BIOMECHANICAL EFFECTS OF CRANIO-CERVICAL POSITIONS ON CERVICAL MUSCULOSKELETAL DISORDERS

REN SICONG

M.Phil

The Hong Kong Polytechnic University

2016

The Hong Kong Polytechnic University

Interdisciplinary Division of Biomedical Engineering

Biomechanical Effects of Cranio-cervical Positions on Cervical Musculoskeletal Disorders

REN Sicong

A thesis submitted in partial fulfilment of the requirements for the Degree of Master of Philosophy

February 2016

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

_____________________________ (Signed)

(REN Sicong)

ABSTRACT

Cervical musculoskeletal disorder become one of the global health problems. It involves the tissue stiffness, muscle weakness, pain syndromes and limited range of movement along the cervical spine. This disease imposes the heavy burden on the economy, society and human well-beings.

Proposed mechanism for this disorder is associated with high intrinsic forces along cervical spine, resulting from various types of movements, as well as with malposition of cervical vertebrae at each level. However, it is not well-understood in static situation due to the difficulty of detecting the low-intensity intrinsic forces in the cervical musculoskeletal system. Furthermore, posture as a predictor of internal load, how does cervical musculoskeletal system distribute the loads under various types of spinal postures? Although considerable research has been devoted to normal motion of the cervical spine, such as flexion, extension, lateral bending and rotation, rather less attention has been paid to protraction in term of biomechanical aspect, especially in a static condition.

Therefore, the aim of this study is to investigate head-neck posture, cervical spinal posture and load sharing in the cervical musculoskeletal system under three static cranio-cervical positions (neutral, protraction and flexion) during two sitting postures

(upright and slump). For investigating the biomechanics of cervical musculoskeletal system and human performance, a platform was established at two levels in this study, including motion capture analysis and musculoskeletal modelling.

This study utilized repeated measure design with ten healthy participants performing six experimental conditions. It included cranio-cervical neutral, protraction and flexion positions under upright and slump sitting postures. Three-dimensional posture angles of seated human were measured using the Vicon motion analysis system (Vicon MX, Oxford, UK). Supporting forces under bottom and foot were measured through two force platforms. For predicting inner cervical vertebral angles and load carrying in musculature and cervical joint at each level, the musculoskeletal model with a detailed cervical spine was developed in AnyBody Modelling System. The musculoskeletal model was partially validated through electromyography and previous literature.

The result showed that there was a significant interaction between the effects of sitting posture and cranio-cervical position on postural angles ($p < 0.05$). There were no significant differences in cranial angle between neutral and protraction, approximately 70 degrees both under upright and slump sitting postures. For the cranio-cervical angle, it was significantly greater in protraction than other cranio-cervical positions ($p < 0.001$), reaching approximately 175 degrees.

In musculoskeletal prediction, the cervical tilt angles at the level of C0C1, C2C1, C3C4 and C5C6 varied significantly (p< 0.05) among neutral, protraction and flexion in upright and slump sitting postures respectively. The slumped posture was associated with greater cervical tilt angles compared with the upright posture. The upper vertebral tilt angles in protraction were almost two times as that of the neutral position while the lower vertebral tilt angles in protraction increased by approximately 40% compared with the neutral position during upright sitting. Cervical tilt angles were the greatest for flexion position ranging from 23 to 43 degrees at each vertebral level. However, there was no significant difference between protraction and flexion at the level of C6C7 and C7T1.

There was a significant interaction between the effects of sitting posture and cranio-cervical position on multifidus cervicis, levator-scapular, trapezius-scapular and trapezius-clavicular muscles ($p < 0.05$). For cervical flexors, it carried approximately 9% of the load in cranio-cervical neutral position during upright sitting. It was also greater than other conditions. As for cervical extensors, load carrying proportions were observed great in cranio-cervical protraction under both upright and slump sitting postures, reaching approximately 95% and 96% respectively.

Cervical joint forces in cranio-cervical flexion were significantly greater than neutral or protraction conditions ($p < 0.05$). The maximum joint reaction forces were 206.3N and 218.6N at the level of C7T1 in cranio-cervical flexion during upright and slump sitting posture, respectively. However, there was no significant difference in joint reaction forces between cranio-cervical neutral and protraction positon.

For the validation of the musculoskeletal model, the mean correlation coefficients between the predicted and measured muscle activities over trapezius-clavicular and cervical erector muscles in various types of cranio-cervical positions were 0.313 and 0.471, respectively. There was a fair degree of relationship between the estimated and measured muscle activity ($0.25 < r < 0.05$, $p < 0.05$).

This study investigated biomechanical characteristics of static cranio-cervical positions under two major sitting conditions through motion analysis and musculoskeletal modelling. These results showed the static behavior of the cervical spine in response to various types of postures. It was concluded that slump posture favored the mobility of cranio-cervical spine and also increased the forward inclination of cervical vertebrae. Cervical extensors including trapezius and multifidus muscles played an important part in maintaining cranio-cervical positions. Cervical flexors produced great force in neutral position. Moreover, superficial muscles were found to be more responsive to the positional changes of head and neck than deep muscles.

In this study, a combination of experimental and computational studies provided a versatile platform for interpreting complicated cranio-cervical behaviors under different static postures. Estimation of cervical spinal posture and load carrying along cervical spine was obtained from the validated musculoskeletal model. This work could provide insight into the effects of static loading on musculoskeletal health, and mechanisms underlying cervical musculoskeletal disorders caused by the sedentary occupation, as well as scientific fundamentals for ergonomics design.

PUBLICATIONS

Peer-reviewed Journal

1. Sicong Ren, Duo Wai-Chi Wong, Hui Yang, Yan Zhou, Jin Lin, Ming Zhang, 2016. Effect of Pillow Height on the Biomechanics of Head-neck Complex: Investigation on Crano-cervical Pressure and Cervical Spine Alignment. Peer J. 4: e2397. DOI: 10.7717/peerj.2397.
2. Sicong Ren, Duo Wai-Chi Wong, Wenhao Li and Ming Zhang. Estimation of spinal posture and load carrying in the cervical spine with different cranio-cervical positions. Prepared to submit to Gait and Posture.

Conference proceedings

1. Sicong Ren, Wenhao Li, Ming Zhang. Biomechanical effects of cranio-cervical positions on cervical musculoskeletal disorders. 39th Annual Meeting of the American Society of Biomechanics. Columbus, Ohio, America, Aug. 5-8, 2015.
2. Sicong Ren, Siyuan Zhu, Ming Zhang. Effects of pillow height on cranio-cervical spine in supine position. Biomedical Engineering International Conference, Hong Kong, Dec. 4-6, 2014.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Prof. Ming Zhang for the continuous support, critical thinking and constructive suggestions for my research study. Whatever the field of study, his guidance helped me a lot in coming up with creative ideas and keeping in-depth thinking about questions. I do really appreciate his profound knowledge of mechanics, the flexibility of problem-solving, and excelsior attitude towards biomechanical study, all of which provide chances for me to improve myself. With his suggestions and encouragement, I am able to widen this study from various perspectives.

A very special thank goes out to Dr. Lizhen Wang, without whose motivation and enthusiasm I would never try my first step in the study of finite element analysis. Dr. Lizhen Wang is the associate professor at Beihang University. It was under her guidance that I developed interests in the human simulation. With her kindness of personality and strong faith in the future of biomedical engineering, I began to search a large amount of information related to this field. She provided me with mental support, career direction and became more of a friend than a teacher.

I must acknowledge Dr. Duo Wai-Chi Wong for offering me professional technical support about model development. Appreciation also goes out to Miss Wenhao Li from

Shandong University for technical assistance in Modeling System in my study. I would like to sincerely express my gratitude to Mr. Fei Yan, Mr. Linwei Chen, and Mr. Jay Dai for huge support in my experimental study. Thanks also go out to Dr. Winson. CC Lee, Dr. MS Wong, Dr. Lei Sun, Dr. Yan Wang and Mr. Zhi Xu for giving suggestions and thought-provoking feedback during my confirmation, seminars and guided studies.

I would like to thank all the participants from different departments in The Hong Kong Polytechnic University for their interests in taking part in this study. I am also so grateful to my beloved family and friends for their encouragement and continuous support. I would like to express my hundreds and thousands of thanks to everyone who gave me a hand, contributed to my study and supported me in my postgraduate life.

Finally, I would like to thank the University Grant Council of Hong Kong for providing financial assistance on research studentship for this study, the Interdisciplinary Division of Biomedical Engineering, The Hong Kong Polytechnic University.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

C7: 7^{th} cervical vertebra

CLAV: Clavicle

CNS: Central nervous system

EMG: Electromyography

LANK: Left ankle

LASI: Left anterior superior iliac

LBHD: Left back head

LEBL: Left elbow

LFHD: Left front head

LFIN: Left finger

LHEE: Left heel

LKNE: Left knee

LOC: Left out canthus

LPSI: Left posterior superior iliac

LSHO: Left shoulder

LTOE: Left toe

LTR: Left tragus

LWRA: Left wrist A

MRI: Magnetic resonance imaging

MVC: Maximum voluntary contraction

RANK: Right ankle

RASI: Right anterior superior iliac

RBAK: Right back

RBHD: Right back head

REBL: Right elbow

RFHD: Right front head

RFIN: Right finger

RHEE: Right heel

RKNE: Right knee

RPSI: Right posterior superior iliac

RSHO: Right shoulder

RTOE: Right toe

RTR: Right tragus

RWRA: Right wrist B

STRN: Sternum

T10: 10^{th} thoracic vertebra

X-ray: X-radiation

CHAPTER 1. INTRODUCTION

1.1 Cervical musculoskeletal disorder- A global health problem

1.1.1 What is cervical musculoskeletal disorder?

Cervical musculoskeletal disorder is becoming a common health problem bothering a great number of people throughout the world. It not only affects the healthy condition of the cervical musculoskeletal system, but causes the dysfunction of the muscles, ligaments, tendons, joints and nerves along the cervical spine. Usually, these disorders could bring different types of neck pain syndromes, limitation of the range of movement of the cervical spine, and sometimes even affect the function of head and upper limbs. The major syndromes of cervical musculoskeletal disorder involve the tissue stiffness, muscle weakness, pain and limited range of movement.

Cervical musculoskeletal disorder results from various types of causes, ranging from acute cervical sprains or strains to chronic accumulative load-bearing (Dutton, 2004). Since the vast set of causes frequently occur in a combinative way so that the etiology of some cervical disorders is complex. Therefore, it is also difficult to make proper and effective treatments according to these syndromes. Inevitably, degenerative changes of the cervical musculoskeletal system could provoke pain source as people grow older.

Cervical spine can be the main source of many pain syndromes around head and neck as well as upper limbs. Several causes could result in pain syndromes, tumor, inflammation, bone fractures, joint dislocation and psychosocial condition (Levin and Neurology, 2007). Due to the multifactorial contributors of the pain syndromes, it is difficult to identify the specific source of developing the cervical spine disorders. Therefore, in the term of the anatomy, the definition of neck pain was put forward according to the symptomatic boundary (e.g. superior nuchal line, the spine of scapula, and superior border clavicle). Cervical spinal pain or neck pain was defined as the symptoms located in the region of the neck with or without radiation to the head, trunk and upper limbs (Guzman et al., 2009b).

However, in several studies, some researchers put forth the definition of mechanical neck pain which is widely used in practical cases (Figure 1-1). The operational definition of mechanical neck pain was summarized that pain mainly located in the posterior aspect of the neck which can be aggravated by the neck movement or by sustained postures (Mansilla-Ferragut et al., 2009, Kanlayanaphotporn et al., 2009). This definition of neck pain not only describes the location of the pain, but also points out the provocative factors for the development of neck pain. However, it still does not indicate the causation of this syndromes.

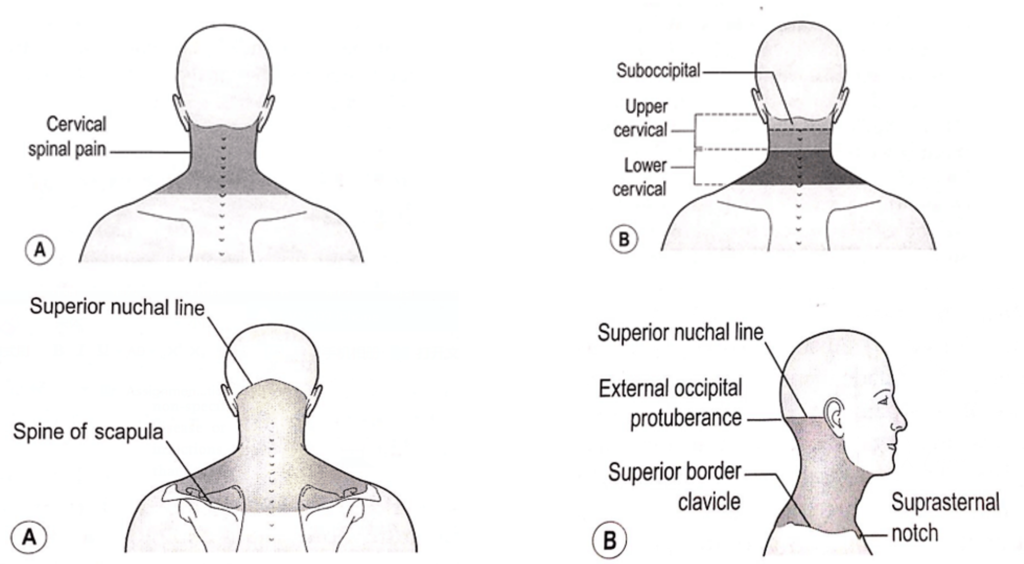

Figure 1-1. Topographical definition of neck pain (Merskey and Bogduk, 1994).

Due to the various types of neck movements and static postures, cervical musculoskeletal system, including muscles, ligaments, tendons, nerves, bones and joints, is easy to get involved in the development of pain syndromes. There exists several causes which are commonly accepted in clinical and research fields. For example, nerve root compression usually caused by cervical spondylosis and cervical disc herniation plays an important part in cervical radiculopathy (Abbed and Coumans, 2007). The level of the compressed nerve root on the cervical spine determines the location of the pain symptom.

The Neck Pain Task Force performed a systematic category to help clinicians provide professional healthcare and also to assess the effect of rehabilitation treatment. The classification of cervical musculoskeletal pain was shown as the following: Grade 1 neck compliant of pain, stiffness, or tenderness and little or no interference with daily activity; Grade 2 neck pain with musculoskeletal signs and limits daily activity; Grade 3 neck pain with neurologic signs; Grade 4 neck pain with tumor, fracture, dislocation and systemic disease (Guzman et al., 2009a).

Cervical stiffness mainly rises from cervical muscle strain or sprain in both dynamic and static conditions. In the daily activity, prolonged awkward posture can be responsible for the cervical stiffness. For example, protraction of head and neck during computer use and hyper flexion of cervical spine while using smart phones. Besides, sleeping position with different types of pillows could also affect the cervical conditions (Gordon et al., 2010). Pillows that are too high or too low are likely to strain the cervical spine and provoke waking cervical stiffness. Although this slight strain around neck usually produces discomfort and complaints, this condition can be relieved for a couple of days and without further professional healthcare or surgical treatment. Furthermore, at injury level, the cervical spine may suffer high load-bearing at a short time or long-term vibration in some dynamic situations. For example, sports injuries or car collision could give rise to strain and tension along cervical spine. This serious strain on the cervical spine leads to the stiffness of facet joint and muscle, which accompanies with the acute or chronic pain to a certain degree. This whiplash injury is also one type of common and troublesome cervical musculoskeletal disorders.

Cervical musculoskeletal disorders involve the cervical musculoskeletal system, and 90% of human body is likely to take part in the interaction with the surrounding environment. Especially, with the high pace of science and technology, the human body is provided with more complex and diverse external environment than ever before. The cervical musculoskeletal disorder is a significant component of occupational musculoskeletal disorder which are the leading cause of disability, injury in health conditions and the loss of productivity and cost (Levin and Neurology, 2007, Giles and Singer, 1998). Moreover, patients and people with the discomfort of the cervical musculoskeletal system always attribute the costs to the loss of work days and payments for the short- and long-term treatments (Chiu et al., 2010).

1.1.2 Prevalence of cervical musculoskeletal disorders

The overall prevalence of neck pain in the general population ranges between 0.4% and 86.8% (mean: 23.1%). In the United States, the 3-month prevalence of neck pain was 31% among general adults (Strine and Hootman, 2007), and the 1-month prevalence of neck pain was 35.9% in adults above 65 years old (Patel et al., 2013). A total of 50%

reported neck pain that lasted for 12 months in Canada, and the rate of associated activity-limiting pain was 11.7% (Hogg-Johnson et al., 2008). In the United Kingdom, the 1-month-period prevalence of neck pain was up to 89% (Webb et al., 2003). A study from Hong Kong reported a similar 12-month prevalence of neck pain of 64.6% (Chiu et al., 2010). The highest prevalence of neck pain in New Zealand was 43% which was far less than that of low back pain. On the basis of the population of Finnish university students, Widanarko et al. (2011) reported the prevalence rate of neck-shoulder pain increased from 25% to 29% in 2000 to 2009 period.

Typically, neck pain is one of the most common symptoms related to the cervical musculoskeletal disorders, with a one-year prevalence of 72% and the disability rates of 11% (Nordin et al., 2009). The prevalence of neck pain is higher in high-income countries than that in low- or middle- income countries. In a study of a large population in Spain, Fernández-de-las-Peñas et al. (2011) showed the 1-year prevalence rate of 26.4% in women and 12.3% in men. Similarly, a higher prevalence of neck pain among women was found compared with men (Hoy et al., 2010, Manchikanti et al., 2008), mainly because female necks were weaker than male necks in term of neck dimension and muscle strength (Vasavada et al., 2008, Dunk and Callaghan, 2005).

1.1.3 Risk factors of cervical musculoskeletal disorders

Overall cervical musculoskeletal disorders are mainly caused by ergonomic, physical and psychosocial factors at work (Dunstan et al., 2012). Computer use during long-term sitting was reported to be one of the most frequently mentioned causations of cervical musculoskeletal disorders (Gerr et al., 2002, Ortiz-Hernández et al., 2003). Moreover, Marcus et al. (2002) showed that personal computer use increased the risk of cervical musculoskeletal disorder as it was related to a number of postures and neck rotation as well as inclination. Based on the study of a large population (1483 young people), Straker et al. (2011) found that neck and shoulder pain may have been caused by computer use, which results from inactivity, postural loading factors and sustained static postures during prolonged sitting. These contributors are shown in Figure 1-2.

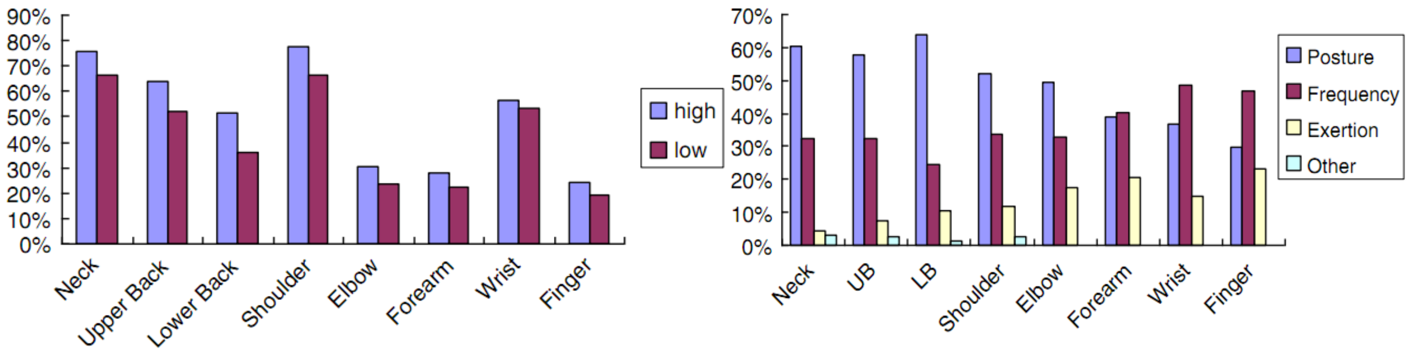

Figure 1-2. Prevalence of musculoskeletal disorders between high and low workload (Left), and risk factors for various types of body segments(Cho et al., 2012).

Epidemiological evidence has identified numerous risk factors which are related to the development of the cervical musculoskeletal system. Generally, these include gender, repetitive movements, high force demands, work posture, vibration, computer work and stress factors (Kitazaki and Griffin, 1997, Magnusson and Pope, 1998). Most evidence suggested the cervical musculoskeletal pain is associated with gender, age, individual health conditions and income (Eltayeb et al., 2009). Ariens et al. (2000) concluded that there was a positive relationship between neck pain and the following work-related risk factors: arm force, neck flexion, twisting or bending of the trunk, duration of sitting, arm posture, workplace design and hand-arm vibration. According to Brink and Louw (2013), several factors of sitting were identified as related to the upper quadrant musculoskeletal pain located around the shoulder region. These contributors were activities during sitting, postural angles, sitting duration and dynamism. However, in their studies, no clear evidence was shown to be related to sitting and quadrant musculoskeletal pain among children and adolescents.

Several risk factors in term of ergonomic aspect identified the height of work layout, computer positon and support to body segment (Winkel and Westgaard, 1996, Harrison et al., 1999, Sommerich et al., 2001). The relationship between monitor height and the musculoskeletal condition is illustrated in Figure 1-3. For human-computer interaction, computer riser and adjustable chair could reduce discomfort positively (Jacobs et al., 2011, Straker et al., 2009b, Straker et al., 2009a). Adjustable chair design should take two factors into account, namely angulation of backrest support and shape of lumbar support (Horton et al., 2010). Lumbar support pillow could favorably change body segment angles of the head, trunk, and upper limb (Majeske and Buchanan, 1984). Ergonomics concentrates the optimal design on the minimal muscle activation, and uses EMG to identify the correlations between workspace with the physiological index of human musculature. It was concluded that seat inclination and monitor height could affect head-neck position which further influence the cervical muscle activity(Burgess-Limerick et al., 1999, Straker et al., 2009b). Backrest inclination of 15 degrees and gaze inclination of 9 degrees below the horizontal were suggested to be ideal in the viewpoint of minimizing muscle activity (Delleman and Berndsen, 2002). However, optimal support to body segment still did not decrease the prevalence of cervical musculoskeletal disorders because of individual difference.

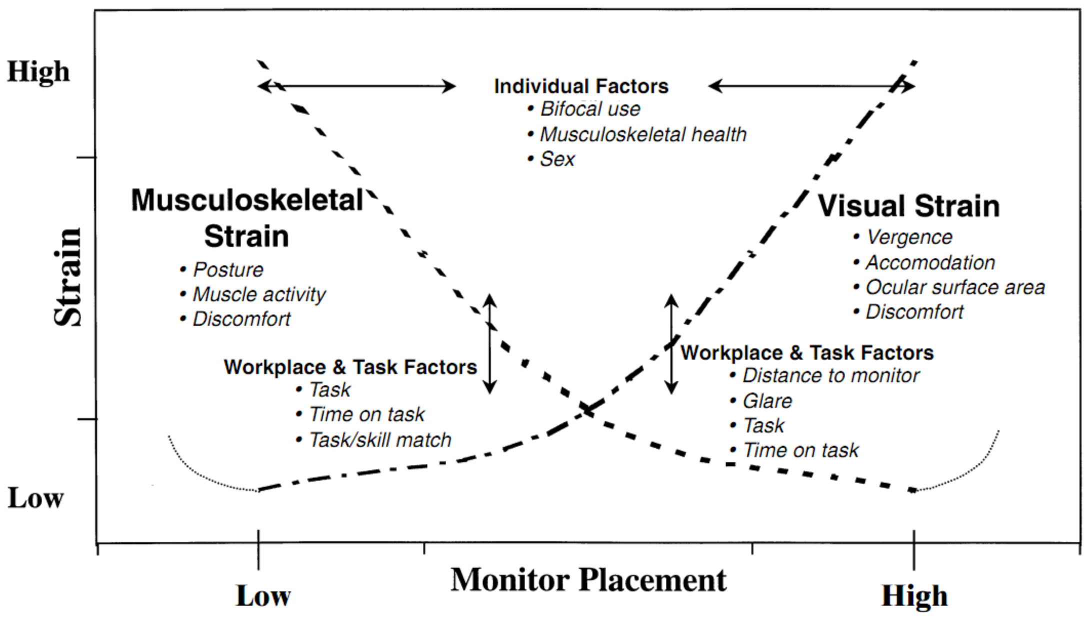

Figure 1-3. Ergonomic aspects related to the musculoskeletal disorders (Sommerich et al., 2001).

Furthermore, the concept of “dynamic sitting” emerged in order to prevent sustained sitting without any movement, because it was pointed out that small, subtle spinal movements may give rise to pain relief (O'Sullivan et al., 2013). For example, sitting on an exercise ball during office work could induce spinal shrinkage in order to prevent prolonged static contraction (Kingma and van Dieën, 2009, McGill et al., 2006).Since computer position highly affected neck posture and muscle activity, in-line document location was less encouraged compared with lateral location (Goostrey et al., 2014). In addition, there were many biomechanical risk factors commonly mentioned including overload on the cervical spine, abnormal stress and strain on muscle, joint and ligament, and mixed combination (Radwin et al., 2001, Buckle and Jason Devereux, 2002).

1.1.4 Prevention and Treatments of cervical musculoskeletal disorders

Cervical musculoskeletal disorder is the most prevalent disorder with progressive and complicated syndromes that could further give rise to the disability of cervical spine (Webb et al., 2003, Hogg-Johnson et al., 2008, Hoy et al., 2010). Among the numerous types of risk factors, biomechanical factors (occupational factors, sports, muscle weakness etc.) are highly related to the risk of limited movement or repetitive abnormal loading on the cervical spine and could provide entry points for the prevention and treatment of cervical spine disorders. Other physiological factors (gene, ageing and sex) are systemic and could only be offered intervention to delay their progress, but not to prevent (Hoy et al., 2010, Widanarko et al., 2011, Patel et al., 2013).

Treatment of cervical musculoskeletal disorders can be offered with a variety of choices. In general, clinicians usually adopt the following treatments: physiotherapy, traction along head and neck, traditional Chinese medicine (for example acupuncture), pain analgesics and surgery (Hudes, 2007). Establishing the proper diagnosis allows treatment to be focused in an individualized way. Although the proper diagnosis can provide efficient and effective access to treatment for patients or people who complain of pain syndromes, sometimes multiple etiologies make it difficult to diagnose. Despite this, several cervical treatment could still be performed to relief pain in a safe manner such as physiotherapy (McKenzie, 1990).

Physiotherapy

Physiotherapy is widely recommended in medical and clinical guidelines because it is a non-invasive treatment with minimal side-effects, which could be adopted in different phrases of the treatment. Physiotherapy mainly features a modification of joint loading and muscle stiffness, thus, it seems to be more reliable for people in the early development of diseases (Cohen, 2015). Therefore, it is regarded not only as a promising intervention prior to surgery, but also a functional method for rehabilitation after surgery. Importantly, physiotherapy is applied to the prevention of disease due to its convenience and flexibility that it can offer people at anytime and anywhere. Since satisfactory relief could be obtained to a large extent, this non-pharmacological approach is highly accepted in various groups of patients. Physiotherapy contains several interventions aiming at relieving pain intensity, improving the range of movement of joints and eliminating muscle trigger points. In clinical practice, the typical physical therapies include needling therapy, thermotherapy, hydrotherapy and manual therapy. Among them, manual therapy focuses on the mechanical process of muscle contraction, which plays a vital part in the treatment of mechanical cervical pain caused by poor postures and repetitive movement (McKenzie, 1990).

Manual therapy

Manual therapy comprises massage, stretching, compression and dynamic interventions (McKenzie, 1990). The common features of them lie in the forms of movement—active and passive range of motion, which are typically effective for the pain syndrome caused by the mechanical factors. Manual therapy considered as a basic and popular treatment is highly recommended in hospitals and clinics.

Massage is widely applied in the management of cervical musculoskeletal disorders. Traditional Chinese and Thai massage therapies are widespread used throughout the word. Especially deep tissue massage is thought to be more effective in decreasing pain sensitivity than other manual therapies (Giles and Singer, 1998). Stretching begins with isometric contraction against manual resistance carried by physiotherapists. The mechanism of stretching may attribute to the combination of creep and plastic deformations which are both the mechanical characteristics (de las Peñas et al., 2005). Elongation of soft tissues during stretching could minimize the inner stress of muscle fibers, thus changing the stiffness of soft tissues and relieving pain intensity. Compression is encouraged for my fascial trigger points and can be performed by maintaining direct pressure over trigger points for approximately 100 seconds, usually using the thumb to apply manual pressure. Dynamic interventions mainly directed in the active movement by individuals. For example, aerobic exercise allows patients to contract affected muscles actively and improve the sense of balance. Exercise programs for chronic cervical pain include postural re-education, strengthening and stretching. Clinicians often address compensatory posture, such as forward head, which arises from poor eyesight or high stress (Dutton, 2004).

Traction

Traction is a mechanical technique used for patients with moderate pain intensity caused by dysfunction of facet joints. Cervical spine could be stretched and enlarged the openings of spinal nerve root located near the facet joint. Usually, this technique is applied to patients without risk of instability in the cervical spine. However, the advantages for pain relief has not been well identified. Traction aims at stretching the muscles and ligaments along the cervical spine and expanding the narrow space between each cervical joints usually caused by poor postures. Traction of the cervical spine can be obtained by manual and mechanical tractions, both of which are performed by pulling the head up and away from the neck (McKenzie, 1990).

Acupuncture

Acupuncture as an ancient medical treatment has been widely used in China and spread throughout the world (Giles and Singer, 1998, McKenzie, 1990). The mechanism of acupuncture has not been fully identified, however, the effects are commonly accepted by the majority of doctors and patients all over the world. The acupuncture needles are inserted into a deep layer of muscles maintaining approximately 15 minutes. Then it could stimulate the central nervous system to secrete chemicals, which is likely to reduce the sensation of pain (White and Ernst, 1999). Compared to other treatments, acupuncture is relatively safe (Giles and Singer, 1998, White and Ernst, 1999).

Medication

Once the soft tissues involved in the inflammation which may induce severe pain intensity, medication treatment is recommended as the first choice for patients with acute cervical pain syndrome. Anti-inflammatory drugs such as naproxen and ibuprofen could help reduce inflammation and relieve pain (Dabbs and Lauretti, 1995). Narcotic injections are utilized to relieve muscle spasms and to prevent quick or abnormal movement due to head-neck activity. On the other hand, drug therapy may cause stomach upset, bleeding problems, and sometimes have adverse effects on an organ such as liver and kidney. However, the efficiency of medicine treatment is still not well proved (Giles and Singer, 1998).

Surgery

Surgery may help patients if other conservative treatments fail to get them better or their symptoms get worse day after day. In general, cervical spine surgery mainly consists of artificial disc replacement and cervical disc fusion (Levin and Neurology, 2007). It is frequently used in cervical disc disorders by removing the location of the disc which is pressing spinal cord or nerve. Although cervical surgery could help repair damaged discs and is generally safe, the risks brought with surgery should not be neglected. Once it fails to perform the surgery in the correct way, adverse effects may come along including infection, excessive bleeding, chronic neck pain, and damage to the nerve or spinal cord (Dutton, 2004). These risk factors could further induce the failure of cervical spine healing.

1.2 Objective of this study

Cervical musculoskeletal disorder has the multifactorial etiology including the physical aspects of human movement, physiological aspects of metabolism and psychosocial aspects. A plenty of information ranging from biomechanics and ergonomics to epidemiology has identified numerous risk factors which are associated with the development of cervical musculoskeletal disorders. The external mechanism, including posture, repetitive movement and duration (Brink and Louw, 2013, Ariens et al., 2000, Ariëns et al., 2001), has been proposed to be the major causation of the cervical musculoskeletal disorders. Despite this, the best and powerful evidence points to the internal mechanism, including strain and stress on the muscles, joints and bones, which allows us to fully understand the complex interaction among muscles and cervical joints.

In dynamic action, proposed mechanism for this disorder is associated with high intrinsic forces along cervical spine, resulting from various types of movements, as well as with malposition of cervical vertebrae at each level. However, it is not well-understood in static condition due to the difficulty of detecting the low-intensity intrinsic forces in cervical musculoskeletal system. Posture as a predictor of internal load, how does cervical musculoskeletal system distribute the loads during different sitting postures with various types of crania-cervical positions? Many studies focused on the motion of cervical spine in anatomical aspect: flexion/extension, lateral flexion and rotation. However, paradoxical motion of head and neck is little studied, while this posture is widely adopted in sedentary high-tech devices use.

Furthermore, there is a lack of a comprehensive model of the cervical spine to analyze mechanical loading under typical working postures. Oversimplification of cervical joints and numbers of muscles is likely to get involved in the misunderstanding of the biomechanical characteristics of the cervical spine. Taking the advantage of a realistic model which includes separated cervical joints and a group of detailed muscles can get fruitful insight into the inner mechanism of load distribution along cervical spine, which may shed light on the development of cervical musculoskeletal disorders.

The overall objective of the research is to investigate the effects of cranio-cervical positions under upright and slump sitting postures on the cervical musculoskeletal system and to provide biomechanical information for understanding the mechanism of the cervical musculoskeletal disorders through experimental measurements and computational modeling. The specific aims are:

1. To construct a 3D human musculoskeletal model in sitting postures;
2. To understand the relationship between cervical spine mechanical load and different cranio-cervical positions; and
3. To investigate the effects of different cranio-cervical positions on the cervical vertebral tilt angle and musculoskeletal load.

It is hoped that the combination of experimental study and computational model would provide efficient access to enhance the knowledge of biomechanical characters of cervical spine under various physical loading conditions induced by different sitting postures during high-tech devices use. Therefore, it is possible to minimize joint and muscle loads along cervical spine through avoiding certain sitting postures which could cause high load. Determining which cervical muscles are likely to get involved in abnormal stress conditions can guide us to build targeted muscles up in order to promote the force-generating ability under static loading conditions.

1.3 Outline of the dissertation

Following the chapter 1, chapter 2 provides a review of the functional anatomy of the cervical spine, and then reviewed biomechanics of the cervical spine and biomechanical factors to the cervical musculoskeletal disorders. At last, previous biomechanical studies are introduced in term of postural measurement, cervical muscle performance and mechanical models in various occupations and daily activities.

Chapter 3 starts with the motion capture of different cranio-cervical positions under upright and slump sitting postures. The basic information of experiment including participants, procedure and equipment is described in the first part of the method. After that, the musculoskeletal modeling of cranio-cervical positions is presented in term of model structure, muscle type, and variables used in this study. Then the validation experiment through electromyography (EMG) is presented. Finally, data analysis is described to illustrate the specific statistical method.

In chapter 4, results of experimental and computational studies are presented. Reliability of experiments is first reported. This chapter summarizes the postural angles of cranio-cervical spine and body segments measured by motion capture system and predicted cervical tilt angles, muscle performance, and cervical joint load simulated by the musculoskeletal model. At last, the validation of the musculoskeletal model is presented by comparing measured one with the predicted one.

Chapter 5 discusses the biomechanical effects of different cranio-cervical positions under upright and slump sitting postures. How cervical spine responding to the postural change is discussed in term of postural angles, load-carrying of muscles and load bearing of cervical joints. Validation of musculoskeletal model is explained by comparing with previous clinical and biomechanical studies, and also with the data obtained from EMG measurement. In the last section of this chapter, the limitations caused by experiment and simulation are further elaborated.

In chapter 6, primary findings and potential applications of this study are summarized. Suggestions on the further biomechanical study of cervical spine behavior under various types of loading conditions are concluded.

CHAPTER 2. LITERATURE REVIEW

2.1 Review on human cervical spine biomechanics

2.1.1 Functional anatomy of cervical spine

Cervical spine can be the major source of many pain syndromes due to its complicated structures, even part of which could get involved in the development of cervical musculoskeletal disorders. The cervical spine is a mechanical structure which is controlled systematically through joints, ligaments and muscles. The primary function of this structure is to counterbalance the weight of the head and then transfer the load to thoracic spine (White and Panjabi, 1990). Meanwhile, it allows sufficient movement of head and neck including flexion/extension, lateral bending and rotation. Importantly, it can protect the spinal cord from being damaged caused by abnormal postures or sudden impact. Both static and dynamic conditions could offer chances to the development of cervical musculoskeletal disorders. In the sagittal plane, the cervical spinal curve was convex anteriorly forming the beginning of S-curve. This physiological curvature produces the ability of absorbing shock and flexibility while muscles and ligaments help maintain stability at each level of cervical joints (Dutton, 2004).

Cervical Vertebrae

Human cervical spine comprises of seven vertebrae. It is a biological evolution that even a giraffe has seven cervical vertebrae which are larger than human. The morphological features of the first and second vertebrae are different from the rest common ones (C3-C7). Due to this special structures, they are able to bear the weight of head and permit head to move in six degrees of freedom. The remaining five cervical vertebrae have small bodies which are articulated with discs, facet joints and soft tissues. Transverse foramen provides access for the artery to travelling from C6 to C1 level (Figure 2-1).

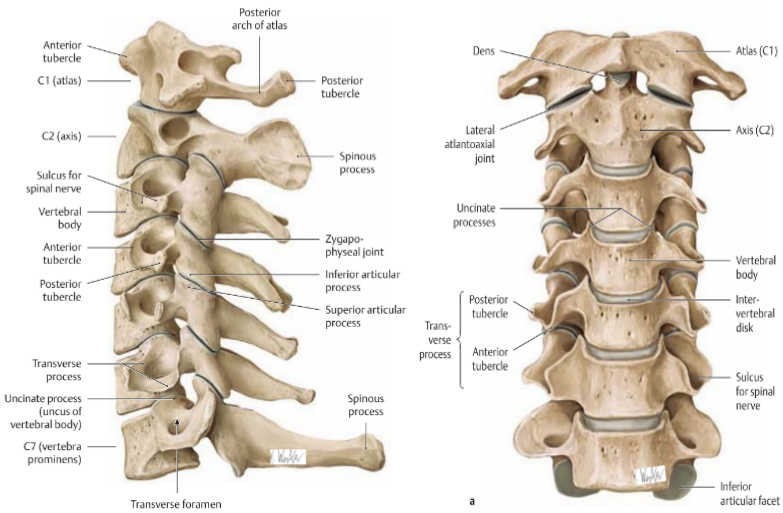

Figure 2-1. Cervical spine in lateral view (Left) and frontal view (Right) (Gilroy et al., 2008).

Cervical Joints

Besides cervical vertebrae, weight-bearing are mainly performed by cervical joints consisting of the intervertebral discs, and facet joints. There are 5 intervertebral discs from C2 to C7 and 14 facet joints from the occiput to the T1 thoracic vertebra. As for the morphology, cervical intervertebral discs are smaller than lumbar discs. Also, the nucleus pulpous is less distinct from the annulus fibrosis. Cervical intervertebral discs have a lower amount of water than the lumbar discs due to the paucity of proteoglycan content. Facet joints are formed by the adjunction of inferior articular facets of one vertebra with the superior facets of the next vertebra. The cervical facet plane is inclined approximately 45° to the vertical plane (White and Panjabi, 1990). This inclination allows considerable flexibility in the sagittal plane, permitting a range of 30 to 60 degrees. Several studies demonstrated that facet joints were the primary source of chronic neck pain (Dutton, 2004, Levin and Neurology, 2007).

Cervical Ligaments

Ligaments are located symmetrically along the cervical spine. Cervical ligaments are responsible for the stability of cranio-cervical region (Gilroy et al., 2008). *The anterior longitudinal ligament* attaches anterior surfaces of the vertebral bodies firmly. It is strong enough to restrict the extreme position of head-neck movement. It is relaxed in flexion and tensioned in extension (Myers, 2009). *The posterior longitudinal ligament* lies posterior to the surfaces of the vertebral bodies while inside the vertebral canal. It becomes broader and thicker in the cervical region compared to that in the thoracic and lumbar regions (Ricciardi, 2015). It could also protect the discs from being moved from the original position. The posterior longitudinal ligament is relaxed in extension and becomes taut in flexion. *The ligament flava* consists of yellow elastic tissue and collagen which features broad and long configuration. It is the special material and configuration that allow the considerable degree of cervical flexion safely (Gilroy et al., 2008). *The interspinous ligaments* are those small and thin ligaments located between each spinous process.

Cervical Muscles

The cervical muscles are responsible for supporting and moving the head. Cervical muscles contraction produces the flexibility of head movement and also allows most mobile for the cervical region in the whole spine (Gilroy et al., 2008). These muscles around neck and shoulder provide different functions in specific activities. According to the locations, cervical muscles can be classified into the superficial muscles (Figure 2-2) and the deep muscles (Figure 2-3) (Ricciardi, 2015).

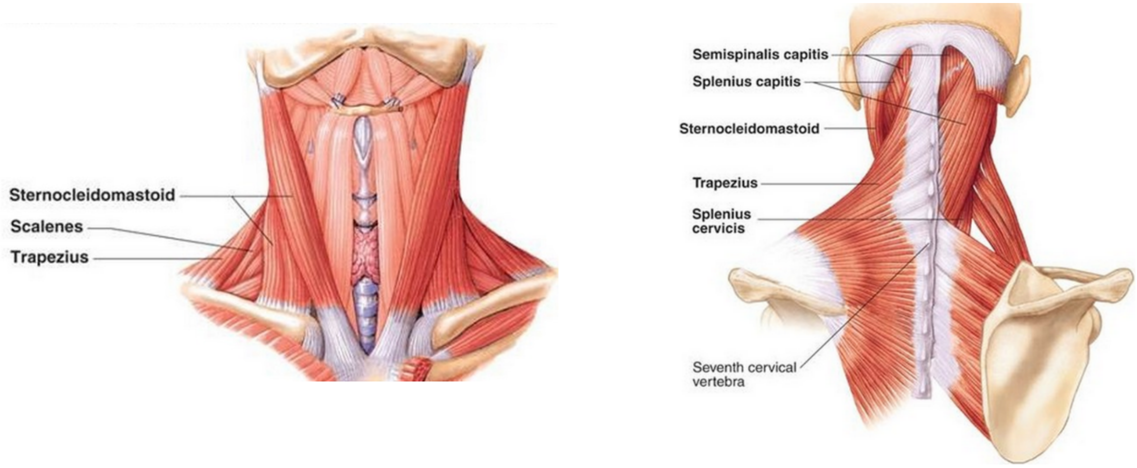

Figure 2-2. Superficial muscles along the cervical spine (https://quizlet.com/38451791/ap-lab-muscles-flash-cards/)

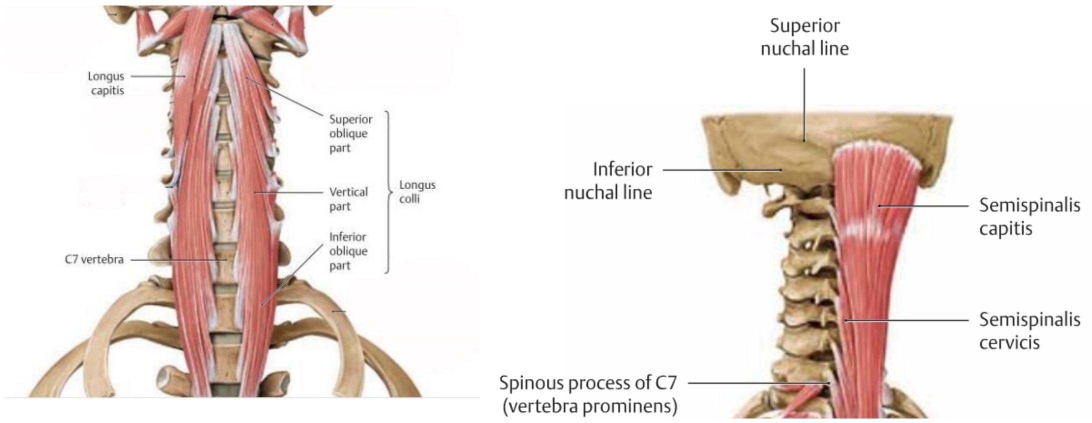

Figure 2-3.Deep muscles along the cervical spine (Gilroy et al., 2008).

Superficial muscles

Trapezius

Of the posterior cervical muscles, trapezius is the most superficial muscle around neck and shoulder regions (Ricciardi, 2015). It is flat and thin in the shape of a triangle. This muscle is usually divided into two parts namely trapezius clavicular and scapular muscles, and sometimes also into three parts including upper, middle and lower trapezius muscles (Gilroy et al., 2008).

Upper trapezius originates from the occipital bone and spinous processes of cervical vertebrae, then inserts in the lateral third of the clavicle as descending part (Giles and Singer, 1998). This part of the muscle is complained in most clinical cases. Middle trapezius muscle rises from the spinous processes of T1-T4, and inserts in the acromion as the transverse part. Lower trapezius muscles originate from the spinous processes of T5-T12 and ends in the scapular spine as ascending part (Gilroy et al., 2008).

Levator scapulae

Levator scapulae are covered by the trapezius. These posterior cervical muscles span the cervical region and thoracic region. Levator scapulae, located beneath of the upper and middle trapezius, is also thin and slender muscles. It originates from the transverse processes of C1-C4 and inserts in the superior angle of the scapula (Ricciardi, 2015). The major function of levator scapulae is to control the movement of the scapula (Giles and Singer, 1998). As the scapula are stable at one point, levator scapulae could produce cranio-cervical movements such as forward head position, rotation and lateral flexion.

Sternocleidomastoid

Of the anterior muscles, sternocleidomastoid is the most superficial and the largest muscle in the anterior cervical region (Gilroy et al., 2008). There are two heads attached to the medial third of the clavicle and the manubrium of the sternum. Then they span across the cervical spine to the mastoid process of the skull (Ricciardi, 2015).

Both contractions of trapezius and sternocleidomastoid muscles could draw the head forward. This posture is regarded as the combination of extension in upper cervical spine and flexion in the lower cervical spine (Myers, 2009).

Deep muscles

Splenius capitis and splenius cervicis

Deep muscles of the posterior cervical region are mainly activations of cervical vertebrae and head (Dutton, 2004). These muscles are small and short, located in the deep layer of nuchal fascia. Splenius capitis originates from the mastoid process of occipital bone and then to the spinous processes of lower cervical and upper thoracic vertebrae (Gilroy et al., 2008). While splenius cervicis locates in parallel under the splenius capitis, it extends from the transverse processes of the upper cervical vertebra to the spinous processes of T3-T6.

Semispinalis capitis and semispinalis cervicis

Semispinalis capitis and semispinalis cervicis are deep to splenius muscles. They mainly take charge of extension along cervical spine (Myers, 2009). Although they are short, these muscles are stout and strong. So they can provide sufficient strength to maintain the position of the head.

Multifidus cervicis

The multifidus cervicis connects each side of spinous processes of cervical vertebrae. They are thin and short which plays an important part in joints stability (Ricciardi, 2015).

Longus capitis and Longus colli

Of the anterior cervical muscles, longus colli is the deepest anterior muscle located in front of cervical vertebral bodies from C2-C6 (Gilroy et al., 2008). Longus capitis is attached inferior to the longus capitis. It starts from the occipital bone and passes along to the transverse processes of C3-C6 (Gilroy et al., 2008). Contraction of both muscles can produce sagittal rotation of the cervical spine and also prevent hyperextension which may cause damage or injury to the cervical musculoskeletal system (Levin and Neurology, 2007).

Patterns of Movement

As for the aspect of anatomy, cervical spine produces several basic movements according to three planes (Figure 2-4). In specific, the pattern of motion in the sagittal plane is flexion of 65 degrees and extension of 40 degrees. Then cervical spine could perform lateral flexion on both sides in the frontal plane, of approximate 35 degrees. According to the plumb line, cervical spine could conduct head rotation of 50 degrees in the horizontal plane (Ricciardi, 2015). These motions are basically simple and all cervical vertebrae move in the same direction.

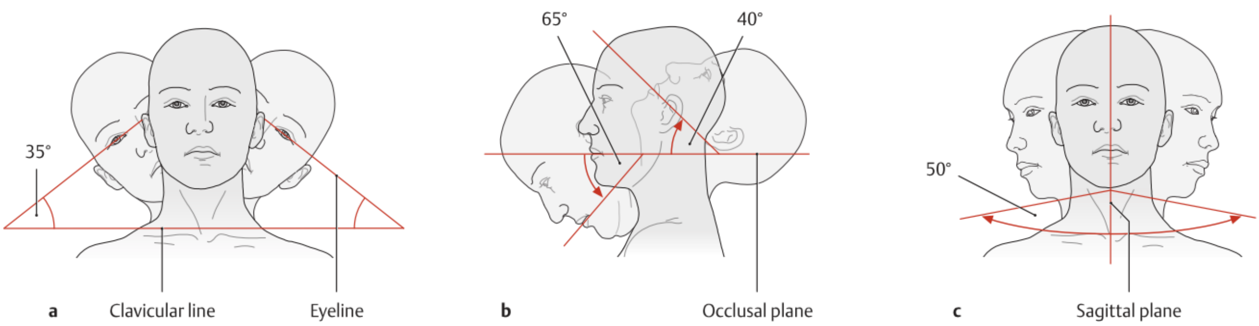

Figure 2-4. Range of motion of the cervical spine (a: lateral bending, b: flexion and extension, c: rotation on both sides) (Gilroy et al., 2008).

However, cervical spine has complex structures which could produce paradoxical movements rather than simple ones. Moreover, usually, these paradoxical movements might induce the development of cervical musculoskeletal disorders. Paradoxical movement is defined as the motion where opposite movement occur at the same time (White and Panjabi, 1990). This pattern of movement could cause various morphological cases further inducing the abnormal stress or strain in the cervical musculoskeletal system. For example, forward head posture requires an extension of upper cervical spine and flexion of the lower cervical spine. At meanwhile, this paradoxical movement translates the center of gravity along the sagittal axis in front of the previous positon. At injury level, buckling can be found in cervical spine under high-speed collision. The influence brought by this type of dynamic paradoxical movements is more severe than by static one.

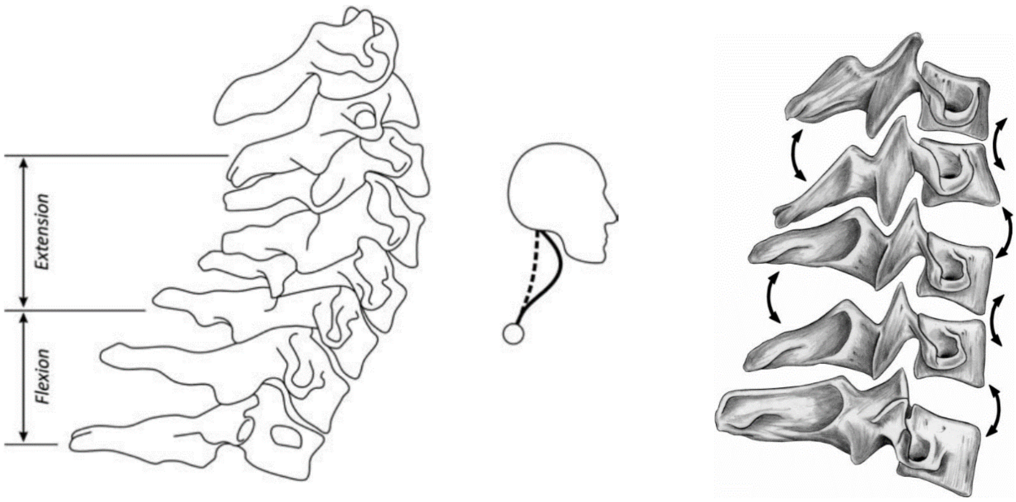

Figure 2-5. Bucking effect on cervical spine (Swartz et al., 2005).

2.1.2 Biomechanics of Cervical Spine

Further understanding of the basic biomechanical information about applied load and how cervical musculoskeletal system responds in various loading conditions is of great significance to take measures to prevent from musculoskeletal problems. Timely intervention and effective ergonomic design could benefit from the basic and applied biomechanics, which could limit excessive load demanded by the human body in work tasks.

The ability of movement and load-bearing is mainly determined by the synergy of cervical joints, vertebrae, intervertebral discs, ligament and muscles (Adams et al., 2006). In general, the ligaments, joint capsules and sometimes stiff muscles could provide extra effort to counterbalance the external load. On one hand, they can keep cervical spine in a stable condition during an array of various motions, especially deviation from the normal range of motion (Yoganandan et al., 2001). On the other hand, too much constraints around cervical spine could also induce discomfort and complaints (Karwowski and Marras, 1998). Prolonged constraints of these passive structures against long-term external loading may lead to overuse, fatigues and finally cervical musculoskeletal disorders.

Biomechanical responses of muscles, ligaments, tendons, joints and vertebral bodies along cervical spine can be various even in the similar loading conditions (Panjabi et al., 1998, Lavallee et al., 2013). Mainly due to their different material properties, micro temperature, and configuration structures, each level of cervical spine shares the different capabilities of load-bearing (White and Panjabi, 1990). On the basis of mechanical testing and mathematical simulation, basic characteristics of cervical discs, ligaments, and muscles are obtained.

The intervertebral disc is a viscoelastic structure, which plays an important part in compression loading-bearing. Although it showed that the forces acted on the discs were greater than the weight of body above when standing in the neutral position, this pure compressive loading still could not damage discs even in prolonged situations (Adams and Dolan, 2005). As a complementary part, facet joint plane offers the different abilities to resist external or internal load from different directions. Therefore, the cervical spine is able to support shear loading, allowing a large range of motion for head-neck complex. The structure of ligament is uniaxial so that it presents effective capability of load- carrying when the load applied along the direction of fibers. Ligaments can resist tensile loading but turn buckle in compressive loading (Yoganandan et al., 2001).

In general, muscles have two important mechanical properties namely elasticity and viscosity (Winter, 2009). The morphology of muscle determines the force it produces. Muscle force can produce moment across several joints. Besides it also creates compressive forces at each level of cervical joint. Cervical spinal muscles attached between each spinous are short, which is suitable for static tasks (Greenwald, 2005). Whereas, superficial cervical muscles with long muscle fibers are more suitable for dynamic tasks. Despite this, the contribution of force-generation prior depends on the physiology rather than the morphology. Muscle stiffness could change according to the external loads which cervical spine bears. The purpose of changing muscle stiffness is to produce more forces to maintain the cervical spine in a stable condition.

The biomechanics of cervical spine could help explain the mechanism of cervical musculoskeletal disorders. Particularly, it helps provide insight into which structures are likely to get involved in the development of cervical musculoskeletal disorders with or without pathological changes. The specific and accurate biomechanical features of the human musculoskeletal system under an array of interactions with the external environment are difficult to estimate. Fortunately, on the basis of mechanical testing and simulation, there is a wealth of information provided by both static and dynamic mechanical behaviors of each level of the cervical spine. Even this, they could only predict or infer the load distribution along cervical spine, because it is difficult to directly measure how human body react to various types of external environment in the real life.

Functional postural biomechanics has been widely applied in modern ergonomic design and rehabilitation science. It could provide comprehensive aspects of the cervical musculoskeletal system (including cervical muscles, joints, tendons, ligaments, discs and nerve system) for designers and clinicians, such as muscle activity, joint reaction load and micro fluid of discs. Therefore, effective strategy and comfort design are likely to be put forth to benefit a considerable number of people who are in the development of cervical musculoskeletal disorders (Karwowski and Marras, 1998).

Postural biomechanics mainly concerns various types of head-neck positions in daily life. A number of studies focused on the neutral position, flexion, extension, lateral bending and rotation along cervical spine. It has been well believed that neutral position of cervical spine could create an optimal resting position for joints and vertebrae, thus minimizing muscle fatigue rather than increasing muscle stiffness to keep the stability of the cervical spine. Also, many studies investigate the whole spine behavior during the sitting, such as upright, slump, habitual sitting postures (Genaidy and Karwowski, 1993, Balasubramaniam et al., 2000, Pynt et al., 2008, Nairn et al., 2013b).

2.1.3 Biomechanical factors related to cervical musculoskeletal disorders

Cervical musculoskeletal disorders can result from acute or cumulative trauma, which depends on force and moment as well as time and frequency. There are two types of forces applied on the various levels of tissues. External loads refer to forces from external objects applied on the human body as a result of gravity (Karwowski and Marras, 1998). Sometimes body postures could also be regarded as external forces generated by gravity of parts of human body. However, in order to counterbalance the extra loads from the environment, the human musculoskeletal system has to generate internal loads to keep body equilibrium in static or dynamic condition (Winter, 2009). Usually superficial and deep muscles are responsible for producing internal loads. Since the distances to the center of the joint created by internal load are much closer than by external loads, muscles have to produce more forces to maintain the musculoskeletal system balanced. Although both external and internal loads determine the joint loads, internal loads play an important part in the development of cumulative trauma due to its great force-generating ability (White and Panjabi, 1990, Karwowski and Marras, 1998).

A high load provides a great chance to cause ruptures in accidents because it can exceed the maximum strength of the musculoskeletal system and finally beyond the load tolerance. It becomes a major risk for acute trauma. However, the low load is far more common in our daily life which brings an array of complaints and discomfort for a prolonged time. Although low-level static construction of muscles produces low forces to the breaking point, musculoskeletal system is likely to get involved in the development of fatigue when it suffers repetitive and sustained tasks. Through electromyography measurement, it was observed that musculoskeletal disorders were highly related to those occupations with a static level of muscle contraction. The range of static muscle load was indicated to be from 2% to 5%MVC during the one-hour task (Mork and Westgaard, 2006).

Posterior cervical muscles play an important part in postural change and maintenance. Cervical spine flexion increases the distance of movement arm from the center of the head to the center of cervical joint at a specific level. Thus, this extra demand in the movement increases the muscle load along the cervical spine to counterbalance it. Based on various biomechanical studies, researchers investigated the cervical extensor muscles activity for different degrees of cervical flexion. Based on clinical cases of postural inspection and biomechanical analysis of cervical loads at lower level, it was reported that subjects with or without neck pain would utilize various patterns in term of frequency of postural change and duration of postural maintenance, and adapt postures required on the necessary movements in their workspace (Cagnie et al., 2012, Young et al., 2012).

2.2 Review on biomechanical analysis of human cervical spine

2.2.1 Research on biomechanical measurement during sitting

Spinal postures of seated human can be different due to frequent posture adjustment during prolonged sitting. A number of clinical experiments were performed to measure spinal postures over skin surface (Claus et al., 2009, van Niekerk et al., 2008) and bony landmarks (Grooten et al., 2013). According to natural spinal curves, postural angles are major divided into four parts including cervical, thoracic, lumbar and sacral angles. For sedentary behavior, qualitative descriptions on the basis of postural deviation identified several sitting postures commonly occurred in daily activity. Generally, these include the lumbo-pelvic upright posture (neutral sitting posture), thoracic upright posture, slump posture, forward leaning, and backward leaning with twist posture. A mixed combination of these sitting postures can be performed subconsciously and sometimes almost one posture could be maintained without change during prolonged computer use (Laperrière et al., 2006, Dunstan et al., 2012).

Previous studies focused on the comparison among different types of sitting postures based on spinal postures. Firstly, optimal sitting postures were provided for the purpose of relieving cervical and lumbar pain syndromes. Neutral sitting posture, defined as pelvic anterior rotation along with a relaxed thoracic spine (O'Sullivan et al., 2012), has been suggested to be ideal working posture because of good alignment in neutral spinal curve including cervical, thoracic and lumbar lordosis. Furthermore, it could require the least amount of energy to maintain position, least stress on body tissues, and obtain optimized breathing and circulation as well as keep balance and share body weight evenly (Genaidy and Karwowski, 1993, Edmondston et al., 2007, Yang et al., 2009). Although the ability to keep a neutral position is advantageous to the human musculoskeletal system during prolonged sitting, this type of posture is seldom utilized in real life because of extra effort to maintain it. Secondly, thoracic upright sitting posture referred to anterior rotation of the pelvis, thoraco-lumbar spine extended in line and with shoulder blades retracted (Caneiro et al., 2010). O'Sullivan et al. (2012) suggested thoracic upright sitting required less activation of spinal muscle, but greater activation of global muscle compared with a neutral position. Thirdly, slump sitting posture was defined as the posterior rotation of the pelvis and relaxation of thoraco-lumbar spine while looking straight (Nairn et al., 2013b). Slumped sitting is commonly adapted when computer use because of relaxing and comfortable feeling, but it could lead to neuromuscular and cumulative trauma disorders acting on spinal muscles, joints and ligament (Pynt et al., 2008). Besides it is also a reference posture when comparing effects of upright sitting among people with pain syndrome or without it.

Additionally, different types of cranio-cervical postures are usually performed with high-frequency rate, which is more closely associated with cervical musculoskeletal disorders (Mostamand et al., 2013). Cervical spine movements, in term of anatomy, include flexion/ extension, lateral bending, and rotation. Besides, coupled movements of cranio-cervical spine involve neutral position, protraction, and retraction. These movements could be often performed during typing task, computer reading and multi screens operation (Briggs et al., 2004). Furthermore, forward head posture was associated with thoracic kyphosis (Quek et al., 2013).

Posture as an indicator of load on human spine provides access to increase the risk of cervical musculoskeletal disorders. Posture deviations are associated with a series of different types of pain syndromes and dysfunctions. A large quantity of studies established the connection of various postures and musculoskeletal disorders, such as neck pain, low back pain and headache (Dankaerts et al., 2006, Tissot et al., 2009, Brink and Louw, 2013). Goniometers were used to measure body segment angles including shoulder, wrist, head and neck angles as well as elbow angle during sitting. Marcus et al. (2002) found that there was a significant interaction between keyboard inner elbow angle and hours task, which suggested that the number of hours-task was strongly associated with neck and shoulder disorders.

Inclinometer was also utilized to measure the postures and movement of the neck and head. Motion adjustment could be accessed through the angles and kinematic data obtained from the inclinometer. Arvidsson et al. (2008) showed that subjects with cervical musculoskeletal complaints were likely to conduct approximately one- hour computer work in a similar motor adjustment strategy as healthy referents did. They indicated that there should be a comprehensive assessment to estimate risk factors for neck and shoulder disorders rather than measuring spinal angles alone. Combined the goniometer and inclinometer to measure the forward and sideways bending of the head, back, and wrist during performing manual work, Juul-Kristensen et al. (2001) showed a significant relationship between a number of repetitive movement of the hand and mean power frequency value of the goniometer data. Although positions and body angular velocities could be calculated from goniometer and inclinometer data, it becomes feasible for field studies when the computers and advanced techniques occur such as three-dimensional measurement.

Many researchers focused on the postural angles during sitting by making the use of various motion analysis systems such as the Vicon motion analysis (UK); the Metrecom electromagnetic digitizer (USA); the Optotrak motion analysis (Canada) and the Peak Motus motion analysis system (USA). A set of reflective markers is usually attached to the skin on both right and left of the skeletal landmarks. Claus et al. (2009) measured the spinal angles using a three-dimensional motion tracking system to make a comparison among body segment angles including thoraco-lumbar angle, lumbar angle, and thoracic angle during flat, long lordosis, short lordosis and slump sitting posture. They found that the lumbar angle was significantly more kyphosed in a slump than the other sitting postures. Also, they pointed out that although sitting in short lordosis posture was advocated by some researchers, it was difficult to keep for prolonged sitting. Based on the combination of the video-based observation method and direct measurements such as electro-goniometer and inclinometer, Juul-Kristensen et al. (2001) found that using both these two methods when assessing work postures and movements could supplement each other. There was also a strong evidence that head, neck, and shoulder posture angles were changed to a certain degree during the data-entry task (Gerr et al., 2002).

However, many studies mainly focused on the lumbar angle and paid little attention to the neck and shoulder angle. Despite four different sitting postures defined according to the spine curve (Claus et al., 2009), it does not apply to the study of head, neck and shoulder angles during different sitting postures. In order to figure out specific factors which may reduce musculoskeletal stress during computer use among children, Straker et al. (2008) quantified the postural effects of adding forearm support during computer use. They showed that the forearm support linked with an altered upper limb posture, but minimal postural changes of the head, neck and trunk. Straker et al. (2009c) found that when the display was lowered, head and neck flexion increased as well as the limited changes of the trunk during typing. This trend suggests that risk of musculoskeletal problems related to information-technology tasks. They pointed out that the height of computer display affected the spinal postures on the sagittal plane.

Neck positional change was greater than thoracic, lumbar and pelvis during prolonged sitting (Nairn et al., 2013a, Dockrell et al., 2012). Nairn et al. (2013a) suggested that less positional change in mid-thoracic were found during lateral bend as a result of muscle control. Young et al. (2012) found that head and neck flexion angles during tablet computing were greater than those reported during desktop computing, and they pointed out that gaze and case designs may be the major reasons for the various postural alteration. Moreover, it could give rise to discomfort and pain in neck and shoulder regions. Hence, the demands for optimized system performance and people's well-being are highly needed.

2.2.2 Research on cervical muscle performance during sitting

Besides postural angles, several studies have focused primarily on the microcirculation and muscle activity since an early age (Mathiassen et al., 1995). In the cervical spine, the muscles often mentioned in musculoskeletal disorders are the levator scapulae, trapezius, supraspinatus, infraspinatus and rhomboids (Cakit et al., 2009). Surface myoelectric activity often collected from the sites of bilateral cervical erector muscles, bilateral thoracic erector muscles, bilateral upper trapezius, wrist extensor bundle and anterior deltoid. Among these muscles, trapezius and levator scapula muscle were regarded as major contributors to neck disability and chronic neck pain (Çakıt et al., 2009). Loading carrying proportions of neck muscles are likely to change due to postural sway during prolonged computer use.

Çakıt et al. (2009) studied the performance of the trapezius muscle microcirculation during a one-hour standardized computer task. They showed that prolonged work decreased both oxygen saturation and blood flow in the trapezius muscle. Similarly, it was observed that oxygenation in the trapezius muscle of both healthy females and patients with neck-shoulder pain decreased significantly (Flodgren et al., 2009, Flodgren et al., 2010), which was in agreement with the study reported by Callaghan et al. (2010). However, through using near infrared spectroscopy (NIRS) and electromyography (EMG), Elcadi et al. (2013) reported that there was no significant difference in oxygen saturation and maximum voluntary contraction (MVC) between healthy subjects and patients with work-related muscle pain. Cook et al. (2004) found that using wrist support resulted in significantly less trapezius muscular activity compared with using forearm support. It was found that muscle fatigue was related to the continued activation of low-force muscle fibers, which was likely to cause neck myofascial pain and tension syndromes facing a group of people performing semi-static tasks (Sjøgaard et al., 2010).

Mork and Westgaard (2006) suggested EMG value was very low for all muscles during sedentary behaviours due to the flexion-relaxation phenomenon. The static level was almost 2% MVC during office work (Vasseljen Jr and Westgaard, 1997). Despite low muscle signal, it was found that an increase of muscle activity was observed as the computer display was lowered from eye level (Straker et al., 2009b, Straker et al., 2008). They supported a principle that the increase meant of muscle activation are thought to be a reaction to the increase in cervical flexion moment (Sommerich et al., 2001).

Straker et al. (2008) also pointed out that the use of forearm support could reduce the muscle activity for the majority of muscle groups for both women and men. This support intervention may lower the risk of musculoskeletal disorders among people who are likely to spend prolonged time using computers. This finding also stressed out the importance of the scientific ergonomic design of human-workstation interface for the cervical musculoskeletal health and well-beings.

Sitting postures can induce different contributions of muscles along the spine due to muscle fatigue, leading to various postural adjustments (Schieppati et al., 2003, Ellegast et al., 2012). A cluster of flexor and extensor muscles, as well as superficial and deep muscles, are actuated in various ways. Sitting in neutral position reduced cervical extensor muscle activity, but increased the demand on thoracic extensor muscle (Edmondston et al., 2011). Nairn et al. (2013a) suggested that group with pain syndromes showed higher EMG values in the abdominals and longissimus, as well as higher pain scores compared with the healthy group. Furthermore, they suggested that there was a positive relationship between muscle activation over the low back and pain scores while activation of abdominal muscle was not significantly associated with the pain complaints. In addition to recording superficial muscle activity, Falla et al. (2007) reported that upright neutral spinal position promoted activation of the deep cervical flexor muscle measured by inserting customized-electrodes.

Additionally, flexed sitting posture caused a higher level of static activity on neck and shoulder muscles compared with the posture with neutral spinal shape (SCHÜLDT et al., 1986). However, slump sitting posture gave rise to lower muscle activity on lumbar and pelvis regions than erect sitting posture (O'Sullivan et al., 2006, Castanharo et al., 2014). For head protrusion, sternocleidomastoid activity was greater than upper trapezius (Ng et al., 2014).

2.2.3 Research on biomechanical models of cervical spine

Although postural angles and muscle physiology in different sitting conditions can be measured, a full-field experimental assessment of load distribution remains difficult, especially for load transfer. It is expected that these difficulties associated with experimental measurements can be overcome with computational modelling. Biomechanical model as one powerful tool to investigate the inner mechanism of the cervical musculoskeletal system has been widely used in the mechanical analysis of cervical spine. Typically these models can be divided into three categories: graphical model, musculoskeletal model and finite element model. Although load on bones, joints and soft tissues can be calculated through various biomechanical models, the results are different. That is because all these spine models are not the same due to different assumptions, a variety of geometry simplifications and numerous equations.

Graphical Model

Several studies were conducted to analyze cervical load on the basis of free body diagram in the sagittal plane (Snijders et al., 1991, Harms-Ringdahl and Schüldt, 1989, Harms-Ringdahl et al., 1986, Harms-Ringdahl, 1985). Parameters from this basic mathematical model are calculated in two dimensions. Force and moment on cervical spine can be calculated through photography and videotaped images. Usually, moment arms were measured from a frame of pictures and the force induced by the weight of the head was set at 6.9% of body weight. The load moment of muscle to counterbalance head was then calculated using static equilibrium equation. Furthermore, through video image, Harms-Ringdahl and Schüldt (1989) calculated maximum neck extension strength in three head-neck positions including much extended, neutral, slightly flexed and much-flexed positions. The results indicated flexed cervical spine position produced higher isometric strength than neutral position, and flexed posture should be avoided during prolonged sitting.

Harms-Ringdahl (1985) suggested that the mechanisms in the development of cervical spine disorders lied in the mechanical load on passive joints and connective soft tissue. Since the muscle activity of trapezius was so low that he thought muscle could not provide enough ability to counterbalance the load induced by head and neck. Therefore, passive joint connective tissues like ligaments and joint capsules played an important part in maintaining fixed postures in balance. Harms-Ringdahl and Schüldt (1989) photographed head and neck positions under different sitting postures in the sagittal plane and then calculated joint load in extreme positions such as fully flexed and extended neck. They suggested that extreme positions were linked with the mechanisms of pain syndromes, because load moment for the C0-C1 in cervical flexion was 1.2 times for that in a neutral position, and for C7-T1 it increased up to 3.6 times.

Focusing on cervio-thoracic load moment under three different sitting postures, Edmondston et al. (2011) found that load moment in slouched posture was significantly greater than that in both neutral and habitual sitting postures. Briggs et al. (2007) reported that thoracic kyphosis was highly relative to significantly high loads and muscle forces in an upright stance, which was likely to lead to degeneration process in the cervical spine and finally lost normal range of motion.

Musculoskeletal model

With the development of computer and software science, biomechanical studies set on a stage where the concept of "Virtual Human" is applied to understand human anatomy and function under various conditions through computer simulation (Chao and Lim, 2013, Lämkull et al., 2007, Damsgaard et al., 2006, Christophy et al., 2012). Musculoskeletal model mentioned in the present review also refers to the inverse static model (ISM). It could provide muscle forces under a defined posture through modifying the current general model. With the detailed output of musculoskeletal modelling system consisting of bone, joint, muscle and soft tissues, it lays a solid foundation for further understanding the biomechanics of human body during various types of sitting and even the mechanism of cervical musculoskeletal disorders at injurious or non-injurious level (Seth et al., 2011).

Previously many studies about biomechanical models focused on the segments of cervical spine among healthy people. Based on the kinematic features of the cervical spine, Snijders et al. (1991) developed a spatial computer model for further understanding how forces work on the cervical spine. This was the first time to manage a number of neck muscles and cervical joints in the calculation. They found that joint reaction forces on C0-C1, C1-C2 and C7-T1 were smallest during extension while increased during flexion. On the other hand, Meghdari and Bahrami (2004) studied pathologic conditions involving degenerated, fused and normal cervical spine. They showed that degeneration of cervical spine could cause a rapid decrease in muscle force and less mobility of cervical spine compared with normal and fused ones.

Based on the Anybody musculoskeletal model system, Rasmussen et al. (2009) showed that the forward inclination of seat pan may decrease the spinal forces, but it was likely to cause muscle fatigue. However, it could relieve when the sufficient coefficient friction was provided. On the basis of the SIMM model, Straker et al. (2009c) investigated the effects of computer display height on cervical biomechanics in term of the muscle moment, capacity and strain. They found that during the head flexion, overall cervical extensor muscle strain increased, but still remained stable during head extension. Meanwhile, the overall cervical extensor muscle capacity decreased from a neutral posture.

Musculoskeletal model on the basis of inverse dynamics could provide access to estimating muscle performance, and also focus on the hypotheses about clinical problems (Seth et al., 2011). Rasmussen et al. (2009) showed that muscle activities of longus colli and longus capitis were inhibited by 55%, and meanwhile that of sternocleidomastoid increased by 17% in the pain group. Oi et al. (2004) showed that maximum flexor moment and peak compressive forces in lower cervical spine were higher than that in the upper spine. In order to investigate their effects on neck loading during flight, simulations of different pilot helmets have been carried on. Mathys and Ferguson (2012) found that head posture, acceleration, and helmet mass played an important role in neck loading and they suggested that lightweight helmet should be recommended for the purpose of preventing neck pain. An optimized helmet should decrease neck load and pressure points, which could further relief neck pain syndrome (den Oord et al., 2012). However, Forde et al. (2011) advised using added weight equipment to avoid awkward flight postures and to minimize cumulative load on the cervical spine.

Finite element model

Finite element model has been applied in the studies of the human cervical spine since an early age. Through geometric construction, material property, boundary and loading considerations as well as validation of the finite element models, more information about cervical spine could be provided such as strain and stress compared with the musculoskeletal models. Furthermore, finite element model provides easy access for the estimation of inner parameters which are not easy to measure in most experimental studies. Finite element models of the cervical spine have been developed for a variety of purposes since the 1980s (Greenwald, 2005).

A number of scientific studies were conducted to investigate cervical spine deformation under a high rate of impact and load at injurious level. In the past time, many researchers focused on several segments of cervical spine, such as C5-C6, C4-C6 and C1-C2, to simulate the response of these vertebral bodies to the impacts, determining inner mechanism of whiplash injury (Clausen et al., 1997, Dauvilliers et al., 1994, Goel and Clausen, 1998). Since impact experiments of car accident do not allow a real human to participate in, computational models could allow researchers to simulate reaction of the human body under different impact loads.

In addition, finite element method of numerical analysis was applied to solve problems at non-injurious level. In order to investigate the mechanism of musculoskeletal disorders, finite element analysis was performed to understand abnormal stress and progress of pathological regions. Linder-Ganz et al. (2007) carried on a study to investigate tissue strain and stress distribution in seated human, and they found that the maximal tissue strains and stresses located in gluteal muscle, not in fat tissue. Motoyoshi et al. (2002) simulated three types of human spines in order to investigate the effects of head posture on occlusion. They suggested that high-level stresses were distributed at different regions of cervical spine due to different head positions. For load-carrying, cervical spine distributes load among discs, facet joints, ligaments and muscles in a complex way. In order to identify the biomechanical behaviour of the cervical spine under different types of loading situations, del Palomar et al. (2008) developed a 3D finite element model of the neck. They found that flex-extension movement produced the highest value in the maximum shear stress of the disc among normal cervical movements. Panzer and Cronin (2009) found that at higher levels of flexion, the ligaments of C4-C5 carried most of the load although the intervertebral disc was major load-bearing segment along cervical spine.

Mainly because of the lack of data on muscular physiological loading and of the complex anatomical structure of the cervical spine, oversimplified loads are often utilized in the finite element studies of the spine. Oshita et al. (2002) demonstrated that whether the simulation showing a good agreement with experimental data mainly depended on the types of loading patterns. Sometimes, the predicted data may deviate from cadaver experimental results to a large degree. That is also the limitation where finite element model lies in. However, musculoskeletal models could calculate muscle force and joint force at specific postures, which allows the prediction of muscle and joint loading. Combined the finite element model and musculoskeletal model at the same time, it provides a far more evidence-based model than the finite element model alone.

2.2.4 Summary of existing biomechanical analysis

There are multifactorial factors related to the cervical musculoskeletal disorder, such as the physical aspects of human movement, physiological aspects of metabolism and psychosocial aspects.

It has been proved that biomechanical studies, ranging from experiments to mathematical models, have made great contributions to the mechanism underlying the cervical musculoskeletal disorders, as well as the understanding of cervical spine biomechanics and the guideline of ergonomics design.

In clinical studies, optimal sitting posture was put forward according to the subject's perception. Although the assessment of subjective survey and postural measurement in the terms of biomechanics were performed in a combinational way, people's perception and comfort may not reflect if certain type of sitting posture is suitable or beneficial to the biomechanical characteristics and health of the cervical spine.

On the other hand, these studies identified risk factors such as posture, movement and duration, however, mechanism underlying the risk factors was rarely investigated due to the limitation of the equipment used in various types of experiments.

Computational studies mainly focused on the simulation of cervical spine under various conditions including the impact, implant, and different ergonomic designs. The proposed mechanism for cervical musculoskeletal disorders has not been well understood because of the complexity of the cranio-cervical structure. However, simplification can be found in the structure of cervical joints, number of cervical muscle groups, as well as the interaction with skull and thoracic-lumbar spine. Specifically, cervical joints from C3 to C7 were considered to be a link which could not allow the movement between each vertebrae.

Therefore, the combination of the experimental and computational studies could provide a comprehensive platform to better understand the biomechanics of the cervical spine under various types of postures.

CHAPTER 3. METHODS

This research was mainly designed for two sections. One is experimental study including postures measurement and electromyography. The other is computational study including the musculoskeletal model. The information obtained from an experimental study, including posture angle, the trajectory of body segments and normalized muscle activity, can be utilized for two purposes: 1) to help construct musculoskeletal model; 2) to validate the musculoskeletal model. Finally, the purpose of building musculoskeletal model was to investigate inner cervical spinal posture and load distribution along cervical spine. The flow chart of preliminary study is as the following (Figure 3-1)

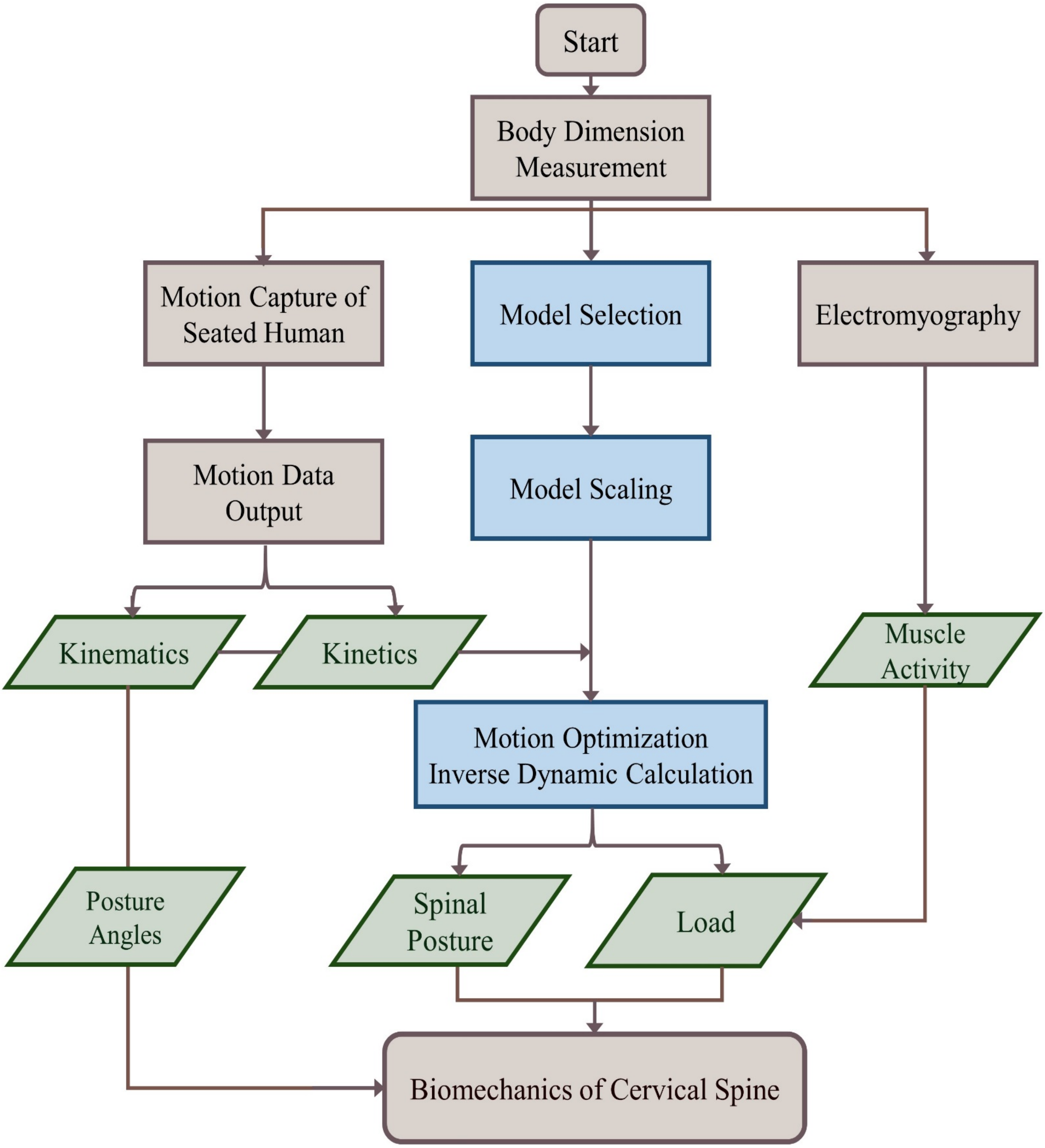

Figure 3-1. Flow chart of this study. This study was designed at two levels, namely experimental and computational studies. Brown boxes stand for the experiments including the motion capture and EMG measurement. The former was used for posture analysis and also for constructing a musculoskeletal model. The latter was for the validation of the model. Blue boxes present the computational study. Green boxes stand for the output from both experiments and simulation.

3.1 Experimental study

3.1.1 Participant

Ten healthy young adults (Gender: five male and five female; Height: 171.9±10.3 cm; Weight: 60.1±11.8 kg; BMI: 20.1±1.5 kg/m2; Age: 26.0±2.9 years) with the experience of computer operation for 3 hours or more per day was recruited in this study. Participants were excluded if they had ever experienced thoracic or cervical spinal pain or injury that required treatment or rest from normal activities, or if they had a limitation on the range of motion (ROM) of the cervical spine. This research was approved by the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University.

3.1.2 Equipment

An 8-camera, infrared motion analysis system (Vicon MX, Oxford, UK) was used to assess the three- dimensional posture angles of seated human. The contact reaction forces were measured through two force platforms (Advanced Mechanical Technology Inc. Newton, Mass, USA). One was placed on the ground and the other was on a chair made of wood without any lumbar or arm supports. The data from motion capture system and AMTI force platforms were collected at 100Hz and 1000 Hz, respectively.

Before the posture measurement, the motion system calibration was performed to guarantee the accurate orientations of the eight cameras located at the corner of the wall, and to obtain sufficient capture volume to get high quality of raw data. According to marker sets for Plug-in gait full body modelling and AnyBody motion capture modelling, there were 35 reflective markers placed on the following skeletal landmarks (Table 3-1):

Table 3-1. Summary of markers set on landmarks

Body Segment	Marker Label	Description
Head	LFHD/ RFHD LBHD/ RBHD LTR/ RTR LOC/ ROC	Left/ Right front head Left/ Right back head Left/ Right tragus Left/Right out canthus
Neck	C7	7th Cervical vertebra
Torso	T10 CLAV STRN RBAK	10th Thoracic vertebra Clavicle Sternum Right back
Upper limb	LSHO/ RSHO LELB/ RELB LWRA/ RWRA LWRB/ RWRB LFIN/ RFIN	Left/ Right shoulder Left/ Right elbow Left/ Right wrist A Left/ Right wrist B Left/ Right finger
Pelvis	LASI/ RASI LPSI/ RPSI	Left/ Right anterior superior iliac Left/ Right posterior superior iliac
Lower limb	LKNE/ RKNE LANK/ RANK LTOE/ RTOE LHEE/ RHEE	Left/ Right knee Left/ Right ankle Left/ Right toe Left/ Right heel

3.1.3 Procedure

Participants were asked to wear lycra pants without T-shirts, and then to do warming up of head and neck to minimize the effects of tissue creep along the cervical spine. Participants performed one minute warm-up which consists of cervical rotation and stretching (Tierney et al., 2005). After markers were attached to participants' skin, they were instructed to sit on one force platform and to step on the other one. Their feet positioned shoulder width apart, and arms relaxed at the side of the body. This study utilized repeated measure design with participants performing six sitting postures. The six experimental conditions included cranio-cervical neutral position (Figure 3-2); cranio-cervical protraction (Figure 3-3); and cranio-cervical flexion (Figure 3-4). Finally, all these three conditions were repeated with upright and slump sitting postures.

In order to control the deviation of sitting postures, each experimental posture was maintained for three minutes for the purpose of allowing participants to be familiar with the motion before data collection. Two laser light beams were adjusted vertical to the sagittal plane of the human body and targeted on reflective markers of C7 and tragus, which was used for the calibration of initial position. To achieve the predefined posture, manual facilitation was provided to keep defined spinal alignment and verbal guidance was also offered to prevent postural deviation (Stenlund et al., 2014, Claus et al., 2009). Each trial was maintained for the 30s for each cranio-cervical posture and three trials were repeated. In this study, the reliability of cranio-cervical posture measurement within participants was also analyzed to detect the accuracy of postural repeatability.

During data collection, participants were required to look straight when performing neutral and protraction, and to breathe naturally as usual. A 1-minute break was taken between each experimental condition to avoid effects of fatigue on cervical region. Typically primary postures were defined as the following:

Neutral sitting posture, defined as pelvic anterior rotation along with a relaxed thoracic spine (O'Sullivan et al., 2012).

Slump sitting posture, defined as the posterior rotation of the pelvis and relaxation of thoraco-lumbar spine while looking straight (Nairn et al., 2013b).

Cranio-cervical neutral posture, defined as turning head to the level of a comfortable stretch at the end of the range on the basis of upright sitting posture (Edmondston et al., 2005).

Cranio-cervical protraction, defined as fully forward chin while looking horizontally (Walmsley et al., 1996).

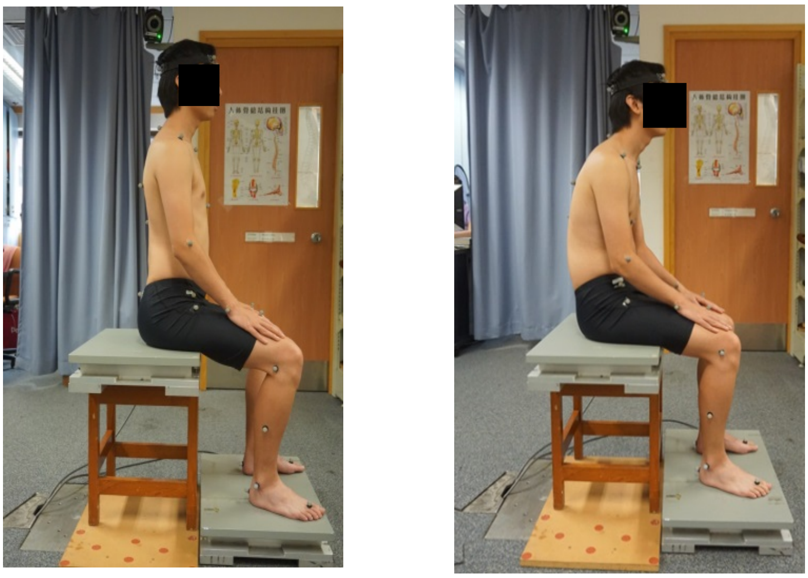

Figure 3-2. Cranio-cervical neutral positions with upright sitting posture (Left) and with slump sitting posture (Right)

Figure 3-3. Cranio-cervical protraction positions with upright sitting posture (Left) and with slump sitting posture (Right)

Figure 3-4. Cranio-cervical flexion positions with upright sitting posture (Left) and with slump sitting posture (Right)

Additional markers were also placed on the lateral canthus, tragus and C7 according to the bony landmarks to obtain postural angles through calculation (Figure 3-5). Typically they were defined as the following (Young et al., 2012):

Cranial angle: angle between global vertical and the vector pointing from tragus to lateral canthus.

Cervical angle: angle between global vertical and the vector pointing from C7 to the tragus.

Cranio-cervical angle: angle between vector pointing from C7 to the midpoint of left and right tragus, and the vector pointing from midpoint of L/R tragus to the midpoint of L/R lateral canthus.

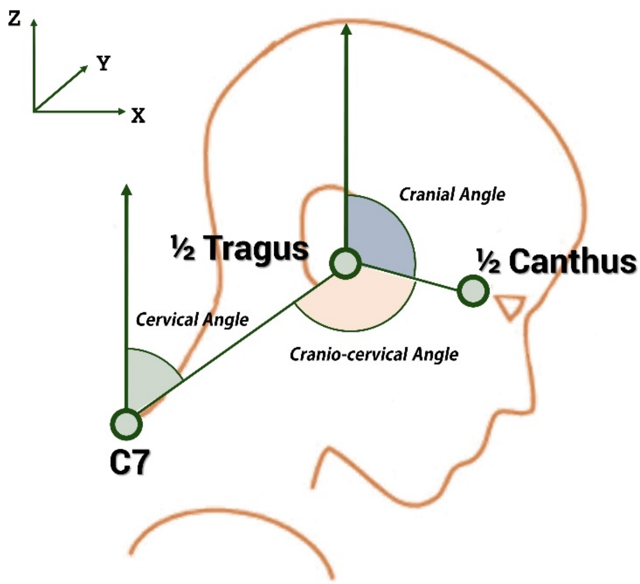

Figure 3-6. Head and neck angles consist of cranial, cervical and cranio-cervical angles. ½ Tragus stands for the midpoint of the left and right tragus and ½ Canthus stands for the midpoint of the left and right canthus. Green, orange and gray sectors suggest the cranial, cervical and cranio-cervical angles, respectively.

According to the coordinates of markers on C7, L/R tragus and outer canthus, segment angles are mainly based on the vector angle equation and anti-trigonometric function:

$$\theta = \cos^{-1}\left(\frac{\mathrm{a}\times\mathrm{b}}{|a| * |b|}\right)$$

3.2 Computational study

The human musculoskeletal system is complex in the term of mechanical and anatomical aspects. Based on the complexity of this system, computational models have to be simplified according to the specific demands thus it can be calculated efficiently. One simplification of the musculoskeletal model is to simulate the skeletal system as a rigid-body system. Moreover, human models based on the computer science need to be further simplified, because the musculature also involves in various geometrical features and mechanical characteristics. The most important mechanism is that each type of muscle is controlled by the central nervous system although the inner mechanism has not been well figured out. Therefore, the other simplification of the musculoskeletal model is to simulate muscle system as one mathematical model such as spring, and hill muscle type (Winter, 2009).

Musculoskeletal models are mainly in three categories namely forward dynamics, inverse dynamics and combination of these two models (Seth et al., 2011). Basically, forward dynamics can calculate the movement force or moment on the foundation of assumed muscular activation such as forces or moments. Oppositely, inverse dynamics can calculate the muscular activation through kinematic data usually obtained from posture capture. In the inverse dynamic model, kinematic data obtained from motion capture places a number of restrictions on the model itself. It is mainly based on the Newton-Euler equation (Greenwald, 2005).

3.2.1 Musculoskeletal modelling

AnyBody modelling system as a human body simulation software is developed to analyse mechanical features of the musculoskeletal system (Rasmussen et al., 2009). AnyBody enables the reconstruction of musculoskeletal models, visualization of human motion, and export of mechanical information. Through scaling an existing model to individual anthropometry, using kinematic data to drive full body model and modifying contact between environments and human body model, AnyBody system is capable of simulating various human movement and motion in a vivid way. The human model consists of several rigid elements including muscles, joints, and bones. Particularly, it can offer many variables such as force, angles, and muscle activity, which is likely to help investigators to identify which element may get involved in the abnormal movement or motion.

In AnyBody modelling system, Newton-Euler equation is applied to calculate force and moment of each segment. On the basis of inverse dynamics, it could only compute redundant forces or moments. Hence, optimization methods as the function of the central nervous system to determine which muscles to be recruited are utilized to determine specific muscle load-carrying. Among these optimization criteria, AnyBody modelling uses min/max criteria to solve this redundancy problem (Damsgaard et al., 2006):

$$\text{Minimize max} \left(\frac{f_i^{(M)}}{N_i}\right)$$

$$\text{Subject to } \mathbf{Cf} = \mathbf{d}$$

$$f_i^{(M)} \geq 0, i \in \{1, \ldots, n^{(M)}\}$$

A large number of muscles can be recruited to counterbalance the external load on the basis of inverse dynamics giving rise to a muscle recruitment problem. Whereas central nervous system (CNS) through electrochemical process activates muscles in an efficient way, minimizing the maximum load acting on the cervical musculoskeletal system. Thus AnyBody modelling system utilized minimum fatigue criterion allowing muscles with low load to share the same activity of that with the high load, which could postpone fatigue of cervical musculature (Rasmussen et al., 2009).

The optimization criteria permit load distribution to be evenly assigned to the muscle system so that certain muscles can not be overloaded, which is also consistent with the physiological phenomena that the CNS first recruits large muscle groups because they are less able to be fatigue than small muscle groups. During prolonged construction both in high and low-intensity conditions, this principle is always performed by CNS. In the equation of muscle recruitment, "Minimize" refers to minimize the total force acting on the muscles and joints system, and "Max" refers to recruit large muscles groups with high capability of force-generation.

Muscle Model

As for the muscle model used in this study, the simplest type of muscle is provided. Muscles in the model were simulated as elastic strings connected from origin to insertion based on the anatomical parameters (Rasmussen et al., 2009). The assumption of this type of muscle does not take muscle length or contraction velocity, neither does the passive elasticity of muscles into account. It assumes that muscle force corresponds to the maximum voluntary contraction of muscle. Although this simple model type has limitations in the aspects of physiology and biomechanics, it is still widely used in many studies whose purpose were to investigate the static motion and muscle load-carrying with small contraction velocities. This study was apt to the requirement of simple muscle model and the assumption can be also applied to model development.

Model Structure

The musculoskeletal model was built in AnyBody modelling system ver. 6.4. Full body model with detailed neck comprises a head, upper limbs, trunk, and lower limbs. Each of the segments was a rigid body with mass properties. Detailed neck model was utilized to simulate cranio-cervical positions specifically. The cervical spine column was modelled by seven rigid bodies as cervical vertebra at each level. Intervertebral discs and ligaments were not included in this model and thus, each vertebra could be treated as a separate movable unit. Joints between each vertebra involved one degree of freedom (dof) universal joint from C0 (skull) to C2, and three dof spherical joints from C2 to T1 shown in the list (Table 3-2).

Table 3-2. List of cervical muscles incorporated into the model

NO	TYPE	Flexor muscles	Origin	Insertion
1	Superficial	LumpedHyoid	T1	C0
		Total LumpedHyoid		
2	Deep	LongusColli	T1	C6
3		LongusColli	T1	C5
4		LongusColli	T1	C4
5		LongusColli	T1	C3
6		LongusColli	T1	C2
7		LongusColli	T1	C1
8		LongusColli	T1	C0
		TOTAL LongusColli		
9	Deep	LongusCapitis	C6	C0
10		LongusCapitis	C5	C0
11		LongusCapitis	C4	C0
12		LongusCapitis	C3	C0
		TOTAL LongusCapitis		
13	Deep	SpleniusCapitis	C7	C0
14		SpleniusCapitis	T2	C0
15		SpleniusCapitis	T3	C1
16		SpleniusCapitis	T3	C2
17		SpleniusCapitis	T3	C3
		TOTAL SpleniusCapitis		

18	Deep	SemispinalisCapitis	C4	C0
19		SemispinalisCapitis	C5	C0
20		SemispinalisCapitis	C6	C0
21		SemispinalisCapitis	C7	C0
22		SemispinalisCapitis	T3	C0
		TOTAL SemispinalisCapitis		
23	Deep	SemispinalisCervicis	T1	C2
24		SemispinalisCervicis	T2	C3
25		SemispinalisCervicis	T3	C4
26		SemispinalisCervicis	T4	C5
27		SemispinalisCervicis	T5	C6
28		SemispinalisCervicis	T6	C7
		TOTAL SemispinalisCervicis		
29	Deep	LongissimusCapitis	C3	C0
30		LongissimusCapitis	C4	C0
31		LongissimusCapitis	C5	C0
32		LongissimusCapitis	C6	C0
33		LongissimusCapitis	C7	C0
34		LongissimusCapitis	T2	C0
		TOTAL LongissimusCapitis		

NO	TYPE	Flexor muscles	Origin	Insertion
35	Deep	LongissimusCervicis	T2	C2
36		LongissimusCervicis	T2	C3
37		LongissimusCervicis	T2	C4
38		LongissimusCervicis	T2	C5
39		LongissimusCervicis	T2	C6
40		LongissimusCervicis	T2	C7
		TOTAL LongissimusCervicis		
41	Deep	MultifidusCervicis	C5	C2
42		MultifidusCervicis	C6	C2
43		MultifidusCervicis	C6	C3
44		MultifidusCervicis	C7	C3
45		MultifidusCervicis	C7	C4
46		MultifidusCervicis	T1	C4
47		MultifidusCervicis	T1	C5
48		MultifidusCervicis	T2	C5

49		MultifidusCervicis	T2	C6
50		MultifidusCervicis	T3	C6
51		MultifidusCervicis	T3	C7
52		MultifidusCervicis	T4	C7
		TOTAL MultifidusCervicis		
53	Deep	Levator-Scapulae	Scapular	C1
54		Levator-Scapulae	Scapular	C2
55		Levator-Scapulae	Scapular	C3
56		Levator-Scapulae	Scapular	C4
		TOTAL Levator-Scapulae		
57		Trapezius-Scapular	T10	Scapular
58	Superficial	Trapezius-Scapular	T8	Scapular
59		Trapezius-Scapular	T5	Scapular
60		Trapezius-Scapular	T1	Scapular
61		Trapezius-Scapular	C7	Scapular
62		Trapezius-Scapular	C6	Scapular
63		Trapezius-Clavicular	C5	Clavicular
64		Trapezius-Clavicular	C4	Clavicular
65		Trapezius-Clavicular	C3	Clavicular
66		Trapezius-Clavicular	C2	Clavicular
67		Trapezius-Clavicular	C1	Clavicular
68		Trapezius-Clavicular	C0	Clavicular
		TOTAL Trapezius		

According to participant’s anthropometric information such as height, weight, and length of the body segment, an individual human body model was developed through modifying and scaling existing model. Six different seated motions including two primary sitting postures with three cranio-cervical positions were simulated.

The kinematic data from motion capture were used to drive human body model through static optimization and inverse dynamic simulation (Figure 3-6). This data were input into the AnyBody file formats which include the units, anthropometry information of participants, ground forces and trajectory of reflective markers. Each marker coordinate was applied to manipulate each body segment in a human model.

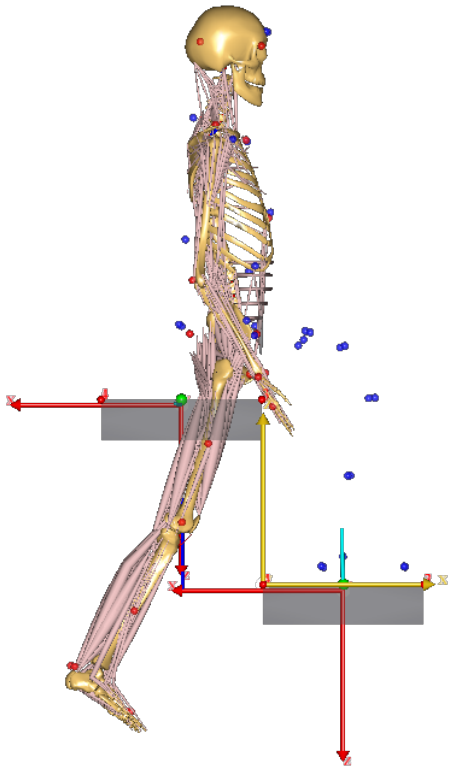

Figure 3-7. Kinematic data from motion capture was used to drive human body model.

Computational analysis was conducted on the basis of inverse dynamic calculations. Inverse dynamic study computed the muscle activation based on the motion data of six experimental conditions. A minimum fatigue principle is used in AnyBody modeling for muscle recruitment. According to minimum fatigue principle of musculoskeletal physiology, groups of large muscles were recruited first to maintain one posture and then deep muscles were recruited in case. As muscle strength is associated with muscle fatigue, computational analysis selects physiological standard to predict muscle force which provides efficiency to numerical calculations, especially for models comprising a large number of muscles.

3.2.2 Variables

In this study, calculation of vertebral angle was based on the tilt method (Crawford et al., 1999). Each vertebral angle was defined as the angle between global vertical and the vector pointing from lower vertebral joint node to the upper vertebral joint node. The joint node at each level of the cervical vertebra can be output from the AnyBody modelling system. This study focused on the neutral, protraction and flexion of the cervical spine, thus, the angles of seven vertebrae were calculated on the sagittal plane. The coordinates of seven cervical vertebral joint nodes on the sagittal plane were obtained from the model and then were connected dot-to-dot to create cervical spinal alignment in six conditions.

Muscle activation as an indicator in the model is regarded as the feedback of ergonomic design. Since the decrease in the muscle envelope is perceived as less fatiguing, the ergonomic design will choose the optimization according to the corresponding human body feedback. Although absolute muscle force could provide detailed information about muscle performance, muscle activity envelope (i.e. f/n) tends to describe the specific capability of force-generation regardless of different muscle strengths. In AnyBody modelling, muscle activity envelope is defined as the percentage of maximum voluntary contraction required to counterbalance the external load in given postures or movements. Then the muscle activations were utilized to calculate joint reaction loads at each level of the cervical vertebra. Load carrying proportion between flexors and extensors was calculated by dividing the muscle force of each muscle group by the total resulting forces.

3.3 Validation

In previous studies, electromyography (EMG) has been widely accepted as a quantitative method of validation to compare the muscle activity calculated through biomechanical models with EMG envelope measured by experiments (Dubowsky et al., 2008). In this study, validation of the musculoskeletal model was performed through the comparison between EMG-based and model-based muscle activities, as well as the comparison with previous studies.

Surface Ag-AgCl electrodes (2228, 3M Health Care, Canada) were attached at the midpoint of muscle belly parallel to its fiber direction. Before electrodes attachment, the skin was shaved and cleaned with 70% alcohol swab (Smith & Nephew Pty, Australia). Each electrode impedance less than 5 kΩ was considered acceptable. These muscles are cervical erector muscles and upper trapezius (Figure 3-7). The sites of EMG attachment were shown as the following:

Cervical erector muscles: electrode was positioned 2 cm away from C4 spinous process (Strimpakos et al., 2005);

Trapezius-clavicular (upper trapezius): electrode location of upper trapezius was the site at the midpoint between C7 and the acromion (Edmondston et al., 2011).

Figure 3-8. Measurement site of electrodes on one participant

The Noraxon system (Noraxon, USA) was utilized to collect ipsilateral muscle electric signals during three cranio-cervical positions in upright and slump sitting postures. For each experimental condition, EMG signal was recorded for 10s at the sampling rate of 1000 Hz. To facilitate comparison with predicted muscle activity, the recorded muscle activity was normalized as a percentage of the maximum voluntary contraction (MVC). Maximal voluntary isometric contraction of these muscles was performed. In order to obtain the MVC of cervical erector muscles, participants were required to attempt neck flexion in a maximal effort to against manual resistance. For trapezius-clavicular, manual resistance was placed on both sides of shoulders when participants attempted shoulder elevation in the maximal effort (Villanueva et al., 1997). Each participant performed three trials of MVC and each trial was performed for 5 seconds.

All the EMG signals were processed in Noraxon program with full-wave rectification, bandpass filter between 20 and 250 Hz, and notch filters at 50 Hz to reduce noise. The average MVC was utilized to normalize the muscle activity values recorded in cranio-cervical neutral, protraction and flexion positions under upright and slump sitting postures.

3.4 Data analysis

The Intraclass Correlation Coefficient, ICC (3, 1) was based on the model consistency type which was utilized to determine reliability for repeated measurements of three spinal angles under six experimental conditions. Since the postural measurement was conducted by the same rater, ICC (3, 1) was selected as the appropriate statistical analysis of intra-rater reliability. It has been shown that ICC of below 0.5 represented as poor reliability; ICC from 0.5 to 0.75 as moderate reliability; and ICC above 0.75 as good reliability (Portney and Watkins, 2000).

A two-way ANOVA for repeated measures, including two within-subject factors (sitting posture and cranio-cervical position), was utilized to determine the effects of sitting posture, cranio-cervical position, and sitting posture × cranio-cervical position interaction on head-neck angles, cervical tilt angles, muscle force and joint reaction force. Multiple post-hoc comparisons were performed using Bonferroni to determine significant differences between comparisons. A paired t-test was undertaken to investigate the temporal differences between upright and slump sitting postures. Descriptive statistical analysis was conducted to compare the body segment angles and predicted muscle activity in each of the cranio-cervical positions under upright and slump sitting postures. The level of significance was set at $p < 0.05$ for all the analyses.

Pearson correlation coefficients were performed to investigate the relationship between

EMG-based muscle activity and predicted muscle activity. Correlation coefficient above 0.75 presents good to the excellent relationship; between 0.50 and 0.75 demonstrates moderate relationship; between 0.25 and 0.50 means the fair degree of relationship; and below 0.25 shows little or no relationship. All analyses were performed using SPSS statistics software, version V21.0 (SPSS Inc., Chicago, IL, USA).

CHAPTER 4. RESULTS

This study focused on the biomechanical study of different cranio-cervical positions under upright and slump sitting postures. Dependent variables obtained from both experiment and simulation, as well as the reliability of the experiment and validation of the model were illustrated in the following sections.

Specifically, external postural angles measured through landmarks on human skin, including head and neck angles as well as the postural angles of body segments, were based on the motion capture system. As for the inner parameters, they were obtained from the musculoskeletal model, for example, cervical spine posture and vertebral tilt angles, as well as cervical muscle load and joint load.

4.1 Intraclass correlation coefficient (ICC) reliability

The reliability of the cranial angle was analysed separately for the six cranio-cervical positions as shown in Table 4-1. The ICC values for five postural angles were good to high ranging from 0.754 to 0.999 in cranio-cervical positions including neutral, protraction and flexion with upright sitting posture, and neutral and flexion with slump sitting. Moderate reliability (ICC values ranging from 0.705 to 0.724) was shown in measuring the angles when performing cranio-cervical protraction in slump sitting posture.

Table 4-1. ICC (3, 1) for cranial, cervical and cranio-cervical angles

	Upright Sitting (ICC)			Slump Sitting (ICC)		
	Neutral	Protraction	Flexion	Neutral	Protraction	Flexion
Cranial angle	0.808	0.889	0.851	0.853	0.715	0.944
Cervical angle	0.754	0.877	0.857	0.724	0.705	0.952
Cranio-cervical angle	0.829	0.841	0.977	0.944	0.769	0.964
Mean	0.999	0.999	0.935	0.999	0.998	0.984

Note:
ICC (3, 1) was based on a two-way mixed consistency type.
Neutral: cranio-cervical neutral position
Protraction: cranio-cervical protraction position
Flexion: cranio-cervical flexion position

4.2 Motion capture analysis: Postural Angles

Head and neck angles

Head and neck angles, including cranial, cervical and cranio-cervical angles, varied significantly among different types of positions (Figure 4-1).

There were no significant differences in cranial angle (head flexion) between neutral and protraction. In this case, the cranial angle was approximately 70 degrees both under upright and slump sitting postures. For cranio-cervical flexion position during upright and slump sitting postures, cranial angles were greater than other four conditions, reaching about 130 and 140 degrees respectively.

Cervical angle (neck flexion) in cranio-cervical neutral position was smallest compared with flexion and protraction, especially during upright sitting posture. The slumped posture with neutral and protraction was associated with the significant increase in cervical angles compared with the upright posture, but the differences were not significant in flexion.

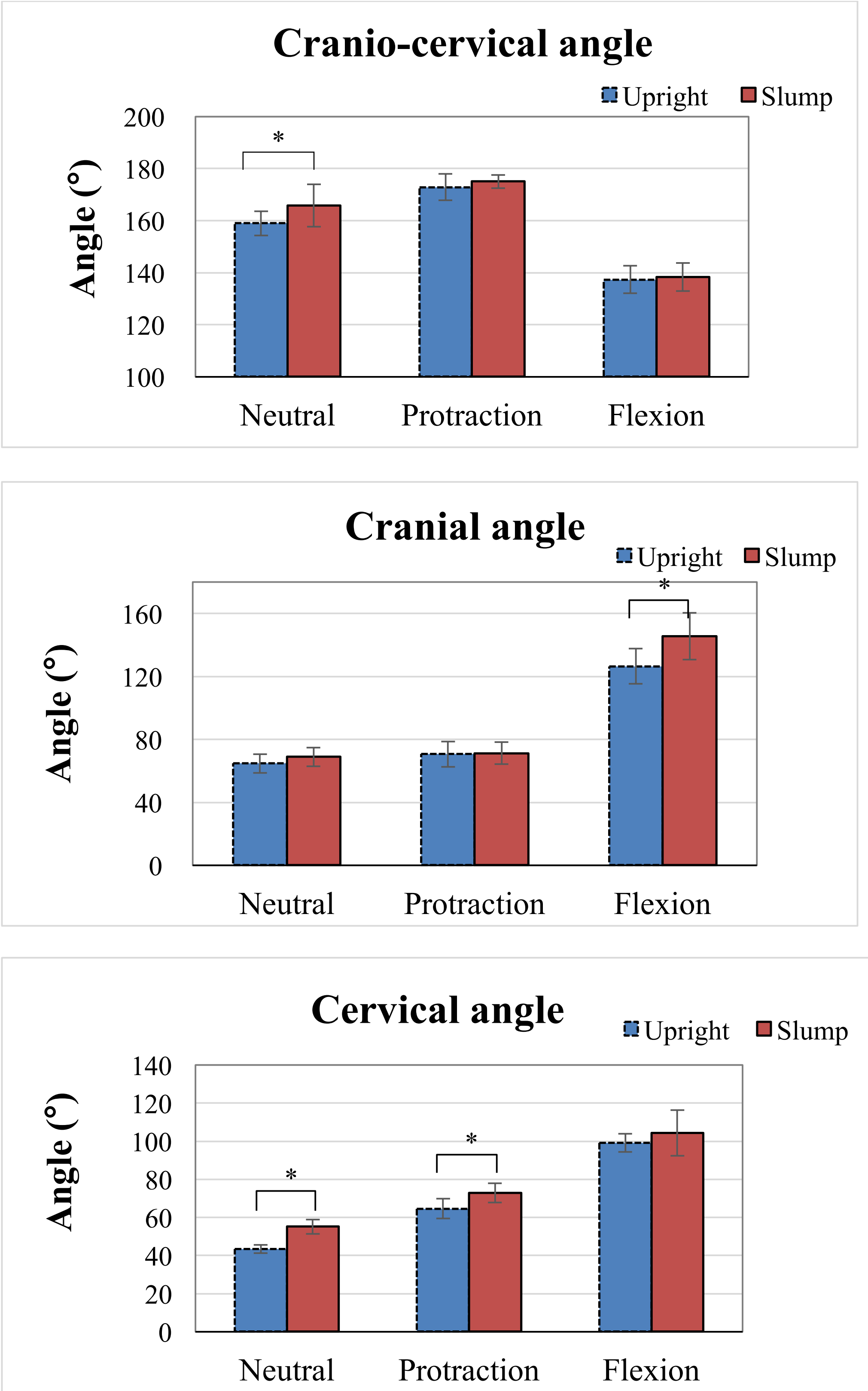

Figure 4-1 Comparison of head and neck angles in six conditions. * represents post-hoc significant differences across two sitting postures. Neutral zone of cranial and cervical angles were approximately 40 and 70 degrees, respectively (Young et al., 2012).

For the cranio-cervical angle, protraction was significantly greater than cranio-cervical neutral or flexion position ($p < 0.001$), reaching approximately 170 degrees. Similarly, slump posture with protraction showed greater cranio-cervical angle than upright sitting posture with protraction. For cranio-cervical flexion position, this angle was observed smaller than neutral and protraction.

Although head and neck flexion angles in protraction position were relatively small, the cranio-cervical angle was greater than that in flexion position. Markers on C7, tragus and lateral canthus were connected dot-by-dot in the photo, and these three markers formed a triangle for neutral and flexion positions. However, they were almost kept in line for protraction position (Figure 4-2).

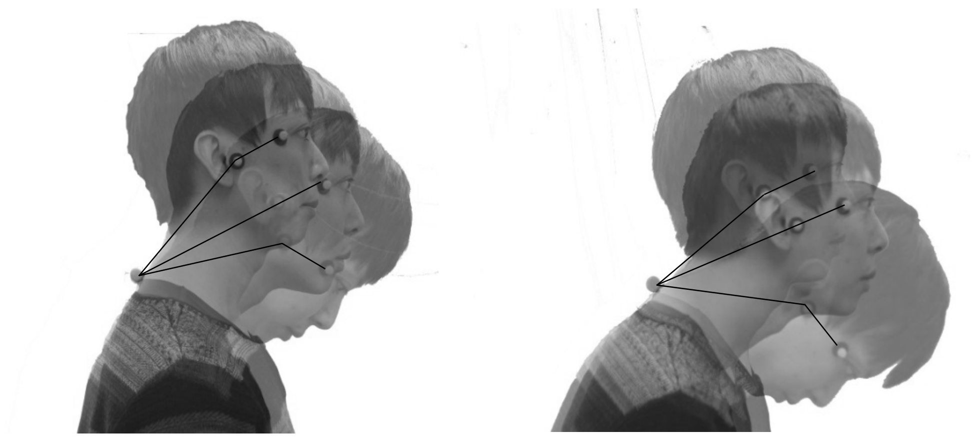

Figure 4-2. Cranio-cervical angles in neutral, protraction and flexion positions during upright sitting (Left) and slump sitting (Right).

There was a significant interaction between the effects of sitting posture and cranio-cervical position on postural angles ($p < 0.05$). Simple main effect analyses showed that head and neck angles in slump sitting posture were significantly greater than in upright sitting posture ($p < 0.05$) (Table 4-2).

Table 4-3 summarised the body segment angles in three cranio-cervical positions under upright and slump sitting postures. For the upright sitting condition, trunk angles (sternoclavicular protraction), upper limb angles (glenohumeral flexion, glenohumeral abduction) and lower limb angles (hip, knee, ankle and subtalar flexion) were similar among cranio-cervical neutral, protraction and flexion positions.

Similarly, variations of the trunk, upper limb and lower limb in three cranio-cervical positions were slightly different in slump sitting posture. Therefore, the postural consistency of trunk, upper limb and lower limb was well performed during different types of cranio-cervical positions.

Table 4-2. Mean (standard error) of head and neck angles, and cervical tilt angles for ANOVA main effects Sitting Posture and Cranio-cervical position

Type of Angle	Sitting Posture			Cranio-cervical positions			
	p value	Upright	Slump	p value	Neutral	Protraction	Flexion
Head and neck angles							
Cranial angle	p =0.002	87.3(2.1)^{A}	95.2(2.6)^{B}	p <0.001	66.8(1.8)^{A}	71.0(2.1)^{A}	136.0(4.1)^{B}
Cervical angle	p <0.001	69.1(0.7)^{A}	77.4(2.0)^{B}	p <0.001	49.3(0.7)^{A}	68.7(1.4)^{B}	101.7(1.5)^{C}
Cranio-cervical angle	p =0.014	156.4(1.2)^{A}	159.7(1.1)^{B}	p <0.001	165.8(1.9)^{B}	175.1(0.8)^{C}	138.3(1.7)^{A}
Cervical tilt angle							
C0C1	p <0.001	1.7(0.8)^{A}	10.0(0.9)^{B}	p <0.001	-12.0(0.8)^{A}	-3.6(1.6)^{B}	33.1(2.1)^{C}
C2C1	p =0.006	21.8(0.6)^{A}	31.1(1.0)^{B}	p <0.001	8.4(0.9)^{A}	17.9(1.1)^{B}	52.8(2.1)^{C}
C3C2	p <0.001	18.5(0.7)^{A}	29.5(1.4)^{B}	p <0.001	8.3(1.0)^{A}	17.5(0.7)^{B}	45.9(2.2)^{C}
C4C5	p <0.001	17.0(0.8)^{A}	28.8(1.8)^{B}	p <0.001	9.6(1.2)^{A}	18.6(0.6)^{B}	40.4(2.2)^{C}
C5C6	p <0.001	20.2(1.1)^{A}	33.9(2.4)^{B}	p <0.001	16.0(1.5)^{A}	25.1(1.0)^{B}	39.7(2.3)^{C}
C6C7	p <0.001	27.3(1.5)^{A}	42.6(2.9)^{B}	p <0.001	26.1(1.8)^{A}	35.2(1.7)^{B}	42.7(2.5)^{C}
C7T1	p =0.01	26.7(1.7)^{A}	42.6(3.5)^{B}	p <0.001	28.2(2.2)^{A}	37.8(2.3)^{B}	38.0(2.6)^{B}

Note:

Neutral: cranio-cervical neutral position

Protraction: cranio-cervical protraction position

Flexion: cranio-cervical flexion position

There was no significant difference when values were marked with the same letter and the ranking pattern was such that A<B<C

Table 4-3. Mean (standard deviation) postural angles of body segments in three cranio-cervical positions under two sitting postures

Type of angles	**Posture Angle (°)**					
	Upright Sitting			**Slump Sitting**		
	Neutral	Protraction	Flexion	Neutral	Protraction	Flexion
Sternoclavicular Protraction	26.0(4.9)	31.8(6.4)	30.2(4.6)	24.2(4.4)	30.9(5.9)	29.7(5.0)
Sternoclavicular Elevation	7.3(8.4)	6.3(7.5)	14.4(6.7)	9.5(5.5)	7.5(7.7)	17.1(6.6)
Glenohumeral Flexion	25.4(7.6)	27.2(7.8)	28.5(4.7)	33.5(9.2)	38.1(10.1)	37.6(7.3)
Glenohumeral Abduction	9.4(5.1)	10.7(5.4)	8.2(5.1)	11.0(4.9)	14.6(7.1)	11.0(5.9)
Hip Flexion	67.5(10.7)	67.6(6.8)	65.9(10.2)	56.3(4.8)	53.5(5.3)	52.6(5.7)
Hip Abduction	7.7(3.9)	8.2(4.0)	8.2(4.3)	9.4(3.2)	8.5(3.8)	8.6(3.6)
Hip Rotation	9.8(4.1)	9.6(4.3)	9.9(4.3)	10.7(5.5)	9.4(6.0)	10.1(5.2)
Knee Flexion	88.1(9.2)	87.6(9.4)	87.9(9.1)	89.2(9.0)	86.5(8.5)	86.8(8.3)
Ankle Plantarflexion	18.8(5.7)	19.2(6.5)	18.8(6.5)	19.6(4.1)	18.1(4.3)	18.5(4.3)
Subtalar Eversion	5.1(6.0)	6.8(6.6)	4.8(6.5)	4.2(4.9)	4.7(3.8)	4.9(3.9)

Note:

Neutral: cranio-cervical neutral position

Protraction: cranio-cervical protraction position

Flexion: cranio-cervical flexion position

4.3 Musculoskeletal modeling

The following section illustrates the results from musculoskeletal modelling. Figure 4-3 presents the configurations of cranio-cervical spine in three cranio-cervical positions under two sitting postures. Figure 4.4. shows the simulation of the whole human body model in six experimental conditions from one participant.

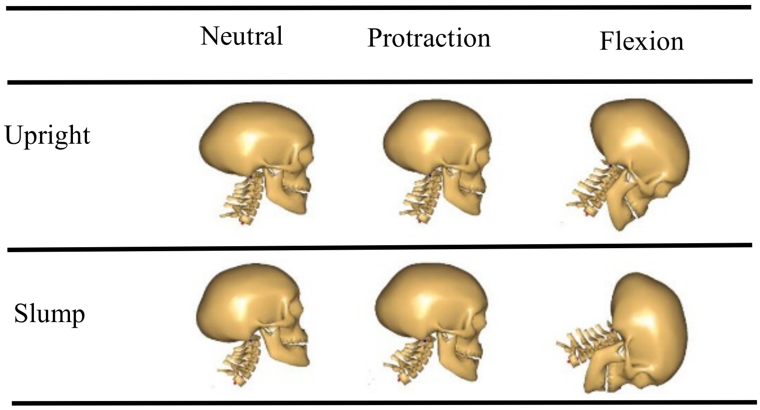

Figure 4-3. Comparisons of cranio-cervical spine in different positions and these configurations were simulated in AnyBody modelling system.

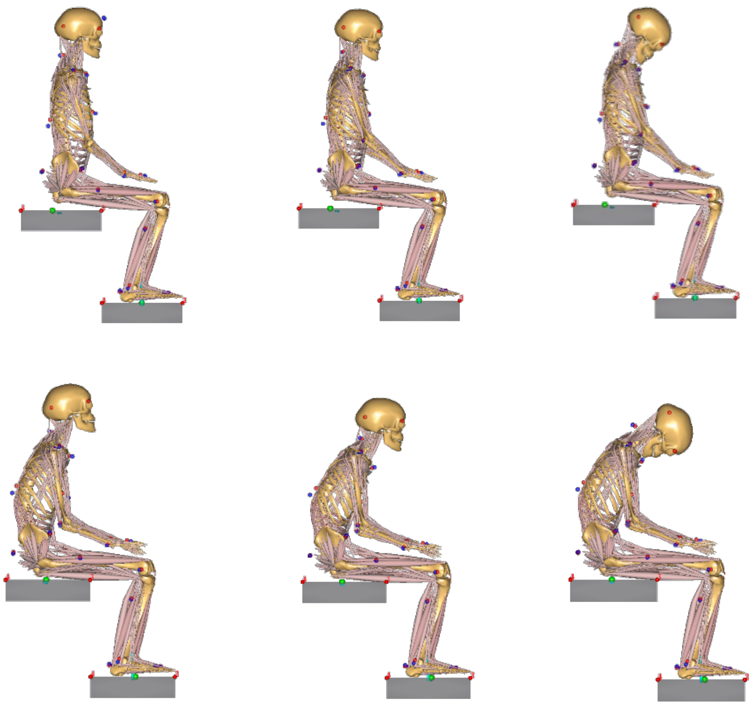

Figure 4-4. Comparisons of the whole human body model in different positions and these configurations were simulated in AnyBody modelling system.

The predicted cervical spinal alignments for six experimental conditions from one participant were shown in the Figure 4-5 and Figure 4-6. In this study, coordinates of seven cervical vertebral joint nodes were obtained from musculoskeletal model to create cervical spinal alignment.

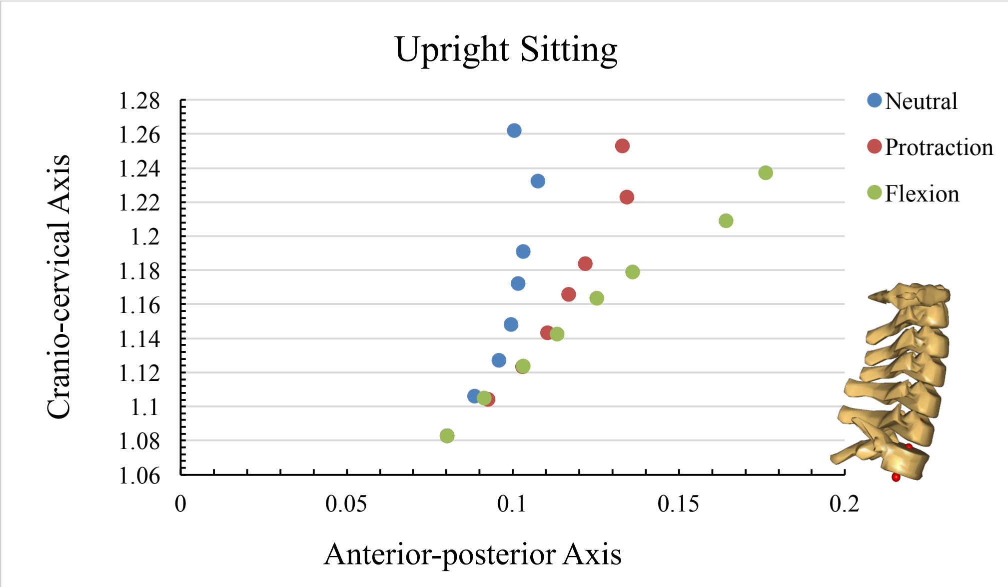

Figure 4-5. Spinal postures in neutral, protraction and flexion in the musculoskeletal model during upright sitting postures.

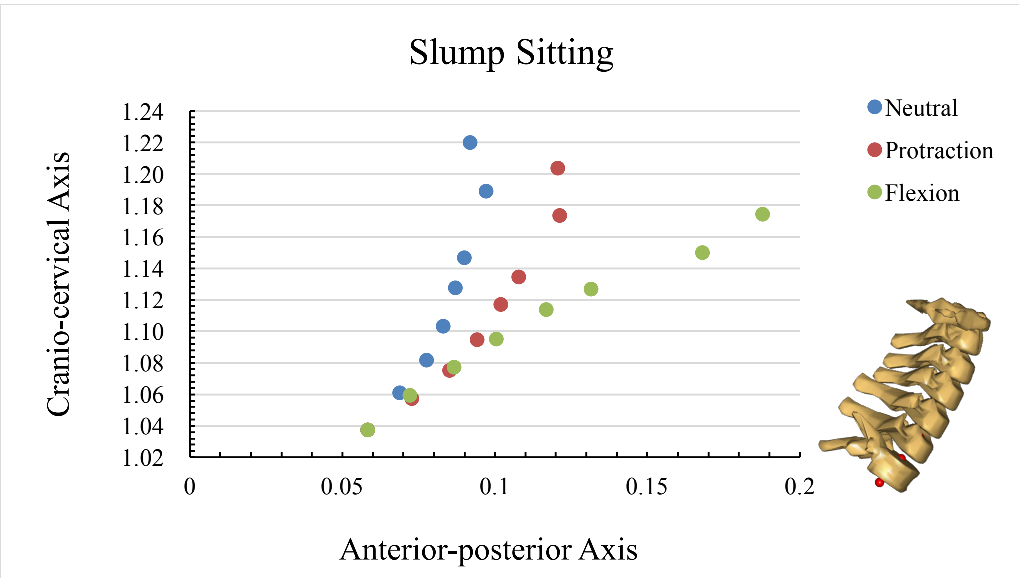

Figure 4-6. Spinal postures in neutral, protraction and flexion in the musculoskeletal model during slump sitting postures.

4.3.1 Cervical vertebral tilt angle

Differences in each cervical vertebral tilt angle in six experimental conditions are illustrated in Figure 4-7. There was a significant interaction between the effects of sitting posture and cranio-cervical position on cervical vertebral tilt angles ($p < 0.05$). Simple main effect analysis showed that cervical vertebral tilt angles in slump sitting posture were significantly greater than that in upright sitting posture ($p < 0.05$) (Table 4-2). Cervical tilt angles at C4C5 level increased from 17 degrees in upright to 28.8 degrees in slump sitting posture, almost increased by 70%.

The cervical tilt angles at the level of C0C1, C2C1, C3C4, C5C6, C6C7 and C7T1 varied significantly ($p < 0.05$) among neutral, protraction and flexion positions. However, there was no statistically significant difference between protraction and flexion at the level of C7T1. The maximum cervical vertebral tilt angles were 28.2, 37.8 and 52.8 degrees in cranio-cervical neutral, protraction and flexion, respectively. Cervical tilt angles were greatest for flexion position ranging from 23 to 53 degrees at each vertebral level.

As for the lower cervical spine, vertebral tilt angles increased as the level increased in neutral and protraction positions. The upper vertebral tilt angles (C0-C2) in protraction were almost two times as that in the neutral position while the lower vertebral tilt angles (C3-C7) in protraction increased by approximately 40% compared with the neutral position during upright sitting.

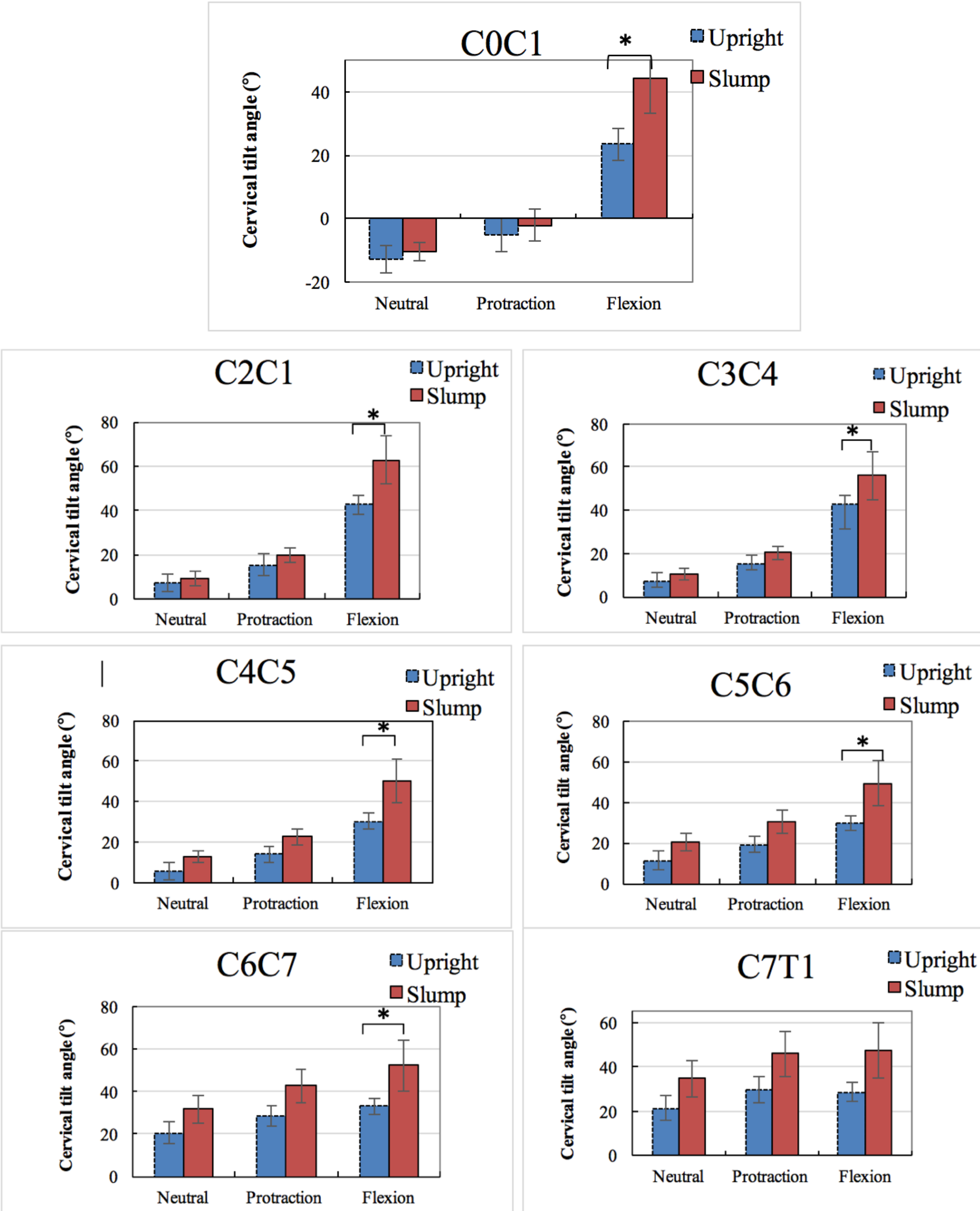

Figure 4-7. Comparison of cervical vertebral tilt angles at each level in cranio-cervical neutral, protraction and flexion during upright and slump sitting postures.

4.3.2 Muscle activation

The posture-related changes in muscle activity along the cervical spine are shown in Table 4-4. Generally, the cervical muscle activities during sitting were relatively small ranging from 0 to 9.5 %MVC.

In the slump sitting posture, there was a large increase in posterior cervical muscles activity compared with the upright posture, but little change in the anterior cervical muscle activity. In contrast, there was an increase in anterior cervical muscle activity (e.g. longus capitis activity) in flexion compared with neutral and protraction, but little difference in posterior cervical muscle activity (e.g. semispinalis cervicis and trapezius-scapular activity).

For both upright and slump sitting postures with three cranio-cervical positions, trapezius muscle activity was greater than any other parts of muscles. Trapezius-scapular activities during neutral and protraction were greater than flexion being increased by 8.1% and 4.2% respectively during upright sitting posture. Conversely, trapezius-clavicular activity in flexion was higher than neutral or protraction, reaching approximately 6.1%MVC and 8.4%MVC in upright and slump sitting posture respectively. Multifidus activity of cervical spine in neutral position was greater than flexion or protraction positions during upright posture. However, as for slump sitting posture, it was observed greater in flexion compared with neutral and protraction.

Table 4-4. Mean (standard error) muscle activity (% MVC) in three cranio-cervical positions under two sitting postures

Muscles along cervical spine	**Muscle Activity (% MVC)**					
	Upright Sitting			**Slump Sitting**		
	Neutral	Protraction	Flexion	Neutral	Protraction	Flexion
LumpedHyoid	2.3(2.0)	0.7(0.9)	0.0 (0.0)	0.9(1.4)	0.0(0.0)	0.0(0.0)
LongusColli	0.9(0.2)	0.5(0.6)	0.1(0.1)	1.9(1.7)	1.0(1.1)	0.3(0.2)
LongusCapitis	0.1(0.2)	0.6(0.4)	4.8(0.8)	0.0(0.0)	0.7(0.2)	6.3(2.8)
SemispinalisCapitis	0.8(0.5)	0.3(0.5)	0.04(0.0)	0.1(0.3)	0.1(0.2)	0.0(0.0)
SemispinalisCervicis	1.8(0.2)	1.7(0.3)	4.3(0.9)	2.3(0.2)	2.3(0.3)	5.6(2.0)
LongissimusCapitis	0.3(0.2)	0.4(0.3)	0.1(0.2)	0.1(0.1)	0.2(0.1)	0.2(0.2)
LongissimusCervicis	0.9(0.4)	1.0(0.4)	2.7(1.0)	1.2(0.4)	1.2(0.4)	3.3(1.5)
MultifidusCervicis	1.2(0.2)	1.2(0.2)	2.4(0.4)	1.6(0.2)	1.6(0.2)	3.3(1.2)
Levator-scapular	0.3(0.3)	0.4(0.2)	3.4(1.1)	0.5(0.4)	0.5(0.3)	4.4(2.3)
Trapezius-scapular	4.9(1.1)	4.7(1.7)	4.5(1.4)	6.4(2.5)	6.4(2.9)	5.9(1.6)
Trapezius-clavicular	2.3(0.6)	3.0(0.6)	5.1(0.6)	2.8(0.9)	3.6(0.8)	7.0(2.4)

Note:

Neutral: cranio-cervical neutral position

Protraction: cranio-cervical protraction position

Flexion: cranio-cervical flexion position

4.3.3 Muscle force

The muscle forces for each of the cranio-cervical positions with specific sitting posture are summarised in Table 4-5. There was a significant interaction between the effects of sitting posture and cranio-cervical position on muscle forces generated by longus colli, longus capitis, semispinalis cervicis, multifidus cervicis, levator-scapular, trapezius-scapular and trapezius-clavicular muscles ($p < 0.05$).

Simple main effect analysis showed that muscle forces generated by semispinalis cervicis, multifidus cervicis, levator-scapular, trapezius-scapular and trapezius-clavicular muscles in slump sitting posture were significantly greater than that in upright sitting posture ($p < 0.05$). Muscle force of semispinalis cervicis in protraction position was slightly greater than neutral position, but the difference was not significant. In contrast, the force generated by longissimus cervicis in protraction increased by approximately 41% compared with the neutral position.

Trapezius-scapular muscle force in protraction was greater than neutral or flexion position, but there was no significant difference. Trapezius-clavicular muscle force increased from 25.9N in the neutral position to 34.8N in protraction position, nearly of 34% increasement.

Table 4-5. Mean (standard error) muscle force (N) for ANOVA main effects Sitting Posture and Cranio-cervical position

Type of Muscle	**Sitting Posture**			**Cranio-cervical positions**			
	p value	Upright	Slump	*p* value	Neutral	Protraction	Flexion
Anterior muscles							
LumpedHyoid	p =0.005	$3.0(0.7)^{A}$	$3.8(3.3)^{B}$	p =0.034	3.9(1.3)	0.7(0.4)	0.6(0.6)
LongusColli	p =0.052	1.3(0.2)	2.8 (0.8)	p =0.003	$3.4(0.8)^{B}$	$2.2(0.7)^{B}$	$0.7(0.1)^{A}$
LongusCapitis	p =0.01	2.3(0.1)	3.8(0.6)	p <0.001	$0.1(0.05)^{A}$	$1.9(1.0)^{A}$	$7.3(0.5)^{B}$
Posterior muscles							
SemispinalisCapitis	p =0.92	3.5(1.9)	3.7(3.3)	p =0.50	2.4(0.8)	2.5(1.4)	5.8(5.7)
SemispinalisCervicis	p =0.001	$12.3(1.1)^{A}$	$17.5(2.0)^{B}$	p =0.02	$10.6(0.6)^{A}$	$11.6(0.7)^{A}$	$22.4(4.2)^{B}$
LongissimusCapitis	p =0.94	2.3(2.0)	3.5(3.3)	p =0.98	0.9(0.8)	1.8(1.5)	5.9(5.7)
LongissimusCervicis	p =0.12	3.9(1.8)	6.0(3.0)	p =0.14	2.2(0.7)	3.1 (1.3)	9.6(5.3)
MultifidusCervicis	p =0.002	$11.5(1.1)^{A}$	$16.3(2.2)^{B}$	p =0.07	10.6(0.7)	11.3(0.6)	19.7(4.4)
Levator-scapular	p =0.23	6.2(1.7)	8.2(3.0)	p =0.008	$1.7(0.8)^{A}$	$4.0(1.6)^{A}$	$16.0(4.8)^{B}$
Trapezius-scapular	p =0.001	$33.1(3.3)^{A}$	$44.7(4.7)^{B}$	p =0.72	36.3(5.4)	40.5(5.8)	39.9(3.9)
Trapezius-clavicular	p <0.001	$31.7(2.2)^{A}$	$42.8(3.1)^{B}$	p <0.001	$25.9(2.8)^{A}$	$34.8(4.4)^{B}$	$51.1(3.4)^{C}$

Note:

Neutral: cranio-cervical neutral position; Protraction: cranio-cervical protraction position; Flexion: cranio-cervical flexion position

There was no significant difference when values were marked with the same letter or without the letter, and the ranking pattern was such that A<B<C.

On the other hand, deep muscles, including longissimus cervicis, longissimus capitis, semispinalis cervicis, and semispinalis capitis, showed smaller force values compared with superficial muscles (Table 4-5). Muscle force of multifidus cervicis in flexion position was greater than neutral or protraction position, reaching about 19N. Muscle force of longus colli in neutral position was greater than other anterior muscle such as lumped hyoid and longus capitis.

Figure 4-8 showed the muscle load proportion when muscle force was normalized to that in upright sitting with cranio-cervical neutral position. Similarly, for slump sitting posture with three cranio-cervical positions, trapezius-scapular forces were greater than any other parts of muscles. However, trapezius-clavicular force in flexion position was greater than neutral or protraction. Multifidus of the cervical spine in flexion position was greater than neutral or protraction position. Deep muscle forces were observed larger in flexion and protraction positions compared with the neutral position.

For upright sitting postures with three cranio-cervical positions, trapezius-scapular forces were greater than any other parts of muscles. This type of muscle belonging to the superficial layer muscles played an important part in maintaining postures. In addition, deep muscle forces during slump posture were greater than upright posture. However, the anterior muscle forces were smaller in slump position than in upright position.

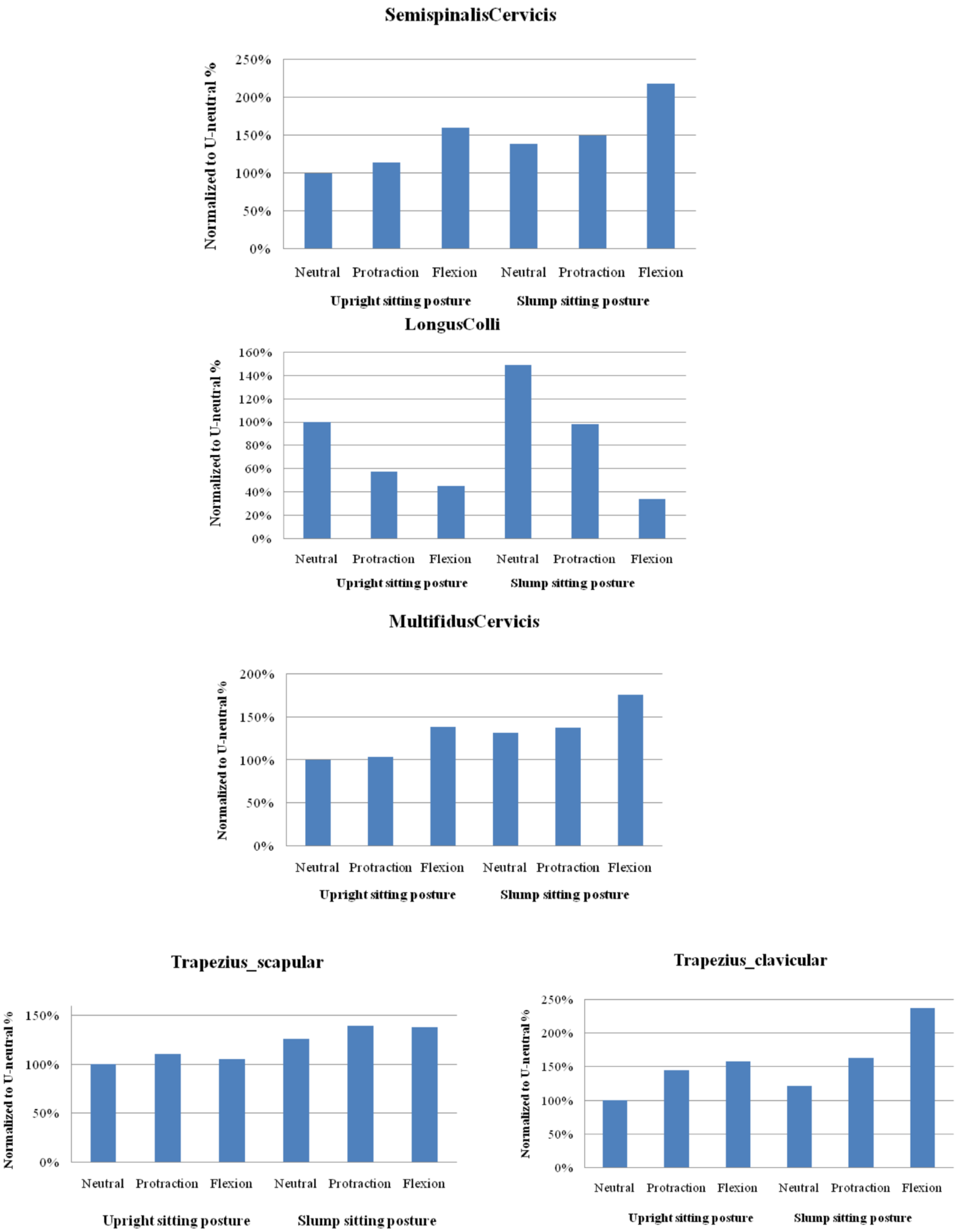

Figure 4-8. Comparison of muscle load proportion (normalized to upright sitting posture with cranio-cervical neutral position) in neutral, protraction and flexion during upright and sitting postures.

The predicted load sharing between cervical flexors and extensors are summarised in Figure 4-9. For cervical flexors, it carried approximately 9% of the load under cranio-cervical neutral position in an upright sitting. It was also greater compared with other conditions. As for cervical extensors, load carrying proportion was observed great under cranio-cervical protraction in both upright and slump sitting postures, reaching approximately 95% and 96% respectively.

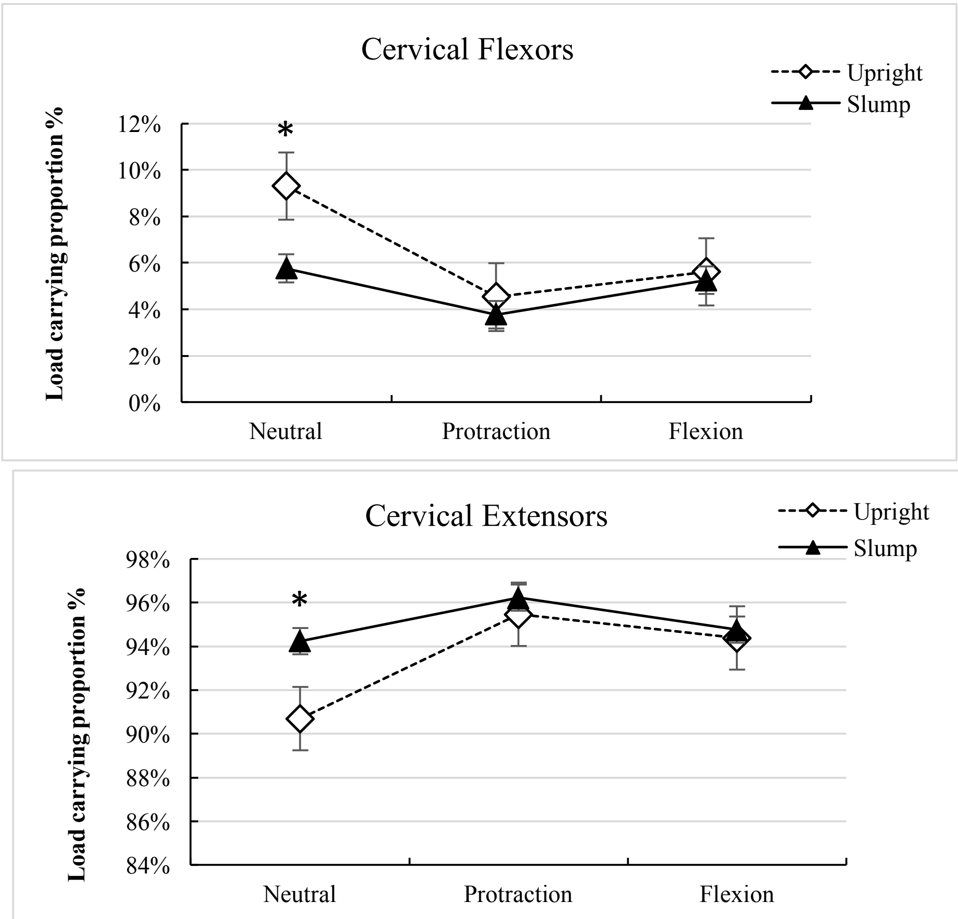

Figure 4-9. Comparison of load carrying proportion between flexors and extensors along the cervical spine in neutral, protraction and flexion during upright and sitting postures.

4.3.4 Joint reaction force

Table 4-6 presents Mean (standard error) for ANOVA main effects Sitting Posture and Cranio-cervical position. There was a significant effect of cranio-cervical positions on joint reaction force at each cervical level ($p < 0.05$). Whereas, there was no significant effect of sitting posture or interaction between sitting posture×cranio-cervical position.

Simple main effect analysis showed that cervical joint forces in cranio-cervical flexion were significantly greater than neutral or protraction position. However, there was no significant difference in joint reaction forces at each cervical level between cranio-cervical neutral and protraction positon. Although lower cervical spine carried the most load produced by different types of cranio-cervical positions, the percentage of increasement decreased from C4C5 to C7T1. For example, joint reaction forces at the level of C5C6 increased by approximately 80% from protraction to flexion, while it increased by 67% at the level of C6C7.

The maximum joint reaction forces at the level of C7T1 were 206.3N and 218.6N in cranio-cervical flexion during upright and slump sitting posture, respectively. Joint reaction forces in neutral and protraction position during slump sitting posture were slightly greater than that during upright sitting posture.

Table 4-6. Mean (standard error) joint reaction forces for ANOVA main effects Sitting Posture and Cranio-cervical position

Joint reaction forces	**Sitting Posture**			**Cranio-cervical position**			
	p value	Upright	Slump	*p* value	Neutral	Protraction	Flexion
C0C1	p =0.084	60.7(6.6)	57.5(7.0)	p =0.001	59.7(6.8)^{A}	51.0(7.7)^{A}	66.7(6.4)^{B}
C2C1	p =0.566	73.6(6.2)	71.3(7.0)	p <0.001	64.9(7.2)^{A}	57.6(7.6)^{A}	95.0(6.2)^{B}
C3C2	p =0.931	88.3(5.9)	87.7(8.0)	p =0.001	71.4(7.5)^{A}	66.0(7.5)^{A}	126.6(9.7)^{B}
C3C4	p =0.943	101.0(6.2)	101.6(9.0)	p =0.001	80.3(8.0)^{A}	75.2(7.8)^{A}	148.4(12.2)^{B}
C4C5	p =0.803	109.5(6.2)	111.8(9.3)	p =0.002	87.3(7.4)^{A}	83.8(6.8)^{A}	160.9(14.2)^{B}
C5C6	p =0.666	119.6(6.8)	123.7(9.7)	p =0.002	98.3(7.5)^{A}	94.9(6.8)^{A}	171.7(15.2)^{B}
C6C7	p =0.577	138.5(8.2)	144.2(10.6)	p =0.003	118.1(8.6)^{A}	114.5(7.7)^{A}	191.5(16.4)^{B}
C7T1	p =0.876	153.0 (28.8)	155.8 (13.6)	p =0.006	130.6(23.4)^{A}	139.5(23.8)^{A}	193.0(17.5)^{B}

Note:

Neutral: cranio-cervical neutral position

Protraction: cranio-cervical protraction position

Flexion: cranio-cervical flexion position

There was no significant difference when values were marked with the same letter or without a letter, and the ranking pattern was such that A<B.

4.4 Validation

The mean correlation coefficients between the predicted and measured muscle activities over trapezius-clavicular and cervical erector muscle during various types of cranio-cervical positions were 0.313 and 0.471 respectively. There was a fair degree of relationship between the estimated and measured muscle activity. See Table 4-7 of the correlation coefficients for each muscle and positions.

During upright or slump sitting postures, there was a good degree of relationship between predicted and measured muscle activity in cranio-cervical protraction, ranging from 0.605 to 0.729.

Table 4-7. Correlation coefficients between the normalized EMG envelopees (MVC) and the estimated muscle activities

Muscles	**Upright Sitting**			**Slump Sitting**			**Mea**
	Neutral	Protraction	Flexion	Neutral	Protraction	Flexion	
Trapezius-clavicular	0.190	0.616	-0.159	-0.499	0.605	0.401	0.31
Cervical erector	0.497	0.729	-0.770	-0.078	0.630	0.924	0.47

Note: Correlation coefficients criteria
0.0 to 0.25: little or no relationship;
0.25 to 0.50: fair degree of relationship;
0.50 to 0.75: moderate to good relationship;
>0.75: good to excellent relationship;

CHAPTER 5. DISCUSSION

This study investigated the effects of three cranio-cervical positions under two sitting postures on the cervical musculoskeletal system and provided detailed insight into head-neck posture, cervical vertebral angles and load distribution along cervical spine. Posture is a significant element for work analysis because it acts as a predictor of internal loads which is not only associated with a number of pain syndromes but relative to the development of musculoskeletal disorders. Postural deviations from the neutral zone are likely to adversely influence the efficiency of musculature and even causes musculoskeletal pathologic conditions.

5.1 Motion capture analysis: Postural angle

The primary finding was that cranio-cervical angles were significantly different among three cranio-cervical positions during upright and slump sitting postures respectively. In order to eliminate the influence of psychology factors while performing a task, posture measurement was analysed without any high-tech devices in the current study. Overall, cranial and cervical angles, as well as cranio-cervical angles in slump sitting position, were greater than those in an upright sitting. In this study, the maximum cranio-cervical angle (approximately 170 degrees) was observed in slump sitting with protraction which has been commonly adopted during computer use. In contrast, Straker et al. (2011) reported an average cranio-cervical angle of 160 degrees during computer use among adolescents. In the previous studies, differences in head and neck postures were driven by various ergonomic designs and work environment. For example, altering desk/monitor height and tilt angle (Burgess-Limerick et al., 1999, Straker et al., 2009b), adding support to several body segments (Straker et al., 2009a), and adopting different types of high-tech devices (Young et al., 2012).

Objective ways to measure posture angles are more powerful to explain the relationship between posture and several pain syndromes than subjective measurements. Objective measurements (including photography, motion capture system, accelerometer, electromagnetic tracking system and so on) provide access to evaluating various sitting postures and postural deviations in the more superior and accurate way (Marcus et al., 2002, Arvidsson et al., 2008, Straker et al., 2009b, Straker et al., 2008) compared to subjective measures such as self-report or comfort rank. Postural deviation from the neutral zone is likely to adversely affect the efficiency of musculature and even cause musculoskeletal pathologic conditions within paradoxical joint positions.

In order to eliminate the influence of different types of information devices, sitting postures were analysed without computer set in the current study. Three common head-neck movements included cranio-cervical neutral, flexion and protraction which frequently occur during computing. In comparison to previous studies of head and neck positions during computer task, cranio-cervical angles were reported greater and head and neck flexion angles were smaller during pretending computer work than for reading book and using tablet (Straker et al., 2008) as well as for desktop and laptop computing (Briggs et al., 2004, Straker et al., 2011). Therefore, postural angles are highly associated with types of information technology and usually spinal variables are different accordingly.

5.2 Musculoskeletal modeling

5.2.1 Cervical vertebral angles

Cervical spinal alignment has been widely investigated in clinical cases through lateral radiographs. Different types of angles were defined to depict cervical spinal posture including Cobb angle, projection angle, absolute rotation angle, tilt angle and spinal angle based on Euler method (Crawford et al., 1999). A great number of studies focused on segmental angles from C1 to C2 and C2 to C7, which treats lower cervical spine as a link (Forde et al., 2011, Meghdari and Bahrami, 2004, Snijders et al., 1991).

Neutral spinal alignment has been highlighted for its efficiency of muscle energy and proper load-bearing of joints and passive tissue (Wallden, 2009). Therefore, neutral spine principle as one common belief was utilized in rehabilitation programs and clinical assessment of neck pain (McGill, 2007). In another aspect, a large deviation from neutral spine position provides potential chances to the development of cervical musculoskeletal disorders. It was found that there was a positive association between cervical pain and cervical lordosis less than 20 degrees (McAviney et al., 2005). Moreover, higher neck slope angles were reported to produce greater muscle thicknesses at the layer of deep cervical flexors (Ishida et al., 2015).

Spinal postures can also be measured by scanning body skin surface or by computational modelling (Leilnahari et al., 2011, Verhaert et al., 2011, Verhaert et al., 2012). In this study, cervical spinal postures in cranio-cervical neutral, protraction and flexion during upright and slump sitting postures were predicted from the individualized musculoskeletal model. Also, in order to depict deviation of cervical vertebra from the vertical position in the sagittal plane, vertebral tilt angle at each level was utilized to present cervical spinal posture.

Slump sitting posture could produce great cervical vertebral tilt angles at all levels of the cervical spine. For example, cervical tilt angle at C4C5 level increased by 70% from upright sitting to slump sitting posture. Although the whole spinal posture could affect the cervical spinal posture, there was no statistically significant difference between protraction and flexion at the level of C7T1. It was also agreed with the study that demonstrated that protraction required flexed lower cervical spine (Morningstar, 2003). Moreover, in the current study, cervical vertebral tilt angles at a lower cervical level were found to be less responsive to positional change compared with upper cervical level, which was in agreement with the study conducted by Black et al. (1996).

5.2.2 Load-sharing of muscles along cervical spine

During upright sitting, different load-sharing of neck muscles was observed in cranio-cervical neutral, flexion and protraction positions. The calculations indicated that the force-generating capacity of the muscles in three positions was much greater in trapezius-scapular than in others (e.g. semispinalis capitis, semispinalis cervicis, longissimus cervicis and multifidus). In the neutral position, the load was distributed more evenly than the other two conditions because of more muscles taking part in the force generation. Although flexor muscles of the neck were weaker than extensors along cervical spine based on muscle force, both two muscle groups played important parts in maintaining head and neck posture. In contrast, for flexion and protraction positions, flexor muscles (lumped hodi, longus colli, and longus capitis) carried a minor portion of the load while extensors produced major forces to counterbalance the weight of the head and neck. Load carrying a proportion of trapezius-scapular in protraction was 1.5 times greater than in neutral position. Furthermore, the force-generating capacity of deep extensors muscles (semispinalis cervicis, longissimus capitis, longissimus cervicis and multifidus) in protraction was much weaker than in flexion position.

Higher load in the slumped posture was associated with significantly greater muscle force than that associated with the upright posture. Trapezius-scapular, trapezius-clavicle and multifidus cervicis were the primary load-bearing muscles among various head-neck positions during slump postures. At the cranio-cervical neutral position, deep extensor muscles were smaller and superficial muscles were greater in slump posture than in upright posture. However, at the level of flexion and protraction, the force-generating capacity of two groups of muscles increased simultaneously. Trapezius-scapular force increased by 44% in protraction and by 47% in flexion during slump compared with that during upright sitting postures. Therefore, superficial muscles were more responsive to changes in head-neck position than deep muscles. Despite this, semispinalis cervicis and multifidus contributed more to force generation with spine held in slump posture than in upright posture.

Loads on cervical spine can be measured in different ways. In term of muscle load, experimental studies were conducted to record muscle activity through electromyography (Sommerich et al., 2001, Straker et al., 2008, Edmondston et al., 2011, Nairn et al., 2013a). On the other hand, in vivo measurement of pressure in the intervertebral disc can obtain joint load with respect to a variety of spinal behaviours in daily life (Wilke et al., 1999). Another method is to calculate load moment based on static biomechanical calculations and photography (Harms-Ringdahl et al., 1986, Briggs et al., 2007, Rasmussen et al., 2009, Edmondston et al., 2011).

Protraction features the anterior translation of skull, and meanwhile extension of the upper cervical spine as well as the flexion of the lower cervical spine (Myers, 2009). This cranio-cervical position allows the paradoxical movement of the cervical spine which gives rise to different load distribution among cervical musculoskeletal system. As for upright sitting posture, muscle activity in protraction was similar to that in a neutral position. Conversely, for slump sitting posture, muscle activity in protraction varied compared with a neutral position. The main reason might lie in that the range of motion in cranio-cervical spine was limited during upright sitting posture, whereas slump posture favoured the mobility of cranio-cervical spine on a large scale. In previous studies, it was also found the increase in cervical extensor activity was relative to the decrease of thoracic extensor activity in forward head posture (Edmondston et al., 2011, Elliott et al., 2007). In this study, the contrasting patterns of muscle activity in protraction during upright and slump sitting postures provide the insight into the change of load distribution associated with spinal posture.

The results also support and help explain the clinical cases that cervical musculoskeletal disorders are common in the extensor muscle group along the cervical spine. For example, common symptoms of cervical musculoskeletal disorders involving pain, loss of joint movement and waking stiffness frequently happen in the posterior region of the neck (Levin and Neurology, 2007). Although extensor muscles are stronger than flexors, they are more likely to carry load-bearing than weak muscle group. Model results were consistent with those calculated previously by Oi et al. (2004), who found that acromial part of trapezius as an extensor contributed significantly to neck extensor strength in the lower cervical spine.

5.2.3 Load-bearing of cervical joints

A number of studies measured the joint load induced by contraction of cervical flexor and extensor muscles. The findings of this study were in accordance with those of Wilke et al. (1999) who reported that absolute pressure of intervertebral disc measured in slump posture was greater than that in an upright posture. For C7T1 load moment, results are in agreement with calculations reported by Edmondston et al. (2011) who showed the cervical load in slouched posture was greater than that in habitual posture, almost increasing by 57.2%. Additionally, there was a significant difference in joint reaction force between neutral and flexion position which was in agreement with the findings calculated by Snijders et al. (1991).

An increase incidence of cervical musculoskeletal disorders can be associated with high intrinsic forces along cervical spine, resulting from various types of postures and movements, as well as with malposition of cervical vertebrae at each level. Cervical spine supports the weight of the head, whereas the load on vertebra may increase three times weight of head acting on cervical spine (Patwardhan et al., 2000). It was estimated that critical load for the human cervical spine was approximately 10.5N in lateral bending (Panjabi et al., 1998). It was also estimated that during full flexion, compressive load approached as high as 580N at the C4-C5 level, while it was highest during extension, reaching approximately 1164N for isometric contraction (Moroney et al., 1988a). In this study, it was found that joint reaction forces at C4C5 were approximately 87.3 and 160.9 N in cranio-cervical neutral and flexion, respectively.

The human cervical spine can bear compressive loads for standing, walking, sitting and running in prolonged time. The compressive load in static condition can reach three times the weight of head caused by the effects of muscle contraction (Patwardhan et al., 2000). The joint load can be estimated through mechanical measurement of the human specimen, computational simulation and free body diagram.

Biomechanical analyses based on the computational and graphical models are invasive to the human body. Unlike lumbar spine, several studies utilized pressure sensor inserted into living body while asking subjects to perform various daily activities. Due to the complex of the cervical spine, this method was rarely used in the measurement of cervical spine load. That is because a number of nerves travel along the cervical spine from the C1 to C7, which can be dangerous to the nerve roots by inserting the sensor into the cervical vertebra.

Since the cervical vertebrae are not placed in a straight line, the cervical curvature allows the vertebral plane to intersect at each level. This determines that the compressive load can be applied in two ways in biomechanical analysis. Applying vertical compressive load on the cervical vertebra was utilized in a number of studies (Moroney et al., 1988b, Panjabi et al., 1998). In the sagittal plane, although vertical compressive load was applied on the whole cervical spine, it brought along with the backward bending moments which could lead to shear force at each level.

Furthermore, without constraints from muscles and ligaments, the specimen could undergo the large deformity even under small vertical compressive load (Patwardhan et al., 2000). To further investigate the biomechanical characteristics of spine, loading pattern changed and “follower load” was put forward to estimate pure compression on each vertebra (Patwardhan et al., 1999, Rohlmann et al., 2001). Patwardhan et al. (2000) found that cervical spine withstood a follower compressive load of 250N without breaking along tangential spine curve. Their findings highlighted the importance of follower load because it may represent the net effects of muscles attached to each vertebra rather than the ones spanned directly from the skull to the lower cervical spine.

Another important load-bearing for cervical spine is a shear force. In daily activities (e.g. flexion, extension, lateral bending and rotation), spine also undergoes shear loading in three-dimensional space in a short or long period of time (Moroney et al., 1988a). It was reported that spinal shear force ranged from 300 to 400N in light manual activities (Castelein et al., 2005).

In porcine cervical load-carrying, it was found that cervical extension resulted in 37% increase in shear stiffness compared to both neutral and flexion positions (Howarth et al., 2013). Gallagher et al. (2010) reported that anterior shear force ranged from 300N to 2700N before rupture at C4-C5. However, spinal loading pattern of porcine, sheep and calf which were widely used in previous mechanical studies was suggested to be unsuitable to represent human spine due to the difference of gravity demand on each cervical vertebra between the human body and reptile animals (Wilke et al., 2011).

In the previous studies, the lumbar musculoskeletal disorder was found to be associated with high shear forces (Skrzypiec et al., 2013). It was estimated that intervertebral discs carried two-thirds of the shear while the facet joints withstood one-third while applying load suddenly (Cyron and Hutton, 1980). On the other hand, the high shear force with high speed even could cause destructive damage when the load was applied suddenly. It was shown that facet joints might carry the entire shear force when the shear load was applied slowly in an anterior direction (White and Panjabi, 1990). However, the musculoskeletal model used in this study was fail to predict the follower load or shear force as this rigid biomechanical model simplified the vertebral geometry in term of the interface and some sophisticated structures like facet joints.

While the changes in cadaveric cervical spine associated with changes in loading pattern are well documented, the changes in living cervical spine are less clear. Especially, biomechanical characteristics of the cervical spine in daily activities are rarely investigated due to the limitation of experimental equipment. In this study, cranio-cervical positions affected joint reaction forces significantly ($p < 0.05$). The maximum joint reaction forces at the level of C7T1 were 206.3N and 218.6N in cranio-cervical flexion during upright and slump sitting posture, respectively. However, there was no significant difference in joint reaction force at each cervical level between cranio-cervical neutral and protraction positon. Sitting postures could influence the joint reaction force at each cervical level, but not significantly.

5.3 Validation of the musculoskeletal modeling

Previous studies examining muscle activity during computer task or different sitting postures used EMG measurements to compare muscle activations in various conditions. Typically, integrated rectified EMG is associated with the generation of muscle force. The timing patterns of EMG signal are often used to valid computational model in term of muscle force. In previous studies, the whole spine in slumped sitting postures induced a higher level of muscle activity in neck and shoulder regions than the posture with a neutral and relatively vertical spine (SCHÜLDT et al., 1986, Caneiro et al., 2010). Results in this study were also in general agreement with the study reported by Edmondston et al. (2011), who indicated activation of neck extensor muscles in the more protracted head position was 40% greater than in more upright postures. Additionally, the findings in deep flexor muscles agreed with those of Falla et al. (2007) who suggested that an upright neutral spinal position promoted activation of the deep cervical flexor muscles through custom electrodes measurement.

In this study, the overall correlation coefficient between the predicted and measured muscle activity over trapezius-clavicular and cervical erector muscle were 0.313 and 0.471, respectively. It demonstrated that there was a fair degree of relationship between the Model-based and EMG-based muscle activity. The highest mean correlation coefficient in cranio-cervical protraction during upright sitting was found for cervical erector muscle, reaching 0.729. However, the correlation coefficients for certain types of cranio-cervical positions were small, such as cranio-cervical flexion during upright sitting and cranio-cervical neutral during slump sitting.

In contrast, a number of studies combined kinematic assessment with surface EMG measurement. They found that flexed head could give rise to high activation in extensor muscles attached to the skull, and also in the posterior aspect of cervical muscles in conjunction with shoulder muscle group (SCHÜLDT et al., 1986, Harms-Ringdahl et al., 1986). Sedentary posture provided limited muscle activity ranging from 2% to 10%MVC in cervical extensor muscles (Mork and Westgaard, 2006, McLean, 2005, Harms-Ringdahl et al., 1986). Despite limited values, cervical extensor muscle activity responses to the load demands induced by the position of head and neck in various ways (Edmondston et al., 2011). Sustained cranio-cervical positions required cervical muscles to counterbalance the gravitational load moment, which further influencing the progress of cervical musculoskeletal disorders.

A number of studies utilized EMG measurement in conjunction with motion measurement. Some studies assessed muscle activity of specific muscles when performing various occupational tasks and simple postural maintenance. For sedentary behaviour or static task, the load was suggested to be placed on the small muscles group (Stock, 1991). However, estimation of load carrying in these small muscles is relatively difficult. Deep layer of cervical muscles were measured by inserting needle electrodes. For example, the longus colli and longissimus cervicis muscles, as well as longus colli and sternocleidomastoid. These measurements were conducted in the human body and some of them were risky or invasive to the musculoskeletal system and neural system due to the complexity of cervical spine. In this study, it was suggested that in cranio-cervical protraction, muscle activities produced by longus colli and longus capitis were approximately 0.5 and 0.6 %MVC during upright sitting while they were about 1.0 and 0.7 %MVC during slump sitting posture. Although there existed limitations in the biomechanical model, it is still a proper way to predict the muscle load which is unable to measure in the physical context.

Anterior cervical muscles are capable of movement generation while counterbalancing the external load. It was suggested that sternocleidomastoid and longus colli were not active during relaxed or habitual sitting which deviates from the neutral position (Vitti et al., 1973). However, it was not in agreement with this study which reported that muscle force produced by longus colli in slump sitting was almost the twice as much as in the upright sitting. The main reason may lie in the muscle recruitment criteria as the musculoskeletal model neglects the effects of muscles co-contraction, especially contraction in the synergy way.

For the posterior cervical muscle, it played an important part in the head movement and position maintenance. The semispinalis capitis was found to avoid head hyperextension, whereas it was inactive during upright position (Takebe et al., 1974). The finding was agreed with the result suggesting that the predicted muscle activity of semispinalis capitis was approximately 0.8 %MVC during upright sitting posture. Additionally, longissimus cervicis muscle was shown to play a vital role in extensor cervical muscle and contributed to lateral bending and rotation in a small degree (Fountain et al., 1966). In this study, longissimus cervicis muscles were found to be more active during cranio-cervial flexion compared to the neutral and protraction positions.

5.4 Limitations

This study mainly consists of experimental measurement and computational simulation. Although combining motion capture system with musculoskeletal modeling could provide further insight into the change of load distribution along cervical spine, there still exist some limitations in both postural assessment and biomechanical model used in current study.

Posture diversity was observed in this study. Since it is difficult to define the specific posture in a numerical way, cranio-cervical neutral, protraction and flexion positions were defined according to the previous study. Even upright and slump sitting postures were not given an accurate definition in both clinical and biomechanical cases. In these clinical studies, subjects were guided to perform postures by oral instruction, and it is not easy for subjects to always keep the same sitting posture. Especially, the individual has his own range of motion and different degree of the flexibility of the cervical spine. Postural deviation from the neutral position was highly different among these subjects. Although three trials were performed for each posture to minimize the variation of the same posture performing, repeatability of cranio-cervical protraction in both upright and slump sitting posture was approximately 0.7 which was not as high as that of the cranio-cervical neutral or flexion position. This type of position allows the mobility and flexibility of the cervical spine, thus, it is challenging to repeat the same cranio-cervical position to keep it stable.

Cranio-cervical positions and sitting postures utilized in this study are the commonly adopted motion during high-tech devices use. In daily life, there are numerous types of spinal postures, for example, flat (upright), long lordosis, short lordosis, habitual and slump sitting postures. Also, it applies to the cranio-cervical positions. Cranio-cervical position always changes when using different heights of tablets, computers and video screens, as well as during prolonged postural maintenance. Even tiny postural adjustment could redistribute the load- carrying among cervical musculoskeletal system, further delaying the fatigue phenomena.

Another limitation lying in the experimental study is marker protocol. Based on the Plug-in Gait marker protocol, major segments were defined such as head, neck, thorax and pelvis. However, the marker set of the cervical spine was not detailed enough to present specific trajectories of seven cervical vertebral segments. In term of number and size of markers, future study should take more small markers to identify vertebral segment compared with the current study. Therefore, it could provide access to the comprehensive understanding of the motion at each level along cervical spine. Specifically, without X-ray of cervical spine under various postural conditions, it is still not easy to verify the correct position of cervical vertebrae.

There are limitations to consider in the musculoskeletal full-body model which includes numbers of bones, joints, and muscles. Since this study mainly focused on cervical spine under various loading patents, a number of muscles along cervical spine was created according to the anatomy. Despite using the detailed neck model in AnyBody modeling system, several simplifications in this biomechanical model still cannot meet the requirement of the complexity of cranio-cervical spine. The cervical spine used in this study consists of seven rigid bodies, 1-dof universal joint, and 3-dof spherical joints from C2 to T1. These joints mainly connected the upper with the lower cervical vertebral body.

Since the full-body musculoskeletal model was utilized in the database, scaling existing modeling did not meet the requirement in term of individual geometric and morphometric characteristics. Generally, model scaling was based on the heights and weights of the different individual, but does not take the gender and age into account. However, Vasavada et al. (2008) suggested that the morphology of female cervical spine at C3-C7 level was smaller than that of the male cervical spine. This study highlighted the importance of scaling method, which is also the limitation of the software itself. As the dimension of vertebral bodies could affect the center of cervical joints as well as the insertion of muscles attached on the specific vertebrae, load distribution is likely to be underestimated under various types of loads acting on the cervical spine.

Furthermore, it is worth noting that there were no cervical intervertebral discs, ligaments, and facet joints in this biomechanical model. Neglecting of these anatomical structures are likely to directly influence the load distribution in the cervical musculoskeletal system. In previous studies, it was found that facet joints undertook approximately 20% of the load and the disc carried the major load nearly 80% (Adams et al., 2006). However, the ligaments were reported to be the primary load-carrying structure in hyper flexion (Panzer and Cronin, 2009). Different parts of the structure in cervical spine take responsibility for different motion. Therefore, another aspect of the future work will be to consider the effects of cervical intervertebral discs, a number of ligaments and several facet joints.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The cervical musculoskeletal disorder has been becoming a global health problem, but the etiology is so multifactorial that the mechanism of the development of cervical musculoskeletal disorder is still not well interpreted. Dysfunctions of physical, physiological and psychosocial conditions could give rise to this disorder, and sometimes combination of these factors may cause severe syndromes along cranio-cervical spine.

A numerous number of studies identified body posture as one external causation of the cervical musculoskeletal disorders as it could directly lead to the change of inner load distribution among cervical musculoskeletal system. Therefore, a combination method was utilized in the current study to investigate how the load was distributed along cervical spine under cranio-cervical neutral, protraction and flexion positions during two typical sitting postures.

This study presented how to utilize the motion capture system in conjunction with a biomechanical model to analyze loading distribution among cervical musculoskeletal system. Motion analysis system was used to obtain cranial angle, cervical angle and cranio-cervical angle as well as the trajectories of various body segments. The data from the experimental study were also used to drive musculoskeletal model to further calculate the cervical tilt angle, muscle load and joint load under six experimental conditions. Both of the methods are non-invasive and radiation-free technique, and thus could be applied to explore the cranio-cervical spine problems.

In the experimental study, the mean ICC value was approximately 0.9 which guarantees a good reliability. There were significant differences in head and neck angles among neutral, protraction and flexion under upright and slump sitting postures. Generally, it was concluded that postural angles in upright sitting posture were found to be smaller than that in slump sitting posture. As for the upright sitting posture, cranial angles between neutral and protraction were shown to be different, but not significantly. Cranio-cervical protraction and neutral position could produce the similar cranial angle as participants were instructed to maintain the eyesight in a horizontal line. Cervical angle in neutral position was found to be the smallest compared with flexion and protraction. Cranio-cervical angle in protraction was greater than that in neutral or flexion position.

The musculoskeletal model simulated three cranio-cervical positions under two major sitting conditions which are commonly adopted during high-tech devices use. These results showed the static behavior of cervical spine in term of the vertebral tilt angle, load-carrying of muscles and load-bearing of joints. In this study, the upper spinal tilt angle in protraction was similar to that in neutral, while the lower one was similar to that in flexion. This evidence fully explained the importance of cranio-cervical positions to cervical spinal alignment as it may affect the transfer of follower load between each of the vertebral body.

Besides the vertebral position, muscle performance was found to be a great of variety among six typical postures although posterior cervical muscles undertook a primary part of load carrying. It was also concluded that extensor muscles including trapezius and multifidus muscles played important parts in maintaining cranio-cervical positions. Moreover, cervical extensors were found to be more responsive to positional changes of head and neck than cervical flexors. Cranio-cervical flexion produced higher load at each level of the cervical joint compared with neutral and protraction positions. Validation experiment demonstrated a fair degree of relationship between measured and predicted muscle activity. This work may provide insight into understanding the mechanism of cervical musculoskeletal disorders caused by static cranio-cervical positions.

This study provided the first estimation of cervical tilt angle and load distribution in protraction position. The musculoskeletal model predicted the muscle load helping offer a clearer interpretation of the potential role of cervical extensors and flexors under various common adoptive postures. It shed light on the biomechanical characteristics of static cranio-cervical behaviors under various types of postures. This may generate benefits to the interpretation of mechanisms underlying cervical musculoskeletal disorders caused by sedentary behavior, the rehabilitation of cervical musculoskeletal disorder, as well as guideline for body building and ergonomic design.

In summary, the major findings from current study included:

1. Slump sitting posture with cranio-cervical neutral, protraction and flexion positions increased cranio-cervical angle and also increased the cervical tilt angle.
2. Cervical extensors were more responsive to positional changes of head and neck than cervical flexors.

6.2 Directions of Further Studies

On the basis of limitations in this study, there is a number of studies could be further explored in the future. Various degrees of cranio-cervical protraction and flexion could be added to analyze the postural changes of the head-neck movement. Although extreme postures are frequently observed in daily activities, continuous paradoxical postural deviation from neutral position ought to be investigated. This combined motion can be generated by cervical spine due to its complexity of mechanical structure, however, it has been rarely investigated in a variety of occupational musculoskeletal disorders.

As for motion capture of head-neck motion, the size of markers should be revised to small ones with a radius of less than 14mm. To further validate the motion of cervical vertebrae, clinical experiments including X-ray, MRI, and ultrasound should be utilized to detect the specific vertebral position and its tilt angle, which could elaborate the change of cervical alignment under different types of loading.

The biomechanical model should be improved to get ligaments, cervical intervertebral discs, and facet joints involved to further investigate the load-carrying structures rather than musculature and cervical vertebral body. Identifying the specific musculoskeletal structures can provide more insight into the mechanism of the development of cervical musculoskeletal disorders. Still in the biomechanical model, the passive and active groups of tissues did not well present.

Furthermore, optimization of resultant muscle force ought to be added another criterion as the musculoskeletal model seldom concerns the co-contraction of antagonist cervical muscles. That is why forces from some of the antagonist muscles along cervical spine were zero in this study. Although min/max criteria are used in AnyBody modeling system as optimization, it is still not enough to predict the load carrying of musculature based on the physiological condition. Therefore, during various types of movement or motion, the muscles on one side and the opposite side will be activated together to counterbalance the weight of the head, maintaining the equilibrium of the human body.

To further determine the biomechanical effects of cranio-cervical positions on the cervical musculoskeletal system, finite element model of cranio-cervical spine combined with the chest will be constructed to explore the transfer of inner force between each of the cervical vertebrae. The boundary conditions and material properties can be obtained from the musculoskeletal model. Prediction from finite element model could identify the biomechanical features of internal structures which will provide rich information on the cervical behavior in term of morphological and mechanical aspects.

A number of studies focused on the mechanical characteristics of cervical spine under compressive, shear and tensile loading, however, few of the simulation studies investigate the clinical problem of cervical spine using mathematical models (Oxland, 2015). The paradoxical motion could lead to excessive lordosis which may cause peak pressure, repetitive strains and finally develop into the disease (Filippiadis et al., 2015). For the future modeling, pressure and the distance between each of the adjacent cervical spinous processes should be investigated under various cranio-cervical positions, because these spinous processes may produce sclerosis as well as edema which are observed in imaging techniques (Giles and Singer, 1998, Levin and Neurology, 2007). Its biomechanical characteristics should be further detected as it responds to postural changes. Mathematical models should be utilized to link valuable measures to the clinical cases which may have more potential applications than calculating the mechanical features alone.

REFERENCES

ABBED, K. M. & COUMANS, J.-V. C. 2007. Cervical radiculopathy: pathophysiology, presentation, and clinical evaluation. *Neurosurgery,* 60**,** S1-28.

ADAMS, M. A., BURTON, K. & BOGDUK, N. 2006. *The biomechanics of back pain*, Elsevier Health Sciences.

ADAMS, M. A. & DOLAN, P. 2005. Spine biomechanics. *Journal of biomechanics,* 38**,** 1972-1983.

ARI NS, G., BONGERS, P., DOUWES, M., MIEDEMA, M., HOOGENDOORN, W., VAN DER WAL, G., BOUTER, L. & VAN MECHELEN, W. 2001. Are neck flexion, neck rotation, and sitting at work risk factors for neck pain? Results of a prospective cohort study. *Occupational and Environmental Medicine,* 58**,** 200-207.

ARIENS, G. A., VAN MECHELEN, W., BONGERS, P. M., BOUTER, L. M. & VAN DER WAL, G. 2000. Physical risk factors for neck pain. *Scandinavian journal of work, environment & health***,** 7-19.

ARVIDSSON, I., HANSSON, G.-Å., ERIK MATHIASSEN, S. & SKERFVING, S. 2008. Neck postures in air traffic controllers with and without neck/shoulder disorders. *Applied ergonomics,* 39**,** 255-260.

BALASUBRAMANIAM, R., RILEY, M. A. & TURVEY, M. T. 2000. Specificity of postural sway to the demands of a precision task. *Gait & Posture,* 11**,** 12-24.

BLACK, K. M., MCCLURE, P. & POLANSKY, M. 1996. The influence of different sitting positions on cervical and lumbar posture. *Spine,* 21**,** 65-70.

BRIGGS, A., STRAKER, L. & GREIG, A. 2004. Upper quadrant postural changes of school children in response to interaction with different information technologies. *Ergonomics,* 47**,** 790-819.

BRIGGS, A. M., VAN DIE N, J. H., WRIGLEY, T. V., GREIG, A. M., PHILLIPS, B., LO, S. K. & BENNELL, K. L. 2007. Thoracic kyphosis affects spinal loads and trunk muscle force. *Physical therapy,* 87**,** 595-607.

BRINK, Y. & LOUW, Q. A. 2013. A systematic review of the relationship between sitting and upper quadrant musculoskeletal pain in children and adolescents.

Manual therapy, 18**,** 281-288.

BUCKLE, P. W. & JASON DEVEREUX, J. 2002. The nature of work-related neck and upper limb musculoskeletal disorders. *Applied ergonomics,* 33**,** 207-217.

BURGESS-LIMERICK, R., PLOOY, A., FRASER, K. & ANKRUM, D. 1999. The influence of computer monitor height on head and neck posture. *International Journal of Industrial Ergonomics,* 23**,** 171-179.

CAGNIE, B., DHOOGE, F., VAN AKELEYEN, J., COOLS, A., CAMBIER, D. & DANNEELS, L. 2012. Changes in microcirculation of the trapezius muscle during a prolonged computer task. *European journal of applied physiology,* 112**,** 3305-3312.

ÇAKıT, B. D., GEN , H., ALTUNTAŞ, V. & ERDEM, H. R. 2009. Disability and related factors in patients with chronic cervical myofascial pain. *Clinical rheumatology,* 28**,** 647-654.

CAKIT, B. D., GENC, H., ALTUNTAS, V. & ERDEM, H. R. 2009. Disability and related factors in patients with chronic cervical myofascial pain. *Clin. Rheumatol.,* 28**,** 647-654.

CALLAGHAN, J. P., GREGORY, D. E. & DURKIN, J. L. 2010. Do NIRS measures relate to subjective low back discomfort during sedentary tasks? *International Journal of Industrial Ergonomics,* 40**,** 165-170.

CANEIRO, J. P., O'SULLIVAN, P., BURNETT, A., BARACH, A., O'NEIL, D., TVEIT, O. & OLAFSDOTTIR, K. 2010. The influence of different sitting postures on head/neck posture and muscle activity. *Manual Therapy,* 15**,** 54-60.

CASTANHARO, R., DUARTE, M. & MCGILL, S. 2014. Corrective sitting strategies: An examination of muscle activity and spine loading. *Journal of Electromyography and Kinesiology,* 24**,** 114-119.

CASTELEIN, R. M., VAN DIE N, J. H. & SMIT, T. H. 2005. The role of dorsal shear forces in the pathogenesis of adolescent idiopathic scoliosis–a hypothesis. *Medical hypotheses,* 65**,** 501-508.

CHAO, E. & LIM, J. 2013. Virtual Interactive Musculoskeletal System (VIMS) in orthopaedic translational research. *Journal of Orthopaedic Translation,* 1**,** 25-40.

CHIU, T. T., LEUNG, A. S. & LAM, P. 2010. Neck pain in Hong Kong: a telephone survey on consequences and health service utilization. *Spine,* 35**,** E1088-E1095.

CHO, C.-Y., HWANG, Y.-S. & CHERNG, R.-J. 2012. Musculoskeletal symptoms and associated risk factors among office workers with high workload computer use. *Journal of Manipulative and Physiological therapeutics,* 35**,** 534-540.

CHRISTOPHY, M., SENAN, N. A. F., LOTZ, J. C. & O'REILLY, O. M. 2012. A musculoskeletal model for the lumbar spine. *Biomechanics and modeling in mechanobiology,* 11**,** 19-34.

CLAUS, A. P., HIDES, J. A., MOSELEY, G. L. & HODGES, P. W. 2009. Is 'ideal'sitting posture real?: Measurement of spinal curves in four sitting postures. *Manual Therapy,* 14**,** 404-408.

CLAUSEN, J. D., GOEL, V. K., TRAYNELIS, V. C. & SCIFERT, J. 1997. Uncinate processes and Luschka joints influence the biomechanics of the cervical spine: Quantification using a finite element model of the C5 - C6 segment. *Journal of orthopaedic research,* 15**,** 342-347.

COHEN, S. P. Epidemiology, Diagnosis, and Treatment of Neck Pain. Mayo Clinic Proceedings, 2015. Elsevier, 284-299.

COOK, C., BURGESS-LIMERICK, R. & PAPALIA, S. 2004. The effect of upper extremity support on upper extremity posture and muscle activity during keyboard use. *Applied ergonomics,* 35**,** 285-292.

CRAWFORD, N. R., YAMAGUCHI, G. T. & DICKMAN, C. A. 1999. A new technique for determining 3-D joint angles: the tilt/twist method. *Clinical Biomechanics,* 14**,** 153-165.

CYRON, B. & HUTTON, W. 1980. Articular tropism and stability of the lumbar spine. *Spine,* 5**,** 168-172.

DABBS, V. & LAURETTI, W. J. 1995. A risk assessment of cervical manipulation vs. NSAIDs for the treatment of neck pain. *Journal of Manipulative and Physiological Therapeutics,* 18**,** 530-536.

DAMSGAARD, M., RASMUSSEN, J., CHRISTENSEN, S. T., SURMA, E. & DE ZEE, M. 2006. Analysis of musculoskeletal systems in the AnyBody Modeling System. *Simulation Modelling Practice and Theory,* 14**,** 1100-1111.

DANKAERTS, W., O'SULLIVAN, P., BURNETT, A. & STRAKER, L. 2006. Differences in sitting postures are associated with nonspecific chronic low back pain disorders when patients are subclassified. *Spine,* 31**,** 698-704.

DAUVILLIERS, F., BENDJELLAL, F., WEISS, M., LAVASTE, F. & TARRIERE, C. Development of a finite element model of the neck. SAE PUBLICATION P-

279. PROCEEDINGS OF THE 38TH STAPP CAR CRASH CONFERENCE, OCTOBER 31-NOVEMBER 4, 1994, FORT LAUDERDALE, FLORIDA, USA (SAE TECHNICAL PAPER 942210), 1994.

DE LAS PE AS, C. F., CAMPO, M. S., CARNERO, J. F. & PAGE, J. C. M. 2005. Manual therapies in myofascial trigger point treatment: A systematic review. *Journal of Bodywork and Movement Therapies,* 9**,** 27-34.

DEL PALOMAR, A. P., CALVO, B. & DOBLAR , M. 2008. An accurate finite element model of the cervical spine under quasi-static loading. *Journal of Biomechanics,* 41**,** 523-531.

DELLEMAN, N. J. & BERNDSEN, M. B. 2002. Touch-typing VDU operation: workstation adjustment, working posture and workers' perceptions. *Ergonomics,* 45**,** 514-535.

DEN OORD, V., MARIEKE, H., STEINMAN, Y., SLUITER, J. K. & FRINGS-DRESEN, M. H. 2012. The effect of an optimised helmet fit on neck load and neck pain during military helicopter flights. *Applied ergonomics,* 43**,** 958-964.

DOCKRELL, S., O'GRADY, E., BENNETT, K., MULLARKEY, C., MC CONNELL, R., RUDDY, R., TWOMEY, S. & FLANNERY, C. 2012. An investigation of the reliability of Rapid Upper Limb Assessment (RULA) as a method of assessment of children's computing posture. *Applied ergonomics,* 43**,** 632-636.

DUBOWSKY, S. R., RASMUSSEN, J., SISTO, S. A. & LANGRANA, N. A. 2008. Validation of a musculoskeletal model of wheelchair propulsion and its application to minimizing shoulder joint forces. *Journal of biomechanics,* 41**,** 2981-2988.

DUNK, N. M. & CALLAGHAN, J. P. 2005. Gender-based differences in postural responses to seated exposures. *Clinical biomechanics,* 20**,** 1101-1110.

DUNSTAN, D. W., HOWARD, B., HEALY, G. N. & OWEN, N. 2012. Too much sitting–a health hazard. *Diabetes research and clinical practice,* 97**,** 368-376.

DUTTON, M. 2004. *Orthopaedic examination, evaluation & intervention*, McGraw Hill Professional.

EDMONDSTON, S. J., CHAN, H. Y., CHI WING NGAI, G., WARREN, M. L. R., WILLIAMS, J. M., GLENNON, S. & NETTO, K. 2007. Postural neck pain: an investigation of habitual sitting posture, perception of 'good'posture and cervicothoracic kinaesthesia. *Manual therapy,* 12**,** 363-371.

EDMONDSTON, S. J., HENNE, S.-E., LOH, W. & ØSTVOLD, E. 2005. Influence of cranio-cervical posture on three-dimensional motion of the cervical spine. *Manual Therapy,* 10**,** 44-51.

EDMONDSTON, S. J., SHARP, M., SYMES, A., ALHABIB, N. & ALLISON, G. T. 2011. Changes in mechanical load and extensor muscle activity in the cervico-thoracic spine induced by sitting posture modification. *Ergonomics,* 54**,** 179-186.

ELCADI, G. H., FORSMAN, M., AASA, U., FAHLSTROM, M. & CRENSHAW, A. G. 2013. Shoulder and forearm oxygenation and myoelectric activity in patients with work-related muscle pain and healthy subjects. *European journal of applied physiology,* 113**,** 1103-1115.

ELLEGAST, R. P., KRAFT, K., GROENESTEIJN, L., KRAUSE, F., BERGER, H. & VINK, P. 2012. Comparison of four specific dynamic office chairs with a conventional office chair: impact upon muscle activation, physical activity and posture. *Applied ergonomics,* 43**,** 296-307.

ELLIOTT, J., JULL, G., NOTEBOOM, J., DURBRIDGE, G. & GIBBON, W. 2007. Magnetic resonance imaging study of cross‐sectional area of the cervical extensor musculature in an asymptomatic cohort. *Clinical Anatomy,* 20**,** 35-40.

ELTAYEB, S., STAAL, J. B., HASSAN, A. & DE BIE, R. A. 2009. Work related risk factors for neck, shoulder and arms complaints: a cohort study among Dutch computer office workers. *Journal of occupational rehabilitation,* 19**,** 315-322.

FALLA, D., O'LEARY, S., FAGAN, A. & JULL, G. 2007. Recruitment of the deep cervical flexor muscles during a postural-correction exercise performed in sitting. *Manual therapy,* 12**,** 139-143.

FERN NDEZ-DE-LAS-PE AS, C., HERN NDEZ-BARRERA, V., ALONSO-BLANCO, C., PALACIOS-CE A, D., CARRASCO-GARRIDO, P., JIM NEZ-S NCHEZ, S. & JIM NEZ-GARC A, R. 2011. Prevalence of neck and low back pain in community-dwelling adults in Spain: a population-based national study. *Spine,* 36**,** E213-E219.

FILIPPIADIS, D. K., MAZIOTI, A., ARGENTOS, S., ANSELMETTI, G., PAPAKONSTANTINOU, O., KELEKIS, N. & KELEKIS, A. 2015. Baastrup's disease (kissing spines syndrome): a pictorial review. *Insights into imaging,* 6**,** 123-128.

FLODGREN, G. M., CRENSHAW, A., GREF, M. & FAHLSTR M, M. 2009. Changes in interstitial noradrenaline, trapezius muscle activity and oxygen saturation during low-load work and recovery. *European journal of applied physiology,* 107, 31-42.

FLODGREN, G. M., CRENSHAW, A. G., HELLSTR M, F. & FAHLSTR M, M. 2010. Combining microdialysis and near-infrared spectroscopy for studying effects of low-load repetitive work on the intramuscular chemistry in trapezius myalgia. *BioMed Research International,* 2010.

FORDE, K. A., ALBERT, W. J., HARRISON, M. F., PATRICK NEARY, J., CROLL, J. & CALLAGHAN, J. P. 2011. Neck loads and posture exposure of helicopter pilots during simulated day and night flights. *International Journal of Industrial Ergonomics,* 41, 128-135.

FOUNTAIN, F., MINEAR, W. & ALLISON, R. 1966. Function of longus colli and longissimus cervicis muscles in man. *Archives of physical medicine and rehabilitation,* 47, 665.

GALLAGHER, K. M., HOWARTH, S. J. & CALLAGHAN, J. P. 2010. Effects of anterior shear displacement rate on the structural properties of the porcine cervical spine. *Journal of biomechanical engineering,* 132, 091004.

GENAIDY, A. M. & KARWOWSKI, W. 1993. The effects of neutral posture deviations on perceived joint discomfort ratings in sitting and standing postures. *Ergonomics,* 36, 785-792.

GERR, F., MARCUS, M., ENSOR, C., KLEINBAUM, D., COHEN, S., EDWARDS, A., GENTRY, E., ORTIZ, D. J. & MONTEILH, C. 2002. A prospective study of computer users: I. Study design and incidence of musculoskeletal symptoms and disorders. *American journal of industrial medicine,* 41, 221-235.

GILES, L. G. & SINGER, K. P. 1998. *Clinical anatomy and management of cervical spine pain*, Elsevier Health Sciences.

GILROY, A. M., MACPHERSON, B. R., ROSS, L. M., SCH NKE, M., SCHULTE, E., SCHUMACHER, U., BROMAN, J., JOSEPHSON, A., VOLL, M. & WESKER, K. 2008. *Atlas of anatomy*, Thieme Stuttgart.

GOEL, V. K. & CLAUSEN, J. D. 1998. Prediction of Load Sharing Among Spinal Components of a C5 - C6 Motion Segment Using the Finite Element Approach. *Spine,* 23, 684-691.

GOOSTREY, S., TRELEAVEN, J. & JOHNSTON, V. 2014. Evaluation of document location during computer use in terms of neck muscle activity and neck movement. *Applied ergonomics,* 45**,** 767-772.

GORDON, S. J., GRIMMER-SOMERS, K. A. & TROTT, P. H. 2010. Pillow use: the behavior of cervical stiffness, headache and scapular/arm pain. *Journal of pain research,* 3**,** 137-45.

GREENWALD, A. S. 2005. Basic Orthopaedic Biomechanics and Mechano-Biology. *The Journal of Bone & Joint Surgery,* 87**,** 2369-2370.

GROOTEN, W. J., CONRADSSON, D., ÄNG, B. O. & FRANZ N, E. 2013. Is active sitting as active as we think? *Ergonomics,* 56**,** 1304-1314.

GUZMAN, J., HALDEMAN, S., CARROLL, L. J., CARRAGEE, E. J., HURWITZ, E. L., PELOSO, P., NORDIN, M., CASSIDY, J. D., HOLM, L. W. & C T , P. 2009a. Clinical practice implications of the Bone and Joint Decade 2000–2010 Task Force on Neck Pain and Its Associated Disorders: from concepts and findings to recommendations. *Journal of manipulative and physiological therapeutics,* 32**,** S227-S243.

GUZMAN, J., HURWITZ, E. L., CARROLL, L. J., HALDEMAN, S., C T , P., CARRAGEE, E. J., PELOSO, P. M., VAN DER VELDE, G., HOLM, L. W. & HOGG-JOHNSON, S. 2009b. A new conceptual model of neck pain: linking onset, course, and care: the Bone and Joint Decade 2000–2010 Task Force on Neck Pain and Its Associated Disorders. *Journal of manipulative and physiological therapeutics,* 32**,** S17-S28.

HARMS-RINGDAHL, K. 1985. On assessment of shoulder exercise and load-elicited pain in the cervical spine. Biomechanical analysis of load--EMG--methodological studies of pain provoked by extreme position. *Scandinavian journal of rehabilitation medicine. Supplement,* 14**,** 1-40.

HARMS-RINGDAHL, K., EKHOLM, J., SCHÜLDT, K., NEMETH, G. & ARBORELIUS, U. P. 1986. Load moments and myoelectric activity when the cervical spine is held in full flexion and extension. *Ergonomics,* 29**,** 1539-1552.

HARMS-RINGDAHL, K. & SCH LDT, K. 1989. Maximum neck extension strength and relative neck muscular load in different cervical spine positions. *Clinical biomechanics,* 4**,** 17-24.

HARRISON, D. E., CAILLIET, R., HARRISON, D. D., TROYANOVICH, S. J. & HARRISON, S. O. 1999. A review of biomechanics of the central nervous system—Part II: Spinal cord strains from postural loads. *Journal of*

Manipulative and Physiological Therapeutics, 22**,** 322-332.

HOGG-JOHNSON, S., VAN DER VELDE, G., CARROLL, L. J., HOLM, L. W., CASSIDY, J. D., GUZMAN, J., C T , P., HALDEMAN, S., AMMENDOLIA, C. & CARRAGEE, E. 2008. The burden and determinants of neck pain in the general population. *European Spine Journal,* 17**,** 39-51.

HORTON, S. J., JOHNSON, G. M. & SKINNER, M. A. 2010. Changes in head and neck posture using an office chair with and without lumbar roll support. *Spine,* 35**,** E542-E548.

HOWARTH, S. J., GALLAGHER, K. M. & CALLAGHAN, J. P. 2013. Postural influence on the neutral zone of the porcine cervical spine under anterior–posterior shear load. *Medical Engineering & Physics,* 35**,** 910-918.

HOY, D., PROTANI, M., DE, R. & BUCHBINDER, R. 2010. The epidemiology of neck pain. *Best Practice & Research Clinical Rheumatology,* 24**,** 783-792.

HUDES, K. 2007. Treat Your Own Neck. *The Journal of the Canadian Chiropractic Association,* 51**,** 125.

ISHIDA, H., SUEHIRO, T., KUROZUMI, C., ONO, K., ANDO, S. & WATANABE, S. 2015. Correlation between neck slope angle and deep cervical flexor muscle thickness in healthy participants. *Journal of Bodywork and Movement Therapies,* 19**,** 717-721.

JACOBS, K., FOLEY, G., PUNNETT, L., HALL, V., GORE, R., BROWNSON, E., ANSONG, E., MARKOWITZ, J., MCKINNON, M. & STEINBERG, S. 2011. University students' notebook computer use: lessons learned using e-diaries to report musculoskeletal discomfort. *Ergonomics,* 54**,** 206-219.

JUUL-KRISTENSEN, B., HANSSON, G.-Å., FALLENTIN, N., ANDERSEN, J. & EKDAHL, C. 2001. Assessment of work postures and movements using a video-based observation method and direct technical measurements. *Applied ergonomics,* 32**,** 517-524.

KANLAYANAPHOTPORN, R., CHIRADEJNANT, A. & VACHALATHITI, R. 2009. The immediate effects of mobilization technique on pain and range of motion in patients presenting with unilateral neck pain: a randomized controlled trial. *Archives of physical medicine and rehabilitation,* 90**,** 187-192.

KARWOWSKI, W. & MARRAS, W. S. 1998. *The occupational ergonomics handbook*, Crc Press.

KINGMA, I. & VAN DIE N, J. H. 2009. Static and dynamic postural loadings during computer work in females: Sitting on an office chair versus sitting on an exercise ball. *Applied Ergonomics,* 40**,** 199-205.

KITAZAKI, S. & GRIFFIN, M. J. 1997. Resonance behaviour of the seated human body and effects of posture. *Journal of Biomechanics,* 31**,** 143-149.

L MKULL, D., HANSON, L. & ÖRTENGREN, R. 2007. The influence of virtual human model appearance on visual ergonomics posture evaluation. *Applied Ergonomics,* 38**,** 713-722.

LAPERRI RE, E., NGOMO, S., THIBAULT, M.-C. & MESSING, K. 2006. Indicators for choosing an optimal mix of major working postures. *Applied ergonomics,* 37**,** 349-357.

LAVALLEE, A. V., CHING, R. P. & NUCKLEY, D. J. 2013. Developmental biomechanics of neck musculature. *Journal of biomechanics,* 46**,** 527-534.

LEILNAHARI, K., FATOURAEE, N., KHODALOTFI, M., SADEGHEIN, M. A. & KASHANI, Y. A. 2011. Spine alignment in men during lateral sleep position: experimental study and modeling. *Biomed Eng Online,* 10**,** 103.

LEVIN, K. H. & NEUROLOGY, A. A. O. 2007. Neck and back pain.

LINDER-GANZ, E., SHABSHIN, N., ITZCHAK, Y. & GEFEN, A. 2007. Assessment of mechanical conditions in sub-dermal tissues during sitting: a combined experimental-MRI and finite element approach. *Journal of biomechanics,* 40**,** 1443-1454.

MAGNUSSON, M. & POPE, M. 1998. A review of the biomechanics and epidemiology of working postures (it isn't always vibration which is to blame!). *Journal of sound and vibration,* 215**,** 965-976.

MAJESKE, C. & BUCHANAN, C. 1984. Quantitative description of two sitting postures with and without a lumbar support pillow. *Physical therapy,* 64**,** 1531-1533.

MANCHIKANTI, L., SINGH, V., DATTA, S., COHEN, S. P. & HIRSCH, J. A. 2008. Comprehensive review of epidemiology, scope, and impact of spinal pain. *Pain physician,* 12**,** E35-70.

MANSILLA-FERRAGUT, P., FERN NDEZ-DE-LAS PE AS, C., ALBURQUERQUE-SEND N, F., CLELAND, J. A. & BOSC -GAND A, J. J. 2009. Immediate effects of atlanto-occipital joint manipulation on active mouth opening and pressure pain sensitivity in women with mechanical neck pain. *Journal of manipulative and physiological therapeutics,* 32**,** 101-106.

MARCUS, M., GERR, F., MONTEILH, C., ORTIZ, D. J., GENTRY, E., COHEN, S., EDWARDS, A., ENSOR, C. & KLEINBAUM, D. 2002. A prospective study of computer users: II. Postural risk factors for musculoskeletal symptoms and disorders. *American journal of industrial medicine,* 41**,** 236-249.

MATHIASSEN, S. E., WINKEL, J. & HAGG, G. M. 1995. Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies - A review. *Journal of Electromyography and Kinesiology,* 5**,** 197-226.

MATHYS, R. & FERGUSON, S. 2012. Simulation of the effects of different pilot helmets on neck loading during air combat. *Journal of biomechanics,* 45**,** 2362-2367.

MCAVINEY, J., SCHULZ, D., BOCK, R., HARRISON, D. E. & HOLLAND, B. 2005. Determining the relationship between cervical lordosis and neck complaints. *Journal of manipulative and physiological therapeutics,* 28**,** 187-193.

MCGILL, S., KAVCIC, N. & HARVEY, E. 2006. Sitting on a chair or an exercise ball: various perspectives to guide decision making. *Clinical Biomechanics,* 21**,** 353-360.

MCGILL, S. M. 2007. *Lumbar spine stability: mechanism of injury and restabilization*, Philadelphia: Lippincott, Williams & Wilkins.

MCKENZIE, R. 1990. *The cervical and thoracic spine: mechanical diagnosis and therapy*, Orthopedic Physical Therapy.

MCLEAN, L. 2005. The effect of postural correction on muscle activation amplitudes recorded from the cervicobrachial region. *Journal of Electromyography and Kinesiology,* 15**,** 527-535.

MEGHDARI, A. & BAHRAMI, A. 2004. A biomechanical model to analyze normal, degenerated, and fused cervical spines using IAR's concept. *IRANIAN JOURNAL OF SCIENCE AND TECHNOLOGY,* 28**,** 423-433.

MERSKEY, H. & BOGDUK, N. 1994. Classification of chronic pain, IASP Task Force on Taxonomy. *Seattle, WA: International Association for the Study of Pain Press.(Also available online at www. iasp-pain. org)*.

MORK, P. J. & WESTGAARD, R. H. 2006. Low-amplitude trapezius activity in work and leisure and the relation to shoulder and neck pain. *Journal of Applied Physiology,* 100**,** 1142-1149.

MORNINGSTAR, M. W. 2003. Cervical hyperlordosis, forward head posture, and lumbar kyphosis correction: A novel treatment for mid-thoracic pain. *Journal of*

Chiropractic Medicine, 2**,** 111-115.

MORONEY, S. P., SCHULTZ, A. B. & MILLER, J. A. 1988a. Analysis and measurement of neck loads. *Journal of Orthopaedic Research,* 6**,** 713-720.

MORONEY, S. P., SCHULTZ, A. B., MILLER, J. A. & ANDERSSON, G. B. 1988b. Load-displacement properties of lower cervical spine motion segments. *Journal of Biomechanics,* 21**,** 769-779.

MOSTAMAND, J., LOTFI, H. & SAFI, N. 2013. Evaluating the head posture of dentists with no neck pain. *Journal of bodywork and movement therapies,* 17**,** 430-433.

MOTOYOSHI, M., SHIMAZAKI, T., SUGAI, T. & NAMURA, S. 2002. Biomechanical influences of head posture on occlusion: an experimental study using finite element analysis. *The European Journal of Orthodontics,* 24**,** 319-326.

MYERS, T. W. 2009. *Anatomy trains: myofascial meridians for manual and movement therapists*, Elsevier Health Sciences.

NAIRN, B. C., AZAR, N. R. & DRAKE, J. D. 2013a. Transient pain developers show increased abdominal muscle activity during prolonged sitting. *Journal of Electromyography and Kinesiology,* 23**,** 1421-1427.

NAIRN, B. C., CHISHOLM, S. R. & DRAKE, J. D. 2013b. What is slumped sitting? A kinematic and electromyographical evaluation. *Manual therapy,* 18**,** 498-505.

NG, D., MCNEE, C., KIESER, J. & FARELLA, M. 2014. Neck and shoulder muscle activity during standardized work-related postural tasks. *Applied ergonomics,* 45**,** 556-563.

NORDIN, M., CARRAGEE, E. J., HOGG-JOHNSON, S., WEINER, S. S., HURWITZ, E. L., PELOSO, P. M., GUZMAN, J., VAN DER VELDE, G., CARROLL, L. J. & HOLM, L. W. 2009. Assessment of neck pain and its associated disorders: results of the Bone and Joint Decade 2000–2010 Task Force on Neck Pain and Its Associated Disorders. *Journal of manipulative and physiological therapeutics,* 32**,** S117-S140.

O'SULLIVAN, K., O'SULLIVAN, P., O'KEEFFE, M., O'SULLIVAN, L. & DANKAERTS, W. 2013. The effect of dynamic sitting on trunk muscle activation: A systematic review. *Applied ergonomics,* 44**,** 628-635.

O’SULLIVAN, K., MCCARTHY, R., WHITE, A., O’SULLIVAN, L. & DANKAERTS, W. 2012. Can we reduce the effort of maintaining a neutral sitting posture? A pilot study. *Manual therapy,* 17**,** 566-571.

O'SULLIVAN, P. B., DANKAERTS, W., BURNETT, A. F., FARRELL, G. T., JEFFORD, E., NAYLOR, C. S. & O'SULLIVAN, K. J. 2006. Effect of different upright sitting postures on spinal-pelvic curvature and trunk muscle activation in a pain-free population. *Spine,* 31**,** E707-E712.

OI, N., PANDY, M. G., MYERS, B. S., NIGHTINGALE, R. W. & CHANCEY, V. C. 2004. Variation of neck muscle strength along the human cervical spine. SAE Technical Paper.

ORTIZ-HERN NDEZ, L., TAMEZ-GONZ LEZ, S., MARTíNEZ-ALC NTARA, S. & M NDEZ-RAMíREZ, I. 2003. Computer use increases the risk of musculoskeletal disorders among newspaper office workers. *Archives of medical research,* 34**,** 331-342.

OSHITA, F., OMORI, K., NAKAHIRA, Y. & MIKI, K. Development of a finite element model of the human body. 7th International LS-DYNA Users Conference, 2002. 205-212.

OXLAND, T. R. 2015. Fundamental Biomechanics of the Spine-What we have learned in the past 25 years and future directions. *Journal of Biomechanics*.

PANJABI, M. M., CHOLEWICKI, J., NIBU, K., GRAUER, J., BABAT, L. B. & DVORAK, J. 1998. Critical load of the human cervical spine: an in vitro experimental study. *Clinical biomechanics,* 13**,** 11-17.

PANZER, M. B. & CRONIN, D. S. 2009. C4–C5 segment finite element model development, validation, and load-sharing investigation. *Journal of biomechanics,* 42**,** 480-490.

PATEL, K. V., GURALNIK, J. M., DANSIE, E. J. & TURK, D. C. 2013. Prevalence and impact of pain among older adults in the United States: Findings from the 2011 National Health and Aging Trends Study. *PAIN®,* 154**,** 2649-2657.

PATWARDHAN, A. G., HAVEY, R. M., GHANAYEM, A. J., DIENER, H., MEADE, K. P., DUNLAP, B. & HODGES, S. D. 2000. Load-carrying capacity of the human cervical spine in compression is increased under a follower load. *Spine,* 25**,** 1548-1554.

PATWARDHAN, A. G., HAVEY, R. M., MEADE, K. P., LEE, B. & DUNLAP, B. 1999. A Follower Load Increases the Load‐Carrying Capacity of the Lumbar Spine in Compression. *Spine,* 24**,** 1003-1009.

PORTNEY, L. G. & WATKINS, M. P. 2000. *Foundations of clinical research: applications to practice*, Prentice Hall Upper Saddle River, NJ.

PYNT, J., MACKEY, M. G. & HIGGS, J. 2008. Kyphosed seated postures: extending concepts of postural health beyond the office. *Journal of occupational rehabilitation,* 18, 35-45.

QUEK, J., PUA, Y.-H., CLARK, R. A. & BRYANT, A. L. 2013. Effects of thoracic kyphosis and forward head posture on cervical range of motion in older adults. *Manual therapy,* 18, 65-71.

RADWIN, R. G., MARRAS, W. S. & LAVENDER, S. A. 2001. Biomechanical aspects of work-related musculoskeletal disorders. *Theoretical Issues in Ergonomics Science,* 2, 153-217.

RASMUSSEN, J., T RHOLM, S. & DE ZEE, M. 2009. Computational analysis of the influence of seat pan inclination and friction on muscle activity and spinal joint forces. *International Journal of Industrial Ergonomics,* 39, 52-57.

RICCIARDI, A. 2015. Thieme Atlas of Anatomy: General Anatomy and Musculoskeletal System. *The Yale journal of biology and medicine,* 88, 100.

ROHLMANN, A., NELLER, S., CLAES, L., BERGMANN, G. & WILKE, H.-J. 2001. Influence of a follower load on intradiscal pressure and intersegmental rotation of the lumbar spine. *Spine,* 26, E557-E561.

SCHIEPPATI, M., NARDONE, A. & SCHMID, M. 2003. Neck muscle fatigue affects postural control in man. *Neuroscience,* 121, 277-285.

SCHÜLDT, K., EKHOLM, J., HARMS-RINGDAHL, K., NÉMETH, G. & ARBORELIUS, U. P. 1986. Effects of changes in sitting work posture on static neck and shoulder muscle activity. *Ergonomics,* 29, 1525-1537.

SETH, A., SHERMAN, M., REINBOLT, J. A. & DELP, S. L. 2011. OpenSim: a musculoskeletal modeling and simulation framework for< i> in silico</i> investigations and exchange. *Procedia IUTAM,* 2, 212-232.

SJ GAARD, G., ROSENDAL, L., KRISTIANSEN, J., BLANGSTED, A. K., SKOTTE, J., LARSSON, B., GERDLE, B., SALTIN, B. & S GAARD, K. 2010. Muscle oxygenation and glycolysis in females with trapezius myalgia during stress and repetitive work using microdialysis and NIRS. *European journal of applied physiology,* 108, 657-669.

SKRZYPIEC, D. M., BISHOP, N. E., KLEIN, A., P SCHEL, K., MORLOCK, M. M. & HUBER, G. 2013. Estimation of shear load sharing in moderately degenerated human lumbar spine. *Journal of biomechanics,* 46, 651-657.

SNIJDERS, C. J., HOEK VAN DIJKE, G. & ROOSCH, E. 1991. A biomechanical model for the analysis of the cervical spine in static postures. *Journal of biomechanics,* 24, 783-792.

SOMMERICH, C. M., JOINES, S. M. & PSIHOGIOS, J. P. 2001. Effects of computer monitor viewing angle and related factors on strain, performance, and preference outcomes. *Human Factors: The Journal of the Human Factors and Ergonomics Society,* 43, 39-55.

STENLUND, T. C., ÖHBERG, F., LUNDSTR M, R., LINDROOS, O., H GER, C. & REHN, B. 2014. Inter- and intra-tester reliability when measuring seated spinal postures with inertial sensors. *International Journal of Industrial Ergonomics,* 44, 732-738.

STOCK, S. R. 1991. Workplace ergonomic factors and the development of musculoskeletal disorders of the neck and upper limbs: A meta‐analysis. *American journal of industrial medicine,* 19, 87-107.

STRAKER, L., BURGESS-LIMERICK, R., POLLOCK, C., COLEMAN, J., SKOSS, R. & MASLEN, B. 2008. Children's posture and muscle activity at different computer display heights and during paper information technology use. *Human Factors: The Journal of the Human Factors and Ergonomics Society,* 50, 49-61.

STRAKER, L., BURGESS-LIMERICK, R., POLLOCK, C. & MASLEN, B. 2009a. The effect of forearm support on children’s head, neck and upper limb posture and muscle activity during computer use. *Journal of Electromyography and Kinesiology,* 19, 965-974.

STRAKER, L., BURGESS-LIMERICK, R., POLLOCK, C. & MASLEN, B. 2009b. The influence of desk and display design on posture and muscle activity variability whilst performing information technology tasks. *Applied Ergonomics,* 40, 852-859.

STRAKER, L., SKOSS, R., BURNETT, A. & BURGESS-LIMERICK, R. 2009c. Effect of visual display height on modelled upper and lower cervical gravitational moment, muscle capacity and relative strain. *Ergonomics,* 52, 204-221.

STRAKER, L. M., SMITH, A. J., BEAR, N., O'SULLIVAN, P. B. & DE KLERK, N. H. 2011. Neck/shoulder pain, habitual spinal posture and computer use in adolescents: the importance of gender. *Ergonomics,* 54**,** 539-546.

STRIMPAKOS, N., GEORGIOS, G., ELENI, K., VASILIOS, K. & JACQUELINE, O. 2005. Issues in relation to the repeatability of and correlation between EMG and Borg scale assessments of neck muscle fatigue. *Journal of Electromyography and Kinesiology,* 15**,** 452-465.

STRINE, T. W. & HOOTMAN, J. M. 2007. US national prevalence and correlates of low back and neck pain among adults. *Arthritis Care & Research,* 57**,** 656-665.

SWARTZ, E. E., FLOYD, R. & CENDOMA, M. 2005. Cervical spine functional anatomy and the biomechanics of injury due to compressive loading. *Journal of athletic training,* 40**,** 155.

TAKEBE, K., VITTI, M. & BASMAJIAN, J. V. 1974. The functions of semispinalis capitis and splenius capitis muscles: an electromyographic study. *The Anatomical Record,* 179**,** 477-480.

TIERNEY, R. T., SITLER, M. R., SWANIK, C. B., SWANIK, K. A., HIGGINS, M. & TORG, J. 2005. Gender differences in head-neck segment dynamic stabilization during head acceleration. *Med Sci Sports Exerc,* 37**,** 272-279.

TISSOT, F., MESSING, K. & STOCK, S. 2009. Studying the relationship between low back pain and working postures among those who stand and those who sit most of the working day. *Ergonomics,* 52**,** 1402-1418.

VAN NIEKERK, S.-M., LOUW, Q., VAUGHAN, C., GRIMMER-SOMERS, K. & SCHREVE, K. 2008. Photographic measurement of upper-body sitting posture of high school students: A reliability and validity study. *BMC musculoskeletal disorders,* 9**,** 113.

VASAVADA, A. N., DANARAJ, J. & SIEGMUND, G. P. 2008. Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of biomechanics,* 41**,** 114-121.

VASSELJEN JR, O. & WESTGAARD, R. 1997. Arm and trunk posture during work in relation to shoulder and neck pain and trapezius activity. *Clinical Biomechanics,* 12**,** 22-31.

VERHAERT, V., DRUYTS, H., VAN DEUN, D., EXADAKTYLOS, V., VERBRAECKEN, J., VANDEKERCKHOVE, M., HAEX, B. & VANDER SLOTEN, J. 2012. Estimating spine shape in lateral sleep positions using silhouette-derived body shape models. *International Journal of Industrial Ergonomics,* 42**,** 489-498.

VERHAERT, V., HAEX, B., WILDE, T. D., BERCKMANS, D., VERBRAECKEN, J., VALCK, E. D. & SLOTEN, J. V. 2011. Ergonomics in bed design: the effect of spinal alignment on sleep parameters. *Ergonomics,* 54**,** 169-178.

VILLANUEVA, M. B. G., JONAI, H., SOTOYAMA, M., HISANAGA, N., TAKEUCHI, Y. & SAITO, S. 1997. Sitting posture and neck and shoulder muscle activities at different screen height settings of the visual display terminal. *Industrial Health,* 35**,** 330-336.

VITTI, M., FUJIWARA, M., BASMAJIAN, J. V. & IIDA, M. 1973. The integrated roles of longus colli and sternocleidomastoid muscles: an electromyographic study. *The Anatomical Record,* 177**,** 471-484.

WALLDEN, M. 2009. The neutral spine principle. *Journal of bodywork and movement therapies,* 13**,** 350-361.

WALMSLEY, R. P., KIMBER, P. & CULHAM, E. 1996. The effect of initial head position on active cervical axial rotation range of motion in two age populations. *Spine,* 21**,** 2435-2442.

WEBB, R., BRAMMAH, T., LUNT, M., URWIN, M., ALLISON, T. & SYMMONS, D. 2003. Prevalence and predictors of intense, chronic, and disabling neck and back pain in the UK general population. *Spine,* 28**,** 1195-1202.

WHITE, A. & ERNST, E. 1999. A systematic review of randomized controlled trials of acupuncture for neck pain. *Rheumatology,* 38**,** 143-147.

WHITE, A. A. & PANJABI, M. M. 1990. *Clinical biomechanics of the spine*, Lippincott Philadelphia.

WIDANARKO, B., LEGG, S., STEVENSON, M., DEVEREUX, J., ENG, A., MANNETJE, A. T., CHENG, S., DOUWES, J., ELLISON-LOSCHMANN, L. & MCLEAN, D. 2011. Prevalence of musculoskeletal symptoms in relation to gender, age, and occupational/industrial group. *International Journal of Industrial Ergonomics,* 41**,** 561-572.

WILKE, H.-J., GEPPERT, J. & KIENLE, A. 2011. Biomechanical in vitro evaluation of the complete porcine spine in comparison with data of the human spine. *European Spine Journal,* 20**,** 1859-1868.

WILKE, H. J., NEEF, P., CAIMI, M., HOOGLAND, T. & CLAES, L. E. 1999. New in vivo measurements of pressures in the intervertebral disc in daily life. *Spine,* 24**,** 755-762.

WINKEL, J. & WESTGAARD, R. H. 1996. Editorial: A model for solving work related musculoskeletal problems in a profitable way. *Applied Ergonomics,* 27**,** 71-77.

WINTER, D. A. 2009. *Biomechanics and motor control of human movement*, John Wiley & Sons.

YANG, Z., SUN, S. & CHEN, G. Evaluating sitting comfort with questionnaire and body pressure distribution: Overview and design. Computer-Aided Industrial Design & Conceptual Design, 2009. CAID & CD 2009. IEEE 10th International Conference on, 2009. IEEE, 1443-1447.

YOGANANDAN, N., KUMARESAN, S. & PINTAR, F. A. 2001. Biomechanics of the cervical spine Part 2. Cervical spine soft tissue responses and biomechanical modeling. *Clinical Biomechanics,* 16**,** 1-27.

YOUNG, J. G., TRUDEAU, M., ODELL, D., MARINELLI, K. & DENNERLEIN, J. T. 2012. Touch-screen tablet user configurations and case-supported tilt affect head and neck flexion angles. *Work: A Journal of Prevention, Assessment and Rehabilitation,* 41**,** 81-91.