., 2013), and the effect of neck muscle fatigue on cervical FRP (Nimbarte et al., 2014; Zabihhosseinian et al., in 2015). In order to perform a system-level evaluation of the biomechanical difference between neck flexion relative to trunk and neck flexion relative to gravity, the effects of trunk flexion on cervical FRP would be necessary. This effect has been evaluated in a study by Pialasse et al. (2009). They investigated the impact of 45º forward trunk flexion on the cervical FRP. It was found that the onset and offset angles of cervical FRP when the trunk was flexed 45º was not significantly different from when trunk was in a neutral posture (Pialasse et al., 2009). The study by Pialasse et al. (2009) focused on the cervical FRP, and no effects of static postural exposures on neck muscle fatigue were investigated. Also, visual inspection of the EMG signals was used to identify the onset and offset angles of the cervical FRP. It has been shown that different methods from previous literature could strongly affect the results of the cervical FRP evaluation (Burnett et al., 2009). Thus, exploring the effects of trunk flexion on cervical FRP through an automated methodology that doesn't employ subjective evaluation (e.g., visual inspection) could be beneficial.

The biomechanical response of the cervical spine in static postures (e.g., muscle forces, estimations of cervical spine joint reaction forces) has also been studied through biomechanical models of the cervical spine. For example, Moroney et al. (1988) proposed a biomechanical model for the cervical spine in order to estimate the compression and shear forces in the C4-C5 joint during neck quasi-static exertions in an upright neck posture. Their model considered 14 pairs of muscles for the neck while the passive tissues (e.g., ligaments) were not included (Moroney et al., 1988). While Moroney et al. (1988) used an optimization approach to estimate the neck muscle forces, Choi and Vanderby (1999) showed that a similar EMG-assisted model could consider antagonist muscles, and reveal the difference in the muscle forces among the participants (inter-participant variability) and trials of the same participant (intra-participant variability) when the external load was the same. These two studies (Moroney et al., 1988; Choi and Vanderby, 1999) estimated the neck muscles forces and the C4-C5 joint reaction forces during neck exertions (e.g., neck flexion and extension); however, the participant's neck was in an upright posture (e.g., no neck flexion angle) and no effect of passive tissues was considered in either of their models. To the best of our knowledge, although different biomechanical models of the cervical spine have been developed (Snijders et al., 1991; Moroney et al., 1988; Vasavada et al., 1998; Choi and Vanderby, 1999; Vasavada et al., 2007; Suderman et al., 2012; Nevins et al., 2014), the cervical spine joint reaction forces during static neck flexion postures considering the role of passive tissues (e.g., ligaments) have not been investigated in detail. The biomechanical difference between the neck flexion angle relative to trunk and the neck flexion angle relative to gravity should be investigated in a biomechanical model of the cervical spine, especially by considering the role of passive tissues (e.g., ligaments) in holding the static neck flexion postures.

The focus of this study was to perform a system-level evaluation of the biomechanical difference between neck flexion relative to trunk and neck flexion relative to gravity, considering both active and passive tissues. It should be noted that there is also motion between head and neck, and this motion will add to the complexity of this research question. After performing pilot studies, the authors decided to consider the head and neck flexion together as a unit. The effects of trunk flexion on cervical FRP (FRP STUDY) were investigated, and it was hypothesized that the onset and offset angles of the cervical FRP would not be affected by the trunk flexion. Also, the effects of static neck flexion angle on neck muscle fatigue were explored (FATIGUE STUDY) in two scenarios: 1) neck flexion relative to trunk when the head and neck were flexed while the participant was standing straight, and 2) neck flexion relative to gravity when the head and neck were not flexed relative to trunk, while trunk was flexed. We hypothesized that in prolonged static postures, the neck flexion relative to gravity generates higher muscle fatigue compared to neck flexion relative to trunk. Also, the neck joint reaction forces at C4/C5 level were estimated using a biomechanical model, and it was hypothesized that both shear and compression reaction forces at C4/C5 level would be greater in neck flexion relative to gravity compared to neck flexion relative to trunk.

Method

This study explored the biomechanical difference (considering both active and passive tissues) between neck flexion relative to trunk and neck flexion relative to gravity in three different ways (FRP STUDY, FATIGUE STUDY, and the biomechanical model). There are methods that are the same for all three studies (Participants, Apparatus, Experimental

Procedure), and the methods that are unique to each study. For readers' convenience, the methods that are common across the three studies are described first. In the following sections, the methods that are unique to each study are presented by the sub-study title, followed by the results of that study. Finally, the overall discussion and conclusion are presented.

Common Methods

Participants

Ten healthy males (all right-handed) reporting no history of chronic problems, injury, or current pain in the neck, shoulders, back, or knees on the days of data collections participated in this study. The mean and standard deviation (SD) of their age and anthropometrics were calculated and the results were: age=34 (8.8) years, stature=177.3 (8.6) cm, body weight=85.3 (21.8) kg, standing elbow height=112.8 (5.7) cm, standing knee height=50.4 (3.2) cm, neck width at C4/C5 (right-left)=12.4 (0.6) cm, neck depth at C4/C5 (anterior-posterior)=12.2 (0.7) cm.

Apparatus

Muscle activity was measured using surface electromyography (sEMG), and the body part orientations were measured using inertial measurement units (IMU). DELSYS Trigno Wireless Biofeedback System (Delsys Inc., MA) that consists of EMG and IMU sensors were employed to record these data. These sensors were used so that their pitch, roll, and yaw angles represented the angular displacement in the sagittal plane, transverse plane, and coronal plane, respectively. A Kin-Com Isokinetic Dynamometer (125E, Chattanooga TN, USA) was used during the neck muscles maximum voluntary contraction (MVC) and submaximal voluntary contraction (SVC) exertions. The Kin-Com generated required resistance against muscle moments and provided real-time visual feedback of the neck muscle moments so that the participant could exert specific neck muscle SVCs, for example, 60% of MVC. Before and after the FATIGUE STUDY, the participants were asked to complete a body-part discomfort (neck, upper back, and lower back) and overall fatigue survey (SURVEY) using a continuous visual analog scale from 0 (no discomfort/fatigue) to 10 (extreme discomfort/fatigue).

Experimental Procedures

The protocol for this study was approved by the Iowa state University IRB (Approval memo found in Appendix). Each participant voluntarily took part in the experiment on two separate days with at least 48 hours rest between the days of participation to control for fatigue and carryover effects. Each day, the participant completed two parts of the experimental procedure. The first part was the data collection for evaluating FRP in neck muscles (FRP-STUDY). The second part was the data collection for evaluating fatigue in neck muscles (FATIGUE-STUDY).

Upon arrival, the participants signed the informed consent form and performed a five-minute warm-up stretching routine focusing on the muscles spanning the neck joint and shoulder girdle. Basic demographic and anthropometric data were collected only during their first participation date. Eight EMG/IMU sensors were attached to the neck at the C4 level at bilaterally symmetric locations. The sensors were denoted as (right and left) anterior, anterolateral, posterolateral, and posterior. The central angles from the anterior midline to the right sensors were approximately 35º (anterior sensor), 70º (anterolateral sensor), 105º (posterolateral sensor), and 150º (posterior sensor) with the vertex of the angles at the center of C4/C5 disc (Moroney et al., 1988). The skin was shaved and then cleaned with rubbing alcohol before attaching the sensors. These eight sensors collected the neck muscle activity at C4/C5 level. In total these eight EMG sensors represented the activity of 14 pairs of muscles in four bilateral groups and each sensor captured the muscle activity of one of these eight groups (R-L Anterior, R-L Anterolateral, R-L Posterolateral, R-L Posterior). The activity of the muscles in each group was considered to be at the same level. According to Choi and Vanderby (1999) "bilateral grouping of these muscles is as follows: Anterior: Platysma, Infrahyoid; Anterolateral: Sternocleidomastoid, Longus colli and cervicis, Scalene anterior; Posterolateral: Scalene medius, Longissimus cervicis, Levator scapulae, Splenius cervicis; Posterior: Multifidus, Semispinalis cervicis, Semispinalis capitis, Splenius capitis, Trapezius" (Choi and Vanderby, 1999, p.122-123). Additionally, one EMG/IMU electrode was attached to the upper back at the third vertebrae of the thoracic spine. This sensor collected the orientation of the upper back (no EMG data). The anterior and anterolateral sensors collected EMG data at the rate of 2148 Hz, the posterolateral and posterior sensors collected EMG data at the rate of 3704 Hz, and the orientation data at the rate of 74 Hz. The different rate of data collection for the EMG sensors was a result of the data collection software that had predefined options depending on whether the orientation data was collected or not. The upper back sensor collected the orientation data at the rate of 74 Hz. The two parts of the experiment (FRP STUDY and FATIGUE STUDY) were then performed as follows:

1) FRP STUDY: The participant wore a baseball cap with an EMG/IMU sensor attached to its back. This sensor collected orientation of the head at the rate of 74 Hz (no EMG data). Depending on the participation day, the participant was asked to stand upright with their trunk at a neutral posture (FRP-0), or they were asked to lie on a fixture with 45^{o} of trunk flexion (FRP-45) (Figure 5.1). Then, the participant was asked to do a slow, controlled neck flexion movement in four phases. Phase 1 (NEUTRAL) was a neutral posture where the participant's head and neck were in the neutral posture relative to trunk. They held this posture for five seconds. In phase 2 (FLEXION), the participant flexed their head and neck in a slow controlled way over five seconds and achieved maximum flexion. Phase 3 (FULL FLEXION) lasted for five seconds, and

the participant held that maximum flexion posture. In phase 4 (EXTENSION), the participant extended their head and neck back to the neutral posture over five seconds. The FRP data collection was repeated five times. Training trials were done before the data collection to ensure that the participants learned how to move their neck smoothly and steadily during Phase 2 and Phase 4. In FRP STUDY, only the two posterior sensors were attached to the neck to collect the underlying muscle activity and neck orientation data.

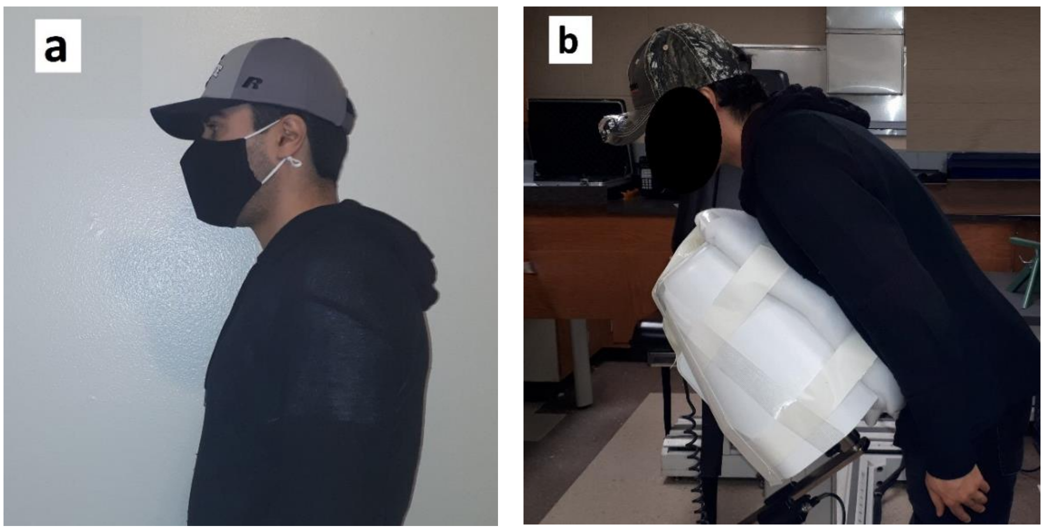

Figure 5.1 Participant’s posture at the beginning of condition FRP-0 (a) and condition FRP-45 (b)

2) FATIGUE STUDY: Before performing the FATIGUE STUDY, the neck muscles MVC and SVC were collected. All eight neck EMG/IMU sensors were attached to the participant’s neck to collect the activity of the neck muscles. The participant was positioned on the dynamometer seating system. Shoulder straps were used to fix their trunk posture, and the padded handle arm of the dynamometer transducer was slightly touching their head (at the forehead, back of the head, and sides of the head depending on the direction), while their head

and neck were not bent or rotated. The center of rotation of the dynamometer was at participant's C7 height when they were sitting on the dynamometer seating system (Figure 5.2). On the first participation day, MVC exertions of neck flexion, extension, and right and left lateral bending were collected, respectively. Each MVC exertion was collected for two seconds and was repeated twice with three minutes rest between the exertions. The maximum of the generated moments out of the two repetitions were recorded in these four directions (flexion, extension, and right and left lateral bending) by monitoring the dynamometer visual feedback. Then, 60% of this maximum value was calculated for each direction as SVC-60%. On both participation days, the participant was asked to exert SVC-60% of neck flexion, extension, right and left lateral bending, respectively. Visual feedback helped the participant to get to and then to hold the SVC-60%. Each SVC-60% exertion was collected for two seconds, with three minutes rest between the exertions. The MVC was not repeated on the second participation in order to reduce the risk of injury. The SVC-60% data collections were later used as the reference EMG in the EMG normalization procedure.

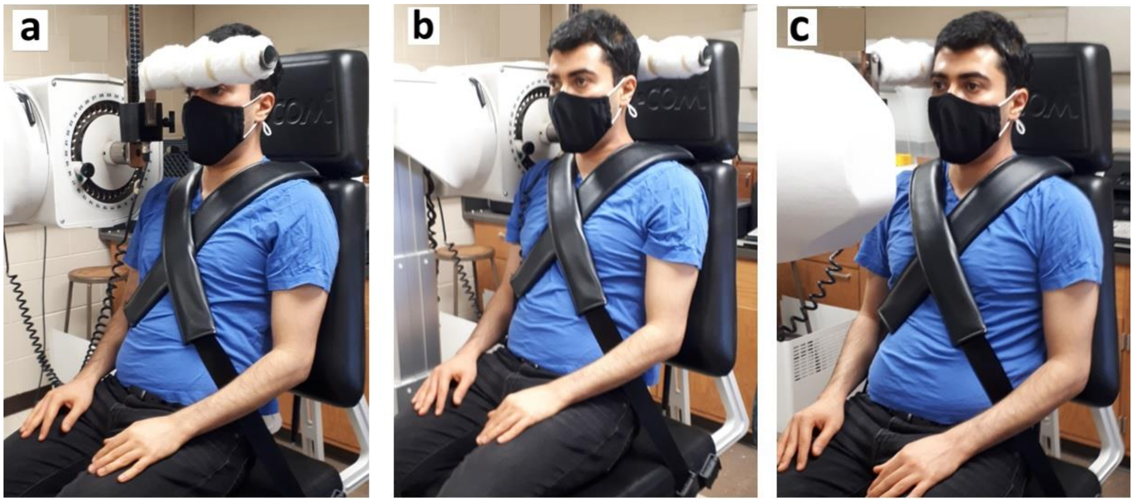

Figure 5.2 Participant's position on the dynamometer seating system during neck flexion (a), extension (b), and right lateral bending (c) exertions

The FATIGUE STUDY then commenced. The participant was asked to wear the baseball cap with laser light on the bill of the cap and the EMG/IMU sensor attached to its back. Participants were asked to stand straight and look forward in their natural posture with no head, neck, or trunk flexion/extension, lateral bending, or axial rotation. The orientation of the sensors at this posture were collected and used as the reference posture. The participant was asked to stand next to a height-adjustable table and be at HN-45 or T-45 posture (depending on the condition of the day).

In condition HN-45, the height of the table was adjusted at around 5 cm below their standing elbow height. The participant was standing upright with their torso slightly touching the edge of the table. The participant was asked to flex their head and neck in their natural way so that the head reached the 45º of flexion relative to trunk while the trunk remained upright. The position of the laser beam on the table was marked. The participant was asked to hold that posture for 30 minutes by keeping the laser beam on the marked position and keeping the slight contact between their torso and the edge of the table (Figure 5.3.a).

In condition T-45, the table height was adjusted at around 20 cm above their standing knee height. The participant was asked to lean against a fixture that generated a 45º trunk flexion posture so that their head and neck were not flexed relative to trunk, while their trunk was flexed 45º. The position of the laser beam on the table was marked. The participant's trunk was supported by the fixture at 45º, and the participant's head was held at 45º to vertical by keeping the laser beam on the marked position (Figure 5.3.b). During both HN-45 and T-45 conditions, the head, neck, and trunk postures were monitored using the real-time orientation data from the posterior, posterolateral, upper back, and cap sensors to ensure that the participants were keeping the static posture during the 30 minutes. The EMG/IMU sensors collected data during the last 35 seconds of each minute of the static neck flexion posture providing 30 data collections (over 30 minutes of static posture). In order to capture the subjective evaluation of discomfort and fatigue, the participants were asked to complete the SURVEY immediately before and after the 30-minute static neck flexion posture.

Upon completion of the FATIGUE STUDY, the sensors and the baseball cap were removed, the participant went through a five-minute cool-down and stretching exercise and then was free to go. It should be noted that conditions FRP-0 and HN-45 were performed on the same day, and conditions FRP-45 and T-45 were performed on the same day, but the condition order was randomized for each participant.

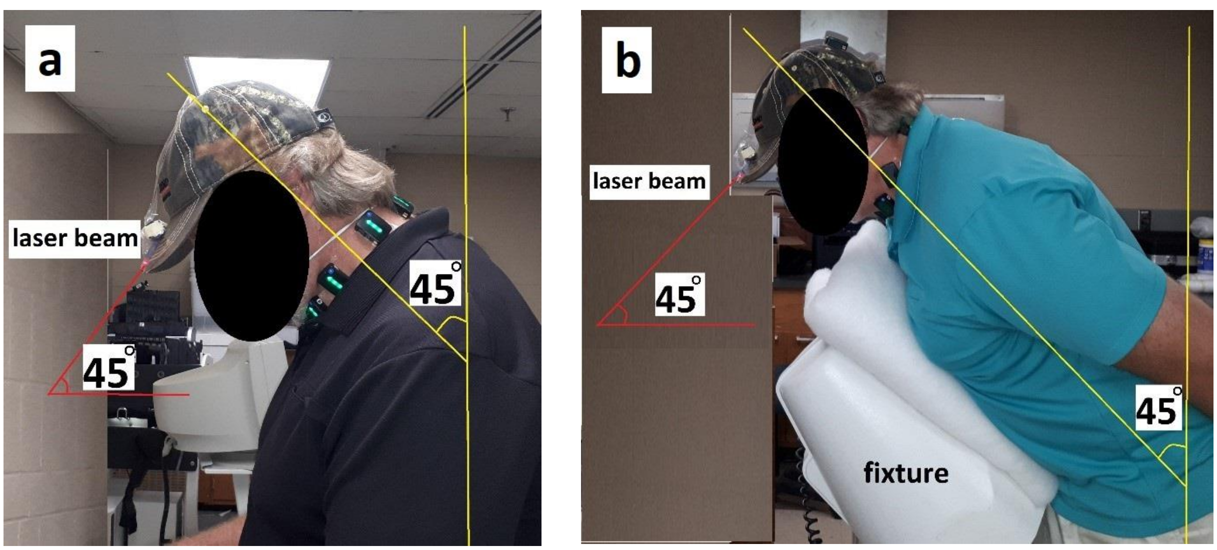

Figure 5.3 Participant’s posture during condition HN-45 (a) and condition T-45 (b)

Methods and Results Unique to FRP STUDY

Data Processing

The EMG data of the neck posterior sensors were demeaned and then filtered using the Butterworth filter (high pass=10Hz, low pass=400Hz, band-stop=60Hz, and 120Hz). The orientation data (pitch, roll, yaw) of the posterior, posterolateral, upper back, and cap sensors were filtered using lowpass Butterworth filter (low pass=16 Hz). The pitch angle of the sensor attached to the baseball cap was used as the head angular displacement in the sagittal plane and was called PITCH.

The first step in the analysis of the FRP STUDY was to obtain the start/end of each phase. First, the moving standard deviation (Moving-SD) with one-second window size was calculated for the PITCH. Then, two times of the standard deviation of PITCH during the first second of phase 1 (NEUTRAL-no motion) was used as a benchmark to find the start and end time of head motion on the Moving-SD data. Consequently, the start of Phase1 to the end of Phase 4 were determined by this angular measure. This method was confirmed by checking the PITCH angles visually.

The EMG data from the right and left posterior sensors were rectified and smoothed using a 4 Hz lowpass Butterworth filter (Burnett et al., 2009; Nimbarte et al., 2014). Moving average filter with a one-second window size was used on the EMG data (Figure 5.4). The root mean square (RMS) of the EMG data during phase 2 (FLEXION), phase 3 (FULL FLEXION), and phase 4 (EXTENSION) were calculated and denoted by RMS-Phase2, RMS-Phase3, and RMS-Phase4, respectively. The occurrence of the FRP was confirmed if RMS-Phase3 was smaller than 80% of the RMS-Phase4, and simultaneously, RMS-Phase3 was smaller than 90% of the RMS-Phase2.

For the cases that the FRP occurred, the flexion relaxation ratio (FRR) was calculated as RMS-Phase2 divided by the RMS-phase3. Also, the extension relaxation ratio (ERR) was calculated as the RMS-phase 4 divided by the RMS-Phase3. The mean and standard deviation of the EMG data during phase 3 (FULL FLEXION) was calculated, and the mean +2 standard deviations was found. This value was used as the intercept of a threshold line to find the onset and offset of the FRP. Starting from the midpoint of phase 3 (FULL FLEXION), where the

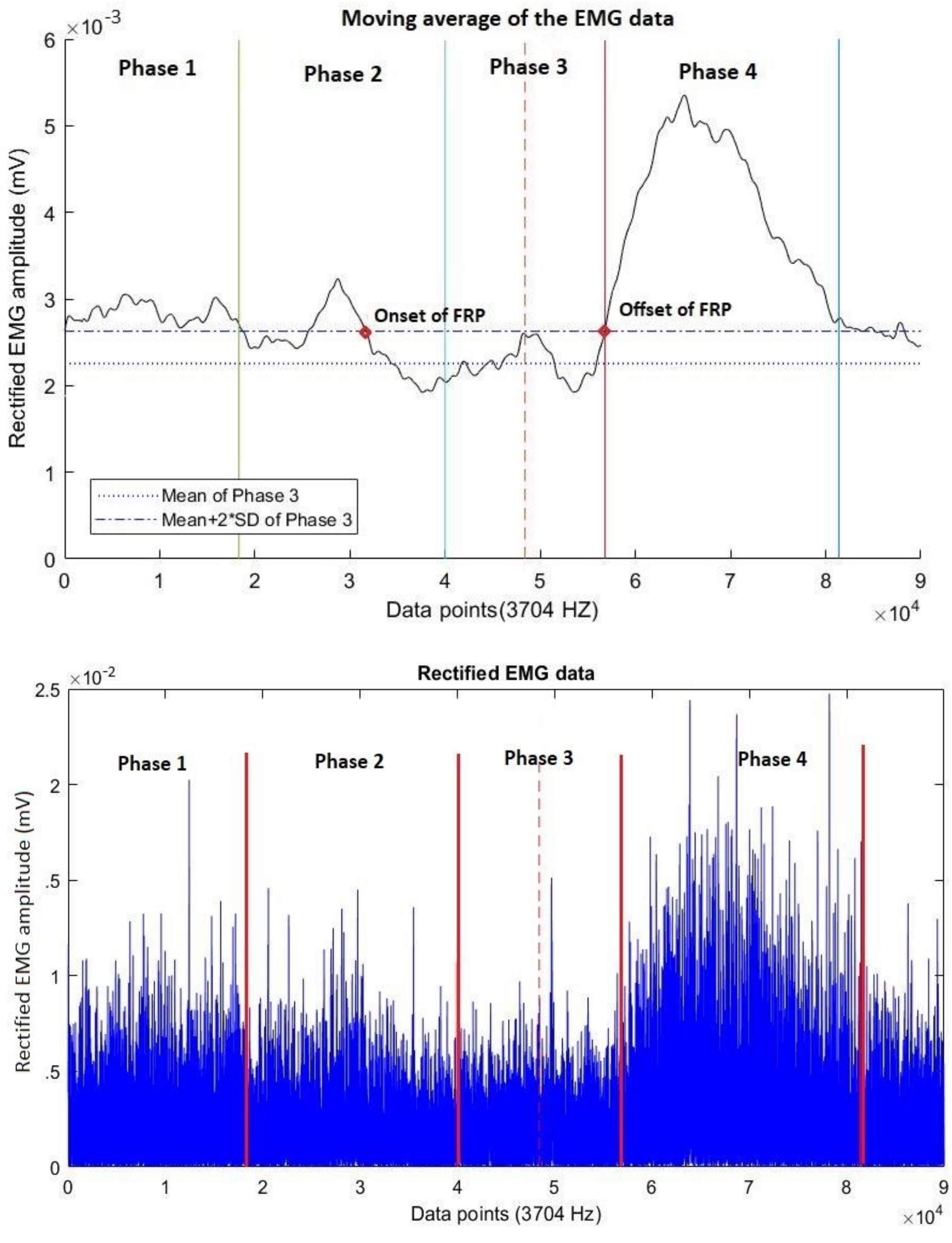

Figure 5.4 The FRP data and the threshold that was used to find offset and onset of the FRP (top) and the rectified EMG data during Phase 1 to Phase 4 (bottom)

threshold line intersected the EMG graph on the left side, it represented the onset of the FRP, and where the threshold line intersected the EMG graph on the right side, it represented the offset of the FRP (Figure 5.4). The corresponding data points on the PITCH dataset were found as the onset and offset angles of the FRP and were converted to the percentage of the maximum flexion angle (ONSET% and OFFSET%, respectively). The average values for FRR, ERR, ONSET%, and OFFSET% of right and left posterior muscles for all repetitions were calculated for each participant and condition. It should be noted that during some of the repetitions, the sensors were detached from the skin due to the extreme movements of the neck, and the data were corrupted. These repetitions were not included in the data processing.

Dependent and Independent Variables

The independent variable for the FRP STUDY was the body posture with two levels of FRP-0 and FRP-45. The dependent variables were the values of the FRR, ERR, Onset%, and Offset%.

Statistical Analysis

The statistical analyses were performed using JMP Pro 15. The overall significance level of 0.05 was used. In the FRP STUDY, the normality of the FRR, ERR, ONSET%, and OFFSET% (all grouped by condition FRP-0 and FRP-45) and the equality of the variances were checked using the Shapiro-Wilk test and Levene's test, respectively. Then, t-test or non-parametric Wilcoxon Signed-Rank test (if normality or equality of variances were violated) were used to evaluate the effects of body posture (FRP-0 and FRP-45) on the FRP dependent variables. Also, a Bonferroni correction was employed because several variables were tested together (0.05/4=0.0125). These Bonferroni corrections were done to maintain the experiment-wise error rate at a level of 0.05.

Results

In the FRP STUDY, the occurrence of FRP was observed (at least one occurrence) in six out of ten participants for condition FRP-0 and in seven out of ten participants for condition FRP-45. The mean (SD) of the FRR, ERR, ONSET%, and OFFSET% from the FRP STUDY have been presented in Table 5.1. Further analysis showed no statistically significant difference between conditions FRP-0 and FRP-45 for any of the studied variables.

Table 5.1 The mean (SD) of the FRR, ERR, ONSET%, and OFFSET% from the FRP STUDY (N*=sample size (the number of FRP occurrence in at least one side of the posterior muscles among all the participants and repetitions))

Variable	Condition FRP-0 (N*=18)	Condition FRP-45 (N*=29)
FRR	1.221 (0.110)	1.223 (0.085)
ERR	1.621 (0.339)	1.783 (0.446)
ONSET%	87.3% (13.5%)	89.2% (8.9%)
OFFSET%	96.9% (4.3%)	95.9% (6.7%)

Methods and Results Unique to FATIGUE STUDY

Data Processing

The EMG data of the eight neck sensors were demeaned and then filtered using the Butterworth filter (high pass=10Hz, low pass=400Hz, band-stop=60Hz, and 120Hz). The amplitude of the EMG data in time domain were rectified for the neck SVC-60% exertions. The average of the two-second SVC-60% exertions were calculated, and the greatest value among neck flexion, extension, and right and left lateral bending was used as SVC-60% for the corresponding muscles group of that sensor. For each neck muscle group (eight muscle groups in total), the EMG data (30 data collections) in time domain during the 30-minute static neck flexion posture were rectified, averaged, and then divided by the SVC-60% of the corresponding sensor to normalize the data. This value was denoted as Average Value of Rectified Amplitude (AVRA), and this led to 30 AVRA data points (one AVRA per minute) for each muscle during the 30 minutes of the FATIGUE STUDY. Also, in the frequency domain, the median frequency of the EMG data was denoted as MDF. This process generated 30 MDF data points (one MDF per minute) for each muscle during the 30 minutes of the FATIGUE STUDY.

Dependent and Independent Variables

The independent variable for the FATIGUE STUDY was the body posture with two levels of HN-45 and T-45. Because of the symmetrical nature of the static neck flexion posture, the AVRA and MDF of right and left muscles were averaged led to AVRA and MDF for anterior, anterolateral, posterolateral, and posterior muscles. The value of the 30 data points of AVRA for each day and condition was divided by the value of the first AVRA data point of that participant and condition in order to standardize the change in AVRA across participants and conditions. The difference between the average of the AVRA of the last three minutes and the first three minutes was calculated as the change in AVRA and was simply denoted as D-AVRA for each muscle. Positive D-AVRA showed an increase in muscle AVRA and represented fatigue occurrence in that muscle. Similarly, the difference between the average of the MDF at the last three minutes, and the first three minutes was calculated as the change in MDF and was simply denoted as D-MDF for each muscle. Negative D-MDF showed a decrease in muscle MDF and represented fatigue occurrence in that muscle. Also, the subjective responses to the SURVEY before the 30-minute static task were subtracted from the values collected after the 30-minute static task, and the values were denoted as D-SURVEY scores. Greater D-SURVEY scores represented a higher increase in body-part discomfort and overall fatigue. The D-AVRA and D-MDF for anterior, anterolateral, posterolateral, and posterior muscles and D- SURVEY for neck, upper back, lower back, and overall fatigue were the dependent variables of FATIGUE STUDY.

Statistical Analysis

The statistical analyses were performed using JMP Pro 15. The overall significance level of 0.05 was used. The normality of the D-AVRA and D-MDF were checked using the Shapiro-Wilk test. To check the evidence for fatigue development, t-test or non-parametric Wilcoxon Signed-Rank test (if normality was violated) was used. D-AVRA>0 or D-MDF<0 were considered evidence for fatigue occurrence. As four groups of muscles (anterior, anterolateral, posterolateral, and posterior) were evaluated, a Bonferroni correction was employed (0.05/4=0.0125).

For the muscles in which measurable fatigue occurred, the effect of body posture on the muscles fatigue was evaluated. The difference between conditions HN-45 and T-45 was calculated for each participant. The normality of the differences for each dependent variable was checked using the Shapiro-Wilk test. Then, paired t-test or non-parametric Wilcoxon Signed-Rank test (if normality was violated) was employed. Also, the effect of conditions HN-45 and T-45 on D-SURVEY scores was evaluated following a similar procedure. In evaluating the effects of HN-45 and T-45 on the dependent variables, a Bonferroni correction was employed whenever several variables were tested together. These Bonferroni corrections were done to maintain the overall significance level of 0.05, and to control the experiment-wise error.

Results

The statistical analyses using paired t-test showed that during the 30 minutes of the static neck flexion posture, AVRA increased significantly (D-AVRA>0) in posterior muscles for both conditions HN-45 and T-45 (p=0.0033, and p=0.0018, respectively), and in posterolateral muscles for condition T-45 (p=0.0028). No other significant evidence of muscle fatigue occurrence was found for any of the muscle groups using either D-AVRA or D-MDF results. Thus, posterior muscles were further analyzed to find the significant effects of condition (HN-45 and T-45) on their D-AVRA results. The paired t-test revealed that D-AVRA was greater in condition T-45 for posterior muscles (p=0.0229). This means that condition T-45 caused higher fatigue in these muscles compared to condition HN-45. Figures 5.5 illustrate how AVRA increased during conditions HN-45 and T-45 for posterior muscles.

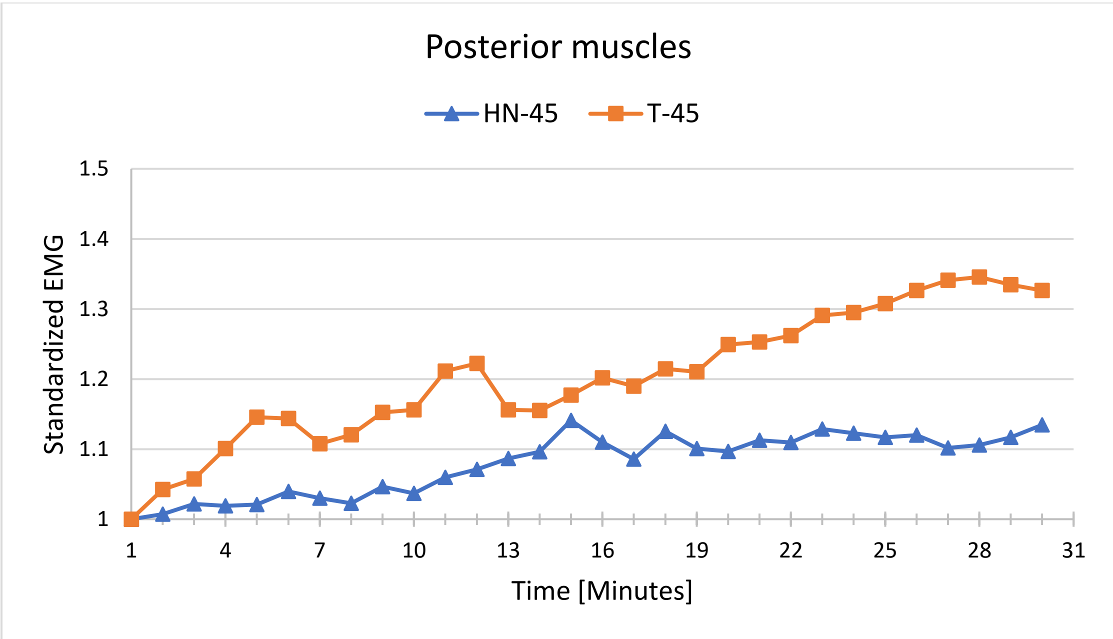

Figure 5.5 Standardized EMG AVRA for posterior muscles (average of all ten participants) during the 30 minutes of FATIGUE STUDY for conditions HN-45 and T-45 (increase in AVRA shows fatigue occurrence)

Also, the analysis of the SURVEY variables showed that the increase in neck discomfort during the 30-minute static neck flexion posture was higher in condition T-45 compared to condition HN-45 (p=0.0088) while no significant effect of condition was found for upper back discomfort, lower back discomfort, and overall fatigue scores.

Methods and Results Unique to Biomechanical Model

Developing the Biomechanical Model

An EMG-based biomechanical model was developed for the cervical spine based on the neck biomechanical model by Choi and Vanderby (1999). The origin of the coordinate system was located at the center of the C4/C5 disc with the positive axes of x, y, and z in left, posterior, and superior directions, respectively (Figure 5.6). The angle between the z-axis and the gravitational direction in the mid-sagittal plane was found for each participant based on the orientation data of the neck posterior sensors during the first three minutes of FATIGUE STUDY. The external moment was generated by the participant's head weight, and the internal moment was generated by their neck muscles and ligaments at C4/C5 level. The weight of the head was estimated as 7.3% of the participant's body weight (Clauser et al., 1969), exerted at about -1.3 cm, and +2.5 cm distance from the auditory meatus in y and z directions, respectively (Becker, 1972). The muscles cross-sectional area (CSA), the center of action, and the angle of the line of action at C4/C5 level were based on the neck biomechanical models by Moroney et al. (1988) and Choi and Vanderby (1999). The muscles CSA and center of action were customized for each participant by multiplying their neck width at C4/C5 level (right-left) and neck depth at C4/C5 level (anterior-posterior) in the reference values (Moroney et al., 1988, Choi and Vanderby, 1999) (Table 5.2).

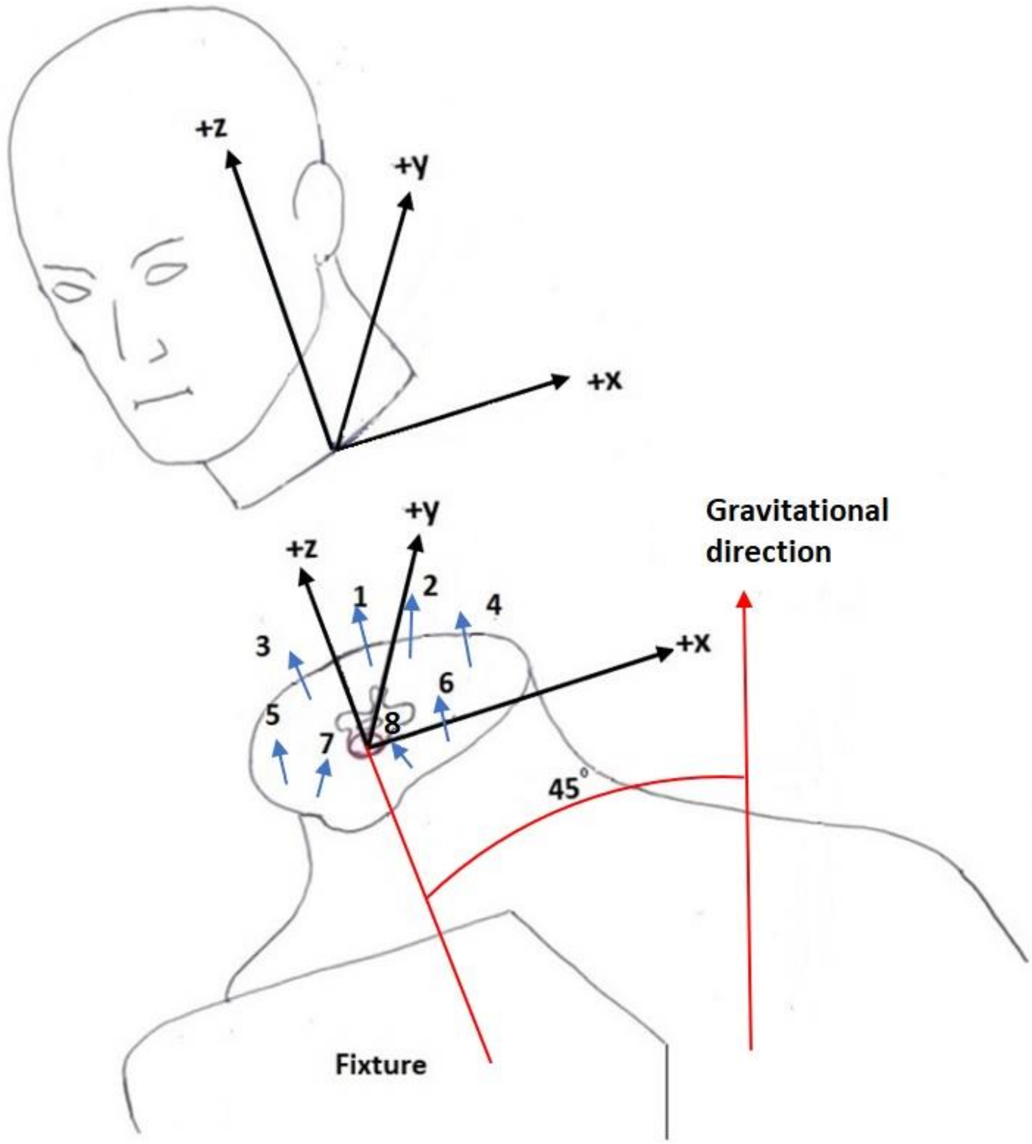

Figure 5.6 The coordinate system was located at the center of the C4/C5 disc with the positive axes of x, y, and z in left, posterior, and superior directions, respectively. The blue arrows represent the resultant muscle forces for each muscle group (1-2=posterior, 3-4=posterolateral, 5-6=anterolateral, and 7-8=anterior muscle groups)

Table 5.2. The muscles cross-sectional area (CSA), the center of action, and the angle of the line of action at C4/C5 level. (Exact numbers from Moroney et al. 1988, p-717). All the values are for left side muscles. (*The ratios should be multiplied by participant's neck width at C4/C5 level (right-left) and neck depth at C4/C5 level (anterior-posterior); **The ratios should be multiplied by participant's neck width at C4/C5 level; *** The ratios should be multiplied by participant's neck depth at C4/C5 level)

Muscles	CSA ratio*	Center of action ratio		The angle of the line of action (º) with the three axes		
		+x**	+y***	+x	+y	+z
Platysma	0.0040	0.208	-0.353	115	105	30
Infrahyoid	0.0128	0.135	-0.343	90	90	0
Sternocleidomastoid	0.0301	0.396	-0.088	75	58	37
Longus colli and cervicis	0.0055	0.115	-0.049	80	90	10
Scalene anterior	0.0075	0.228	-0.049	105	90	15
Scalene medius	0.0079	0.240	0.010	105	103	20
Longissimus cervicis	0.0051	0.260	0.108	80	90	10
Levator scapulae	0.0228	0.323	0.147	110	90	20
Multifidus	0.0083	0.073	0.176	140	70	45
Semispinalis cervicis	0.0189	0.073	0.275	95	90	5
Semispinalis capitis	0.0248	0.188	0.284	90	90	0
Splenius cervicis	0.0030	0.260	0.225	80	100	15
Splenius capitis	0.0120	0.250	0.304	77	105	20
Trapezius	0.0144	0.188	0.373	120	90	30

As mentioned before, the average AVRA of the first three minutes of FATIGUE STUDY for each neck sensor was used as the normalized muscle activity for the corresponding group of muscles. This included 14 pairs of muscles in eight groups. The muscle forces were calculated using Equation 5.1 (Cholewicki et al., 1995; Choi and Vanderby, 1999).

$$\text{Muscle force [N]} = (\text{normalized EMG})^{1/1.3} * \text{CSA [cm}^2\text{]} * \sigma \text{ [N/cm}^2\text{]} * (0.6)^{1/1.3} \quad (5.1)$$

where CSA represents the physiological cross-sectional area of the muscle, σ=35 [N/cm2] is the maximum force produced by muscle per CSA. To reflect our technique of normalizing EMG data by SVC-60% instead of MVC, a "Modifier" that is equal to $(0.6)^{1/1.3}$ was added to the Cholewicki et al., (1995) model.

The net moment generated by passive tissues about the sternum was calculated as 522.7 Ncm in condition HN-45 and 0 Ncm in condition T-45 based on McGill et al. (1994). These moments were translated to the C4/C5 level using the differences in moment arms and were modified by the participants' anthropometric measurements. Posterior longitudinal ligament (PLL), ligamentum flavum (LF), and inter+supraspinal ligament (ISSL) were the passive tissues included in this model to generate the net passive tissue moment (Figure 5.7.a). The ligament forces were considered as forces produced by linear springs located at the center of the ligament CSA (all on the y-axis) that generated force along the z-axis (Figure 5.7.b). The forces of these springs were considered to be linearly related to their stiffness and their distance from the origin of the coordinate system. The ratios of their distance from the center of disc at C4/C5 were measured based on cross-sectional anatomy of the neck (Eycleshymer and Schoemaker, 1911; Dixon et al., 2015), and the ratios of their stiffness were approximated based on the data by Chazal et al. (1985) at the start point of linear force-displacement behavior of each ligament. Equation (5.2) shows how the value of the generated forces by these three ligaments are related.

$$F_{(PLL)} = (0.254) * F_{(LF)} = (0.623) * F_{(ISSL)} \qquad (5.2)$$

where F represents the generated force by each ligament. Also, the distance from the center of the C4/C5 disk as a percentage of neck depth at C4/C5 (anterior-posterior) was multiplied by the participant's neck depth at C4/C5 (anterior-posterior) to calculate each ligaments moment arm for that participant.

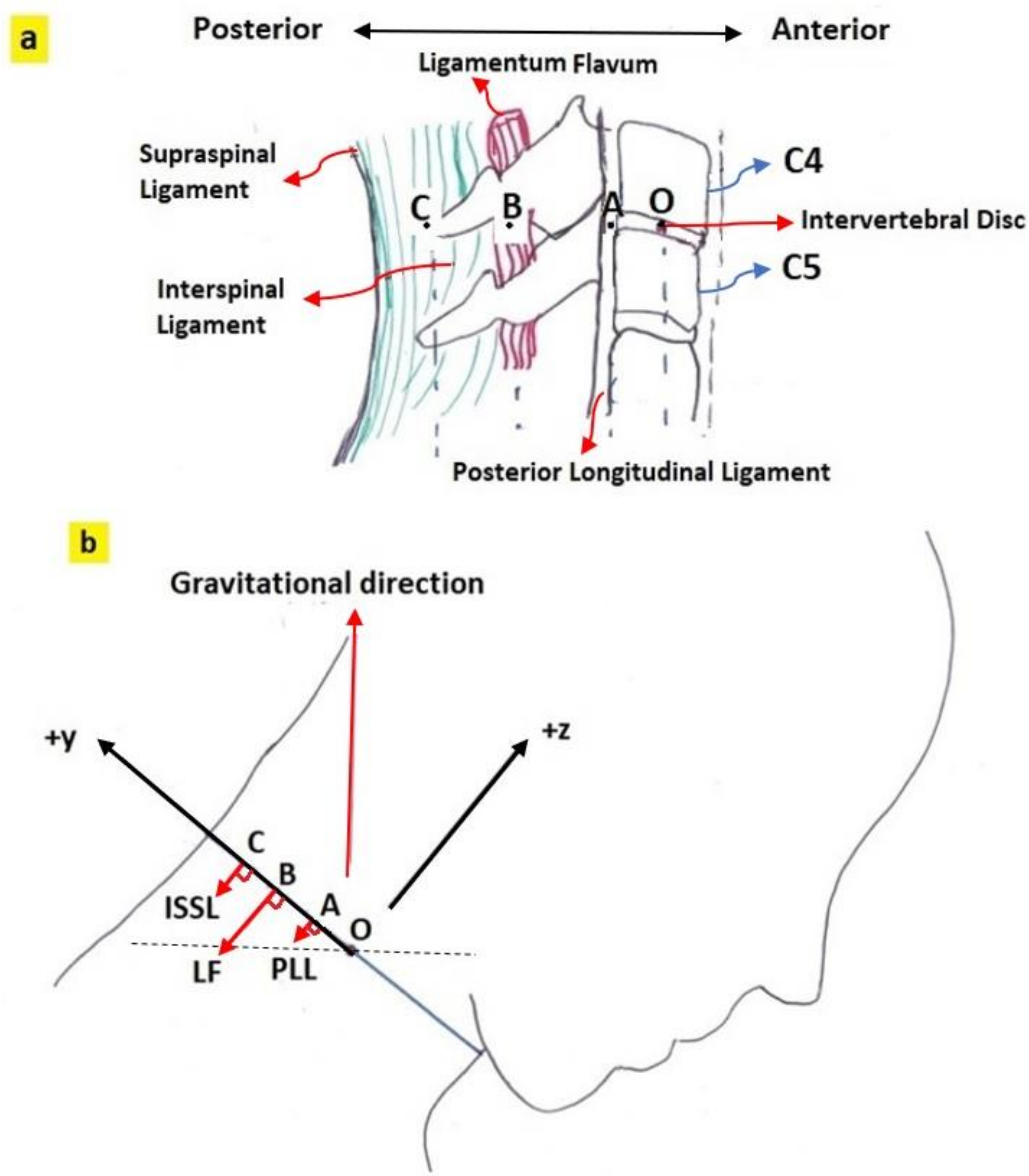

Figure 5.7 The cervical spine ligaments of the biomechanical model. a) The passive tissues included in the biomechanical model, b) Forces generated by the ligamnets: posterior longitudinal ligament (PLL), ligamentum flavum (LF), and inter+supraspinal ligament (ISSL)

The summation of the squared difference between external and internal moments about the x, y, and z directions was minimized (Equation 5.3), and the common gain (G) was found as a coefficient that linearly modified the internal moments about the three axes (Cholewicki et al., 1995; Choi and Vanderby, 1999).

$$Minimize(\sum_{k=x,y,z}(GM_{internal} - M_{external})^2) \quad (5.3)$$

where $M_{internal}$ is the moment generated by muscles and ligaments at the C4/C5 joint, and $M_{external}$ is the moment generated by the weight of the head at the C4/C5 joint. The value of G was multiplied by the muscles and ligaments forces. Then, the force equilibrium equations in x, y, and z directions were used to calculate the C4/C5 joint reaction compression force, net shear force, and the angle between shear force and +x.

Dependent and Independent Variables

For this biomechanical model, the independent variable was the body posture with two levels of HN-45 and T-45. The dependent variables were the estimated C4/C5 joint reaction compression force, shear force, and the angle between shear force and +x.

Statistical Analysis

All the statistical analyses were performed using JMP Pro 15. In all analyses, the overall significance level of 0.05 was used. For the C4/C5 joint reaction compression force, shear force, and the angle between shear force and +x, the difference between conditions HN-45 and T-45 was calculated for each participant. The normality of the differences for each dependent variable was checked using the Shapiro-Wilk test. Then, paired t-test or non-parametric Wilcoxon Signed-Rank test (if normality was violated) was employed. In evaluating the effects of HN-45 and T-45 on the dependent variables, a Bonferroni correction was employed (0.05/3=0.0167). The Bonferroni correction was done to maintain the overall significance level of 0.05, and to control the experiment-wise error.

Results

The mean (SD) of the estimated neck muscle forces and ligament forces during conditions HN-45 and T-45 have been shown in Table 5.3. Table 5.3 also presents the estimated muscle forces per their CSA for conditions HN-45 and T-45. The mean (SD) of the joint reaction forces on the superior cross-section of the C4/C5 level (the neck cross-section attached to the head) have been illustrated in Table 5.4. The results of the paired t-test showed that the C4/C5

Table 5.3 The mean (SD) of the neck muscle forces, ligament forces, and the muscle forces per CSA for conditions HN-45 and T-45

Muscle/Ligament	Force (N)		Forces per CSA (N/cm2)	
	HN-45	T-45	HN-45	T-45
Right Platysma	1.11(1.57)	0.86(0.58)	1.7(2.2)	1.4(0.8)
Left Platysma	1.30(0.98)	0.93(0.58)	2.1(1.5)	1.5(0.8)
Right Infrahyoid	3.56(5.04)	2.75(1.85)	1.7(2.2)	1.4(0.8)
Left Infrahyoid	4.18(3.14)	2.98(1.85)	2.1(1.5)	1.5(0.8)
Right Sternocleidomastoid	10.51(11.90)	8.90(4.58)	2.2(2.2)	1.9(0.8)
Left Sternocleidomastoid	7.93(6.91)	11.49(8.25)	1.7(1.3)	2.4(1.5)
Right Longus colli and cervicis	1.94(2.19)	1.64(0.84)	2.2(2.2)	1.9(0.8)
Left Longus colli and cervicis	1.46(1.27)	2.12(1.52)	1.7(1.3)	2.4(1.5)
Right Scalene anterior	2.64(2.99)	2.23(1.15)	2.2(2.2)	1.9(0.8)
Left Scalene anterior	1.99(1.74)	2.88(2.07)	1.7(1.3)	2.4(1.5)
Right Scalene medius	4.99(1.70)	6.23(2.24)	4.1(1.2)	5.2(1.6)
Left Scalene medius	4.61(2.24)	7.24(2.45)	3.8(1.5)	6.0(1.7)
Right Longissimus cervicis	3.22(1.10)	4.02(1.44)	4.1(1.2)	5.2(1.6)
Left Longissimus cervicis	2.97(1.44)	4.67(1.58)	3.8(1.5)	6.0(1.7)
Right Levator scapulae	14.39(4.91)	17.97(6.45)	4.1(1.8)	5.2(1.6)
Left Levator scapulae	13.29(6.45)	20.88(7.07)	3.8(1.5)	6.0(1.7)
Right Splenius cervicis	1.89(0.64)	2.36(0.85)	4.1(1.2)	5.1(1.6)
Left Splenius cervicis	1.74(0.85)	2.74(0.93)	3.8(1.5)	6.0(1.7)
Right Multifidus	6.04(2.21)	9.94(1.95)	4.7(1.3)	7.9(1.2)
Left Multifidus	7.01(2.49)	11.58(4.01)	5.5(1.6)	9.2(2.8)
Right Semispinalis cervicis	12.53(4.59)	20.62(4.05)	4.3(1.2)	7.2(1.1)
Left Semispinalis cervicis	14.55(5.17)	24.03(8.32)	5.0(1.4)	8.4(2.5)
Right Semispinalis capitis	16.44(6.02)	27.06(5.32)	4.3(1.2)	7.2(1.1)
Left Semispinalis capitis	19.10(6.78)	31.53(10.91)	5.0(1.4)	8.4(2.5)
Right Splenius capitis	7.96(2.91)	13.10(2.57)	4.3(1.2)	7.2(1.1)
Left Splenius capitis	9.24(3.28)	15.26(5.28)	5.0(1.4)	8.4(2.5)
Right Trapezius	9.55(3.49)	15.71(3.09)	4.3(1.2)	7.2(1.1)
Left Trapezius	11.09(3.94)	18.31(6.34)	5.0(1.4)	8.4(2.5)
Posterior longitudinal ligament	14.72 (5.91)	0		
Ligamentum flavum	57.95 (23.28)	0		
Inter+supraspinal ligament	23.61 (9.49)	0		

joint reaction shear force in condition T-45 was significantly greater than condition HN-45 ($p=0.0005$). No significant effect of these conditions was found for joint compression force and the angle between the shear force and +x.

Table 5.4 The mean (SD) of the joint reaction forces on the superior cross-section of C4/C5 level (the neck cross-section attached to the head). (* significance difference between condition HN-45 and condition T-45)

Variable	Condition HN-45	Condition T-45
Compression force (N)	331.64 (100.81)	311.49 (79.05)
Shear force (N)	35.69 (18.12) *	48.92 (19.05) *
The angle between shear force and +x (º)	92.16 (6.62)	93.18 (9.41)

Discussion

The main goal of this study was to evaluate the biomechanical difference between the neck flexion of 45º relative to gravity and the neck flexion of 45º relative to trunk. Two different studies (FRP STUDY, and FATIGUE STUDY) and a biomechanical model were used to clarify this research question. In the FRP STUDY, it was hypothesized that the onset and offset angles of the cervical FRP will not be affected by the trunk flexion. The results of the FRP STUDY supported our hypothesis as no significant effect of 45º of trunk flexion (comparing the FRP-0 and FRP-45) on the ONSET% and OFFSET% was found. This is consistent with the findings of a similar study by Pialasse et al. (2009) and implies that 45º of trunk flexion will not affect the neck muscles and passive tissues cooperation as a system during the neck flexion/extension motion (Phase 1 to Phase 4). Also, no significant effect of condition (FRP-0 and FRP-45) on FRR and ERR values were found. This contradicts Pialasse's findings, where 45º of trunk flexion resulted in greater ERR values (Pialasse et al., 2009). Also, the ERR values with and without 45º trunk flexion in Pialasse's study (~3.4 and 2.4, respectively) were greater than this study (~1.8 and 1.6, respectively). Ten male participants showed a greater ERR in condition

FRP-45 (1.783) compared to condition FRP-0 (1.621); however, more participants may be needed to distinguish a significant difference. Twelve females and seven males (19 participants) were recruited in Pialasse's study (Pialasse et al., 2009). Also, it should be noted that comparing the ONSET% and OFFSET% in this study (~88.2% and 96.4%, respectively) with similar studies such as Pialasse et al., (2009) (~74.1% and 92.7%, respectively), Nimbarte et al., (2014) (~80.2% and 96.9%, respectively), and Mousavi-Khatir et al., (2016) (~67.5% and 95.1%, respectively) confirms the overall validity of our established procedure. These findings also imply the need for establishing a consistent procedure for studying FRP in the cervical spine.

On the other hand, the increase in AVRA during the 30 minutes of FATIGUE STUDY showed that neck posterior (condition HN-45 and T-45) and posterolateral (condition T-45) muscle groups fatigued while the MDF data didn't show fatigue occurrence in any of the neck muscle groups. These findings are consistent with the previous studies (Szeto et al., 2005; Vijendren et al., 2020; Sarker et al., In Press) and imply that in studying the neck muscles using EMG, the EMG amplitude-based measures of fatigue are more responsive to muscle fatigue than the traditional median frequency measures of muscle fatigue. Szeto et al. (2005) found no significant decrease in the EMG median frequency of cervical erector spinae muscles for prolonged static postures during 20 minutes of screen-based typing tasks. Vijendren et al. (2020) showed an increase in EMG amplitude of upper trapezius descendens muscles during prolonged microscope usage for about 18 minutes without breaks. Sarker et al. (2020) found a significant increase in the EMG amplitude of neck extensor muscles during prolonged neck flexion of 45º for 60 minutes with either a three-minute break after 30 minutes or two 90-second breaks after each 20 minutes while no significant change in median frequency of the EMG signals was found (Sarker et al., 2020).

In the FATIGUE STUDY, it was hypothesized that in prolonged static postures, the neck flexion relative to gravity generates higher muscle fatigue compared to neck flexion relative to trunk. The results showed that condition T-45 (neck flexion relative to gravity) caused higher fatigue in neck posterior muscles than condition HN-45 (neck flexion relative to trunk). Consistent with these findings, the subjective evaluation through the SURVEY revealed higher neck discomfort in condition T-45 compared to HN-45. The role of passive tissues in holding neck flexion postures is consistent with these findings. As the FRP STUDY shows, the passive and active tissues will cooperate similarly with and without 45º of trunk flexion. In other words, in condition HN-45, the neck is flexed relative to trunk (somewhere in Phase 2 in FRP STUDY), and the stretched passive tissues have a role in holding the posture. However, in condition T-45, the neck is neutral relative to trunk (Phase 1 in FRP STUDY), and the passive tissues don’t appear to have a significant role in holding the posture. To the extent of our knowledge, none of the existing risk assessment tools consider this distinction when assessing neck flexion angles. If the assessment of the risk of muscle fatigue is the goal of the work assessment, it should be noted that the neutral neck relative to trunk, while trunk is flexed, shouldn’t be considered as neck flexion of 0º. Actually, the risk would be greater than when only the head and neck were flexed, and trunk had no flexion. Also, there was evidence for muscle fatigue in posterolateral muscles only for condition T-45. This could be because the posterior muscle group had a more dominant role in exerting the required neck extension moment than the posterolateral muscle group. This is consistent with the previous literature that considers all the muscles in the posterior group and two muscles in the posterolateral group as neck extensors (Posterior group: upper trapezius, semispinalis cervicis, semispinalis capitis, splenius capitis, and multifidus; Posterolateral group: splenius cervicis, and levator scapulae) (Schomacher and Falla 2013; Kesserwani, 2020).

The role of passive tissues is seen when the neck is flexed relative to trunk. This means that in condition T-45, although higher muscle fatigue and neck discomfort was achieved compared to condition HN-45, the passive tissues were not helping to hold the posture. This could be an important factor in comparing condition T-45 to condition HN-45 with regard to neck musculoskeletal problems. Our results show that T-45 causes higher neck muscle fatigue and neck subjective discomfort, but the long-term effects of these two conditions are not described by this study. In general, from the findings of this study, we recommend that the work assessment tools should consider both measures of neck flexion angle (relative to gravity, and relative to trunk), in their assessment tools.

The biomechanical model in this study was based on the EMG-based model of the cervical spine by Choi and Vanderby (1999). The C4/C5 compression force in neck flexion of 45º for both conditions (HN-45 and T-45) was about 23% of this value during maximum neck extension at an upright neck posture (1372.4 N) by Choi and Vanderby (1999). Also, the C4/C5 joint shear reaction force in neck flexion of 45º was about 20% (HN-45) and 27% (T-45) of this value during maximum neck extension at an upright neck posture (181.8 N), while consistent with our findings, this estimated shear force was almost at the anterior-posterior direction (Choi and Vanderby, 1999).

It was hypothesized that both shear and compression reaction forces at C4/C5 level would be greater in neck flexion relative to gravity compared to neck flexion relative to trunk. This hypothesis was rejected for compression reaction force at C4/C5 level, but it was confirmed for shear reaction force at C4/C5 level. The biomechanical model found no significant effect of condition (HN-45 and T-45) on the C4/C5 compression force. The mean of C4/C5 compression force was 331.64 (N) and 311.49 (N) for conditions HN-45 and T-45, respectively, and the average of the participants' head weight was 61.09 (N). It means that holding a 45º degrees of flexion using either HN-45 or T-45 method exerts a compression force (at C4/C5 level) of about 5.25 times the weight of the head. It would be equal to more than 38% of the person's whole-body weight. Additionally, there was no difference between HN-45 and T-45 with regard to the angle between the C4/C5 joint shear reaction force and the x-axis. This angle was very close to 90º for both conditions. This shows the bilaterally symmetric nature of the FATIGUE STUDY task and the neck muscles. Also, it shows that the C4/C5 joint shear reaction force was exerted almost completely in the anterior-posterior direction. The shear joint reaction force was significantly higher in condition T-45 than condition HN-45. In condition HN-45, the flexion is performed by the head and neck together. It leads to less flexion in the neck, and consequently, the component of the head weight in the y-direction will be smaller compared to condition T-45. However, the difference in shear reaction force between condition HN-45 and T-45 was statistically significant the clinical significance of this difference should be further evaluated. It has been shown that sustained application of static shear force could induce intervertebral degeneration such as nucleus pulposus cavity loss and border disruption through an in vivo study on rats (Kim et al., 2012). Future studies could clarify the potential clinical importance of the difference in shear reaction force between conditions HN-45 and T-45.

The contribution of the findings of this study could be described from two viewpoints. First, the importance of a system-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion was presented. The cervical spine was not investigated separately, but the combination of head/neck and trunk were explored in sagittal plane flexion postures. It is recognized that the human body linkage is working as a system in making and holding different body postures; for example, it was shown that holding a static trunk flexion posture could lead to neck muscle fatigue. Also, active and passive tissues are cooperating together (e.g., lumbar and cervical FRP), and both of them should be considered in studying the biomechanics of the human body. Secondly, it is hoped that the findings of this research could enhance the work assessment tools and ergonomic interventions. The work assessment tools should note that the body segments shouldn't be assessed separately. As mentioned previously, trunk flexion could lead to neck muscle fatigue; however, the neck might be in a neutral posture relative to trunk. On the other hand, in implementing ergonomic interventions, the human body should be considered as a linkage model. For example, if the height of a workstation is adjusted to decrease trunk flexion angles, it would affect neck postural exposure too. Additionally, if the postural exposure in the neck is required to be modified, it could be done through modifying trunk postures as well and they will interact with one another.

There are some limitations in this study that should be noted. Ten male participants were recruited in this study. This provided us with higher homogeneity in the data; however, the generalization of the findings to females should be made cautiously. All the biomechanical models are based on some assumptions and simplifications. The biomechanical model presented in this study employed assumptions and simplifications that were described throughout the paper. This model could be improved step by step in the future to enhance the accuracy and reliability of its results. Also, it should be noted that the main goal of this study was to evaluate the biomechanical difference of 45º of neck flexion relative to gravity and relative to trunk. Neck flexion of 45º was chosen for this study because the pilot studies showed that it could be a good candidate to test our hypothesis while the participants could perform the experimental tasks. More levels of neck flexion angle will add to the generalizability and applicability of our findings.

Conclusion

The main goal of this study was to evaluate the biomechanical difference between the neck flexion of 45º relative to gravity and relative to trunk. The results showed that the cooperation between neck muscles and passive tissues will happen with and without 45º of trunk flexion. Also, the results showed that T-45 causes higher neck muscle fatigue and neck subjective discomfort compared to HN-45, but the long-term effects of these two conditions are not clear because of the difference in the role of passive tissues in holding these postures. The biomechanical model showed that neck C4/C5 joint reaction compression force was the same for conditions HN-45 and T-45. The difference in shear reaction force between condition HN-45 and T-45 was statistically significant; however, the clinical significance of this difference should be further evaluated. This study presented the importance of a system-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion, and the findings of this research could enhance the work assessment tools and ergonomic interventions.

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Appendix: IRB approval memo

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 07/10/2020

To: Gary Mirka

From: Office for Responsible Research

Title: **Effects of neck postural exposure in the sagittal plane on the cervical spine fatigue and discomfort**

IRB ID: **20-221**

Submission Type: Initial Submission **Review Type:** Expedited

Approval Date: 07/10/2020 **Approval Expiration Date: N/A**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp.**
- Retain signed informed consent documents **for 3 years after the close of the study,** when documented consent is required.
- **Obtain IRB approval prior to implementing** any changes to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks to subjects or others.**
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are

protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to **post-approval monitoring by Iowa State University's Office for Responsible Research**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.

- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.

- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

CHAPTER 6. GENERAL CONCLUSIONS

To address the important research questions posed in this study, a series of inter-related research projects were conducted. In this chapter, the conclusions from the preliminary studies that provided important foundational results will be discussed. This discussion will be followed by the conclusions from the primary study that focused on this important concept of the systems-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion.

Preliminary Studies

The first preliminary study (Chapter 2) was a systematic review of the archival journal literature on the broad topic of the relationship between sagittal plane neck flexion and musculoskeletal problems of the neck. This review revealed clear evidence of a positive correlation between neck flexion and neck problems in working populations. This review further showed that 20º of neck flexion was a good cut-off angle for high- and low-risk neck flexion postures. This systematic review motivated a more formal, detailed biomechanical and physiological assessment of sagittal plane neck flexion.

One practical aspect of the physiological assessment of neck flexion was the exploration of the effect of breaks during static neck flexion on the fatigue development of the cervical neck extensors (Chapter 3). The results of this study showed that of the work-rest strategies tested, the best strategy for preventing neck muscle fatigue for static neck flexion of 45º had frequent but short breaks (10-minute static work posture and 36 second relaxation period). This is shorter than most of the recommendations in the literature, which may balance the physiologic data with the acceptability of task interruption. Determining the best work-rest cycle strategy for performing work requiring neck flexion is important as more and more office work is performed on laptops and tablets. Other types of work may also require long periods of neck flexion to complete tasks.

Future work can be done considering the effects of different strategies on the other aspects of an occupation, including physical and cognitive performance (such as productivity and accuracy). It could help to determine the appropriate strategy for each specific occupation.

Chapter 4 was a paper that focused on an important methodological consideration in performing EMG-based studies. When performing an experiment across several days, normalization of EMG is an important procedure to control for the day-to-day variability. Performing maximum voluntary contractions on each of these days is problematic, particularly for sensitive regions of the body like the cervical spine. The study outlined in Chapter 4, provided a novel method for predicting maximum voluntary contraction EMG through the extrapolation of submaximal voluntary contraction EMG values. The results of this study showed promise for creating a margin of safety for those that conduct research on the cervical spine that requires multiple days of data collection.

Collectively, these three preliminary studies provided important theoretical, biomechanical and methodological insights that informed the primary study of this dissertation.

Main Study

The focus of this study was to perform a systems-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion. There were two primary aspects of this systems-level approach. First, as compared to many previous studies, this work provided an assessment of both the active (muscles) and passive (ligament) components that generate neck extension moments. Second, this study assessed the inter-relationship between trunk posture and the biomechanical response of the cervical musculature. Specifically, this study explored the biomechanical difference between neck flexion relative to trunk and neck flexion relative to gravity, considering both active and passive tissues (Chapter 5). The results show that:

1. The cooperation between neck muscles and passive tissues will occur with and without 45º of trunk flexion.

2. Trunk flexion of 45º did not affect the onset and offset angles of cervical FRP.

3. The 45º of neck flexion relative to gravity (where the head and neck were neutral relative to trunk and trunk was flexed 45º) caused higher muscle fatigue compared to the 45º of neck flexion relative to trunk (where the head and neck were flexed 45º relative to trunk and trunk was upright). Both subjective (neck discomfort) and objective (increase in EMG amplitude of the posterior neck muscles) measurements confirmed this finding.

4. The long-term effects of these two conditions (45º of neck flexion relative to gravity vs. 45º of neck flexion relative to trunk) is not clear because of the difference in the role of passive tissues in holding these postures.

5. The C4/C5 joint compression reaction force was the same when holding 45º of neck flexion relative to trunk (331.6 N) and 45º of neck flexion relative to gravity (311.5 N), while the C4/C5 joint reaction shear force was significantly higher in holding the 45º of neck flexion relative to gravity (48.9 N) compared to the 45º of neck flexion relative to trunk (35.7 N).

The contribution of the findings of this study could be described from two viewpoints. First, a system-level evaluation of the biomechanical response of the cervical spine to sagittal plane flexion was presented. The cervical spine was not investigated separately, but the combination of head/neck and trunk were explored in sagittal plane flexion postures. The goal was to represent the human body linkage as working as a system in making and holding different head/neck postures. For example, it was shown that holding a static "trunk flexion posture" could lead to "neck muscle fatigue" and generate significant "joint reaction forces in the cervical spine". Also, both active and passive tissues are cooperating together (e.g., lumbar and cervical

FRP), and both of them should be considered in studying the biomechanics of the human body. Secondly, it is hoped that the findings of this research could enhance the work assessment tools and ergonomic interventions. The work assessment tools should note that the body segments shouldn't be assessed separately. As mentioned above, trunk flexion can lead to neck muscle fatigue; however, the neck might be in a neutral posture relative to trunk. On the other hand, in implementing ergonomic interventions, the human body should be considered as a linkage. For example, if the height of a workstation is adjusted to decrease trunk flexion angles, it would affect neck postural exposure too. Also, if the postural exposure in the neck is required to be modified, it could be done by modifying trunk postures as well.

Future Work

There are some directions for future work to widen the generalizability of our findings and also, to find some answers to the questions that were generated during accomplishing this study.

1. To consider the effects of different work-rest cycle strategies on the other aspects of an occupation, including physical and cognitive performance (such as productivity and accuracy).

2. To conduct more realistic scenarios where the work-rest cycle is chosen by the participant, and the neck posture is evaluated during the whole working day.

3. To evaluate different levels for neck flexion angle (e.g., 10º, 20º, 30º, and 60º) in studying the biomechanical response of cervical spine to head/neck flexion

4. To design and conduct experimental procedures that explore the difference in the biomechanical response of the cervical spine between head flexion, neck flexion, and their combinations

5. To improve the biomechanical model of the cervical spine by using more accurate measurements of the active and passive tissues in the model (e.g., muscles and ligaments

moment arms in different postures of neck flexion, the angle of the line of action for muscles and ligaments in different postures of neck flexion, and the muscles pennation angle in measuring muscles cross-sectional area).

6. To perform similar studies to evaluate the effects of other neck postural exposures (neck extension, right and left lateral bending, and axial rotation, and their combinations) on the biomechanics of the cervical spine.