The Relationship Between Previous Concussion and Cervical Spine Characteristics in Competitive Athletes

By

Audrey Claire Bentley

Bachelor of Science in Athletic Training, Michigan State University, 2016

Submitted to the Graduate Faculty of

University of Pittsburgh

School of Health and Rehabilitation Sciences

of the requirements for the degree of

Master of Sports Medicine

University of Pittsburgh

2019

UNIVERSITY OF PITTSBURGH

School of Health and Rehabilitation Sciences

This thesis was presented

by

Audrey Claire Bentley

It was defended on

May 1, 2019

and approved by

Erica Beidler, Assistant Professor, Department of Athletic Training

Mary Murray, Co-Director and Assistant Professor, Department of Sports Medicine and Nutrition

Mita Lovalekar, Associate Professor, Department of Sports Medicine and Nutrition
Karthik Hariharan, Instructor, Department of Physical Therapy

Thesis Advisor: Katelyn Allison, Co-Director and Assistant Professor, Department of Sports Medicine and Nutrition

The Relationship Between Previous Concussion and Cervical Spine Characteristics in Competitive Athletes

Audrey Claire Bentley

University of Pittsburgh, 2019

The relationship between cranio-cervical junction (CCJ) characteristics and concussion are poorly understood. Clinicians have established reliable clinical procedures to examine neck endurance, strength, and to detect hypermobility. This cross-sectional study aims to investigate cervical spine characteristics in competitive athletes with and without history of concussion.

Male NCAA soccer and wrestling athletes participated in the study. Clinical evaluations for cervical segmental mobility, neck circumference, proprioception, and deep neck flexor endurance were completed during the 2018-2019 season. Data was tested for normality using be Shapiro-Wilk test. Descriptive statistics (mean, standard deviation, median) were calculated for all variables for athletes with and without history of concussion, and then stratified by sport. Neck muscle performance was compared between athletes with or without history of concussion using an independent sample t-test or Wilcoxon Rank Sum Test for continuous variables as appropriate. Fisher's exact test was used for all categorical variables. Statistical analysis was conducted using SPSS version 24. Statistical significance was set a priori at alpha = 0.05, two-sided.

Neck circumference was significantly greater in the non-concussed group (p=0.004). Percentage of passing head repositioning trials in right rotation was significantly greater for the non-concussed group (p=0.043). No other significant group differences were demonstrated.

This study was one of the first to examine previous concussion history and cervical spine characteristics. Minimal between-group differences in cervical characteristics were demonstrated between concussed versus non-concussed groups. Clinicians should further examine craniocervical junction characteristics in a concussed population and consider the relationship between cervical proprioception with this subgroup. Neck circumference should be assessed during different components of training and competition. Future studies should include a larger sample size, prospectively assess cervical characteristics as risk factors for concussion, and implement more quantitative measures to improve sensitivity of results. This study provides future insight to clinicians seeking to identify any deficits in cervical function and cervicogenic symptoms due to cervical injury after a head-neck segment pathomechanical event.

Table of Contents

List of Tables

List of Figures

1.0 Introduction

Concussion or a mild traumatic brain injury is quite prevalent in the athletic population and occurs when linear and/or rotational forces are applied to the brain causing a neurometabolic cascade. (Harmon KG 2018) The Center for Disease Control reveals that concussions contribute to 282,000 hospitalizations and 2.5 million emergency department visits per year. Approximately 1.6 to 3.8 million sports related concussions occur annually and account for 5-9% of all sport injuries. (Langlois JA 2006, Gessel LM 2007, Harmon KG 2018, Fakhran August 2016)

Clinicians have access to a variety of concussion assessment tools, but protocols are inconsistent between clinical practices. There is an absence of a gold standard for diagnostic measures due to the heterogeneity of sport-related concussions (SRC).(Pardini J 2004, Gessel LM 2007, Collins, Kontos et al. 2016) Sideline assessment of concussion may reveal multiple concerns with each individual displaying symptoms at various periods of time, delayed or immediate. Acute signs and symptoms of concussion involve a wide range of characteristics that indicate an evolving injury; physical signs, neck pain, headache, cognitive, oculomotor, and vestibular impairments, neurobehavioral features, and sleep disturbances may develop in a temporal sequence.(McCrory P November 2012) The long term consequences of concussion are difficult to ascertain and the pathology of post concussive symptom frequency and severity is yet to be fully understood.

Researchers have developed a targeted and comprehensive approach to the clinical practices post-concussion for an athletic population.(Collins M 2014) Post concussive clinical trajectories have been established and include: cognitive/fatigue, vestibular, ocular motor, post-traumatic migraine, anxiety/mood, and cervical trajectories.(Collins M 2014) The cervical trajectory is growing increasingly more relevant in the sports medicine realm, presenting with a cervicogenic pathology and/or headache component. (Broglio S 2014, Collins M 2014, Cheever, Kawata et al. 2016, Collins, Kontos et al. 2016) Cervicogenic headaches are caused by disruptions in the cervical spine that incorporate perceived pain in the head. Research is warranted within this area of study in result of limited empirical data on the assessment, treatment, and prevention of cervicogenic pathologies amongst the concussed population.

Concussive blows effecting the cervical region can result in a neck injury. Cervical spine injuries complicate the care of approximately 4% of individuals admitted to the hospital across the United States.(Cheever, Kawata et al. 2016) Early diagnosis of cervical spine injuries is imperative as delayed or missed diagnoses result in increased morbidity and mortality. In recent years, the topic of sport related head and neck injuries, such as concussion, have been gaining momentum within sports medicine. The effectiveness of current evaluations and treatment management should be evaluated. Given that injury to the cranio-cervical junction (CCJ) may lead to prolonged or chronic symptoms post trauma, the role of CCJ pathology is gaining greater recognition in the initial management of common injuries such as concussion and whiplash.(Mathers SK) (Heikkila and Wenngren 1998) (Pho C 2018) Individuals who have sustained closed head trauma and concussion from sports related injuries may also be suffering from a concurrent – but latent - cervical spine injury. Cervical spine dysfunction may cause symptoms of occipital pain and cervicogenic headache that confound the clinical diagnosis and recovery.(Cheever, Kawata et al. 2016) (Jull GA 2008)

This study seeks to gather normative data on neck muscle performance within a competitive athlete population and to investigate these characteristics in athletes with or without a history of concussion. Furthermore, this study aims to add to the body of literature examining the relationship between deep neck flexor performance and active sport participation following closed head trauma.

1.1 Concussions Within an Athletic Population

A sports related concussion is defined as a traumatic brain injury within an athletic setting that is induced by biomechanical forces caused by a direct blow to the cervical or cephalic region.(McCrory P 2017 Jun; 51) Approximately 3,000,000 concussions occur annually within the United States alone. (Gessel LM 2007) The NCAA surveillance report on concussion reveals that 10,500 collegiate athletes suffered a concussion within the past five years. Concussion reports are vastly growing as there is an increase in recognition, education, and overreporting of sport concussion in all settings.(Graham 2015) High loads of external player-to-player contact resulted in concussion and an estimated 32% of those athletes were football players.(Harmon KG 2018) It was also concluded that athletes participating in specific sports, positions, and athletic playing styles are more at risk for concussion.(Harmon KG 2018)

1.1.1 Concussion Assessment and Management

The diagnoses and management of sport related concussion are complex in nature. Certified athletic trainers (AT) are required to follow strict protocols and guidelines for the concussed athlete. Detailed concussion reports are to be recorded and safely kept in an electronic health record. There are many reliable and valid clinical measurement tools for the concussed athlete.

Cognitive evaluation, visual and vestibular testing, motor control assessments, cervicogenic evaluation and palpations, self-reported symptom questionnaires, balance, and postural assessments are all used in conjunction as diagnostic measures to determine concussion symptomatology and deficits. (Graham 2015) Testing measures that can be commonly seen in an athletic setting are: The Balance Error Scoring System (BESS), Vestibular Ocular Motor Screen (VOMS), Immediate Post Concussion Assessment and Cognitive Testing (imPACT) testing, and the King-Devick test. A detailed multimodal clinical evaluation is key to determining deficits post-concussion and allows clinicians to target and treat specific symptoms to achieve good health status.

Self-reported questionnaires have a common theme of signs and symptoms that may be indicated at baseline and post concussive events, but many lack construct validity and a systematic process. Clinicians must be aware of limitations of each self-report assessment. The Post-Concussion Scale of Signs and Symptom checklist has demonstrated face and content validity(McLeod 2012) and includes: headache, nausea, vomiting, balance problems, confusion, loss of consciousness, personality change, amnesia, dizziness, blurry or double vision, sensitivity to light, sensitivity to noise, pain other than headache, fogginess, feeling slowed down, difficult concentrating, difficulty remembering, trouble falling asleep, fatigue, drowsiness, increased emotions, irritability, sadness, and nervousness. These symptoms are then determined in severity; none, mild, moderate, to severe.(Prevention) In athletic settings, an individual who experiences one or more of these signs or symptoms post-concussion are then referred to a qualified health professional in concussion management.

Sideline assessments of concussion may present multiple concerns to a clinician and each concussed individual may display symptoms at various time periods, delayed. Ten to 20% of individuals with sports related concussion report prolonged concussion symptoms. Clinicians classify these symptoms as post-concussion syndrome (PCS). (Dunkley, Da Costa et al. 2015, Makdissi, Schneider et al. 2017) In most cases, concussion symptoms resolve within 1-2 weeks post-concussion, but each case is subjectively different. PCS elicits a range of symptoms specific to the concussed individual due to brain system dysfunctions and or pre-existing injuries or conditions.(Makdissi, Schneider et al. 2017) Additionally, PCS symptoms may persist well beyond the acute stage of recovery, lasting weeks to months or up to a year, depending on the severity and characteristics of the individual. (Graham 2015)

A subset of individuals may present with a cervicogenic component and exhibit positive indications for further evaluation of the cervical spine. Neck pain and headaches increase in severity and at times vestibular, ocular, or other clinical subsets of concussion may not be present with this subgroup. (Collins M 2014) Upon evaluation, it is important to clarify the type of headache the athlete is experiencing, whether it is dull, throbbing, numbness/tingling, or pressure, as well as identifying the area of irritation (frontal, temporal, occipital, or neck region).(Collins M 2014) Cervical strength, segmental motion, ligamentous and musculature integrity, flexibility, and circumference are ideal areas be assessed. (Broglio S 2014, Harmon KG 2018)

Few clinical assessments are known to differentiate concussions from cervical spine pathologies. A review of clinical test utility in the diagnosis and identification of origin of symptoms for concussion testing found limited clinical tests that showed criterion validity along with advantages and disadvantages.(Cheever, Kawata et al. 2016) Cheever et. al(Cheever, Kawata et al. 2016) identified that the cervical joint-repositioning error test (JRE) and the smooth-pursuit neck-torsion test (SPNTT) showed more than 90% criterion validity for cervical dizziness. However, the JRE requires proper equipment to consistently replicate trials. In patients who are concussed or sustained a whiplash injury, they are unable to carry through the smooth pursuit, therefore establishing a motor control, vestibular, or cervicogenic impairment. With limited clinical tests for differentiating between cervical injury and concussion, there needs to be a call for further research.

1.2 Concussion & the Craniocervical Junction

Concussions may exhibit a wide range of symptomology including, but not limited to, loss of conscious, retro and anterograde amnesia, drowsiness, headaches, cognition issues, and/or unusual emotional behaviors. (Covassin, Savage et al. 2017) Post-traumatic headaches are highly prevalent in post-concussive patients. These patients have a variety of headaches involving vestibular and/or cervicogenic systems.(Defrin 2014) Cervicogenic headaches tend to be aggravated by neck movements or postural movement and begin at the neck to the anterior region of the head. Interestingly, in a case study of patients with PCS and neck pain, symptoms resolved after vestibular and cervical spine rehabilitation. The study concluded that spinal therapy coupled with vestibular therapy was the most advantageous for return to play. (Heikkila and Wenngren 1998) In post-concussion syndrome, these symptoms may appear and not resolve for weeks to months, causing delayed return to play status for athletes.(J.J. Leddy 2016)

Cervical spine injuries, in many cases, present with very similar symptomologies to concussion suggesting possible links. In fact, the CCJ and elements of the cervical spine play an influential role on concussion prevention and could possibly be an important component in rehabilitation programs. When a concussion is sustained, rapid head displacement followed by neck deformation is coupled together. It has recently been acknowledged that increased neck strength reduces the risk of concussion by decreasing head acceleration, change in velocity, peak rotational velocity, and displacement of the CCJ.(Viano 2007, Jin X and Viano D 2017) Comparatively, weakness of the neck musculature specifically the deep neck flexors and decreased neck circumference has been found to put an athlete at greater risk for concussion.(Collins, Fletcher et al. 2014) Atrophied suboccipital musculature, specifically the rectus capitis, is associated with greater cervicogenic pain post-concussion.(Fakhran August 2016) It is evident that neck musculature has an influential factor on the nature of concussion. Research is warranted to investigate the relationship between deep neck flexor strength and endurance with patients who are at risk or who have a history of concussion. This relationship could be the first step before assessing the relationship with severity of concussion.

1.2.1 Craniocervical Junction Anatomy

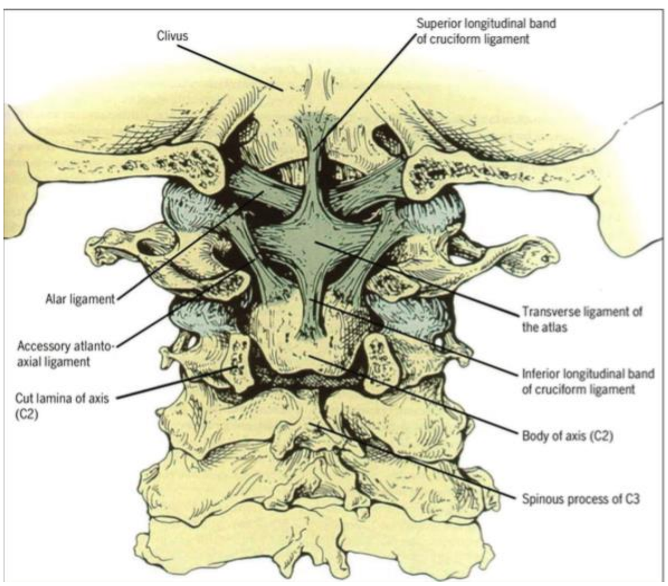

Figure 1. Posterior view of the upper cervical region (Cramer 2005)

To understand the pathokinesiology of the cervical spine, it is useful to visualize the functional anatomy of the cervical region. The cervical spine houses the spinal cord and is composed of seven skeletal vertebrae, C1-C7, segmented by fibrous intervertebral discs. To simplify this region, the vertebral column will be described as two divisions: the upper and lower regions. By separating these segments, the upper region consists of C1-C2 and the lower C3-C7. They provide architectural mobility and stability for the craniocervical junction (CCJ) connecting to the cranium and extending to the thoracic vertebrae.(Lopez, Scheer et al. 2015) Ultimately, the cervical spine allows for protections of the spinal cord and its vital neurovascular structures. The segmental vertebrae increase in size towards the thoracic spine having coupled movements to withstand various loads. (Lopez, Scheer et al. 2015)

The upper C1-C2 region, or the CCJ, is a crucial craniospinal region for the connection of osseous structures, their articulated synovial joints, ligaments, and musculature. Importantly, the CCJ connects the vascular and cerebrospinal fluid systems in the cranial region to the spinal canal. The two major joints within the CCJ are the atlanto-occipital joint and the atlantoaxial joint.(Schmidt JD and Blackburn JT 2014, Lopez, Scheer et al. 2015, Bogduk N Novermber 2000) Accessory atlantoaxial ligaments, particularly the alar ligament, and the tectorial membrane are also important passive restraints.(Mathers SK) Osseous structures in the CCJ such as the occiput, the atlas, and the axis are key to the cervical range of motion. The occipital condyles articulate with the atlas (C1) to allow for cranial flexion and extension. (Swartz, Floyd et al. 2005, Lopez, Scheer et al. 2015) The atlas articulates with the odontoid process by the transverse ligament and sits superiorly on the axis (C2). The apical, alar, and transverse (portion of the cruciform ligament) ligaments work as static stabilizers and prevent displacement posteriorly. This articulation provides cranial rotation and the musculature surrounding the CCJ permits proprioception and stability.(Schmidt J and Blackburn J 2014) (WF 1980, Martin, Bruner et al. 2010, Lopez, Scheer et al. 2015) Inferior to the axis sits the lower region of the five cervical vertebral segments, C3-C7.

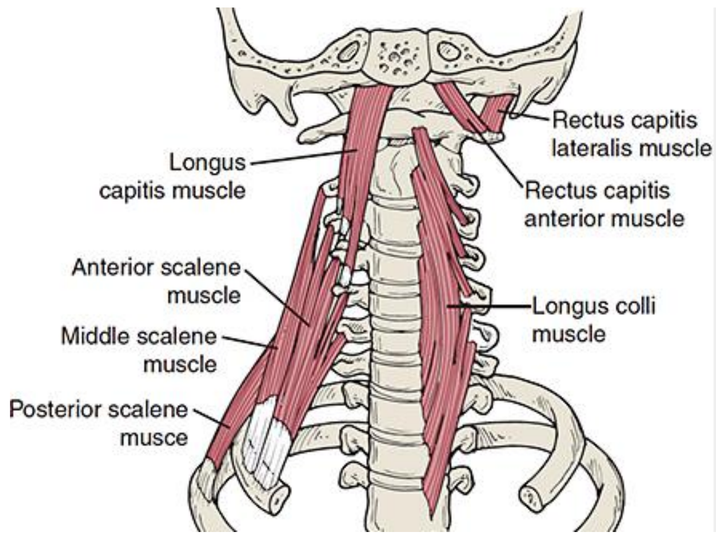

Figure 2. Dynamic Stabilizers of the Cervical Region (Kisner 2018)

The major spinal segmental dynamic stabilizers, known as the longus capitis and coli (Figure 2.), are innervated at C3- C6 and C3- T3 insert into the occiput and the anterior arch of the atlas. (CR 2015) These deep neck flexors are located on the anterior surface of the cervical spine and lay deep to the superficial flexors, the sternocleidomastoid and the anterior scalene. The longus capitis is responsible for flexion of the head and cervical vertebrae when functioning bilaterally. Unilaterally, the longus capitis is responsible for coupled cervical and cranial rotation and lateral flexion. (CR 2015) (Jull GA 2008) The longus coli allows for craniocervical flexion, ipsilateral side flexion and limited cervical rotation. (Jull GA 2008, CR 2015) Additional deep neck flexors such as the rectus capitis posterior minor and major, obliquus capitis superior and inferior, semispinalis capitis, and splenius capitis maintain cervical lordosis and stability. (al. 2011, O'leary

S May 2009) Research suggests that the deep neck flexor group should be evaluated during a clinical assessment of mechanical dysfunction or neck pain, particularly in a whiplash mechanism. (Barton PM 1996, Jull GA 2008) Imbalances in these deep neck flexors may result in postural deformities, mechanical instability, and/or injury. Empirical evidence also suggests that an imbalance of deep cervical flexion, along with neck pain, can present a delay in proprioception and segmental motor control with susceptibility to future injury.

Cervical musculature is responsible for 80% of mechanical loads applied to the cervical spine. (Mihalik JP 2011) Studies have hypothesized that cervical strength is a preventative measure for concussion risk and may lower severity of head and neck trauma. (Mihalik JP 2011, Schmidt J and Blackburn J 2014) Athletes who have reduced muscle strength are thought to have a deficiency in preparatory and reactive forces that are important to counteract head acceleration, thus leading to future research questions.(Schmidt J and Blackburn J 2014)

1.2.2 Biomechanics of the Craniocervical Junction

Motion of the cervical spine requires complementary segmental motion from the multiplane vertebrae. (Van Mameren, Drukker et al. 1990) Normative ranges of motion for the cervical spine are 80 to 90 degrees of flexion, 70 degrees of extension, 20 to 45 degrees of later flexion, and 90 degree of rotation bilaterally. (WF 1980) The altanto-occipital region (C0-1) ranges from 15-20 degrees of flexion and lateral flexion in the sagittal and frontal planes. (Mathers SK , WF 1980) Additionally, the atlanto-axial region has a rotational component of up to 50 degrees.(WF 1980, Bogduk N Novermber 2000) The restricted mobility of the atlanto-axial region is attributed to the transverse, alar, and apical ligaments, which are imperative to the stability of structures. (Swartz, Floyd et al. 2005) Dynamic movement of C1 on C2 provide unique displacement compared their inferior segments. During flexion, the articular surface of the atlas anteriorly rolls and posteriorly glides. Extension provides the opposite motion of rolling posteriorly and gliding anteriorly. The dens are static in rotational movement and the atlas rotates toward the side of rotation. During rotation, the alar ligament is stretched and the contralateral longus capitits, longus coli, anterior scalenes and ipsilateral sternocleidomastoid are also stretched. (Mathers SK , Osmotherly PG 2013) Accessory atlantoaxial ligaments and the tectorial membrane are important passive restraints that should be identified. (Mathers SK) The transverse and alar ligament (Figure 3.), specifically, play critical roles in excessive rotation and lateral flexion restriction. (Mathers SK) Clinicians have found that if the integrity of the alar ligament is compromised, then moderate to severe hypermobility may occur resulting in mechanical instability.(Mathers SK) Once the alar and transverse ligament in the CCJ are irreversibility elongated, the structure consists of mainly inelastic collagen fibers leading to chronic hypermobility of the CCJ.(Mathers SK) It is imperative for clinicians to consider the CCJ upon cervical spine evaluations.(al. 2011)

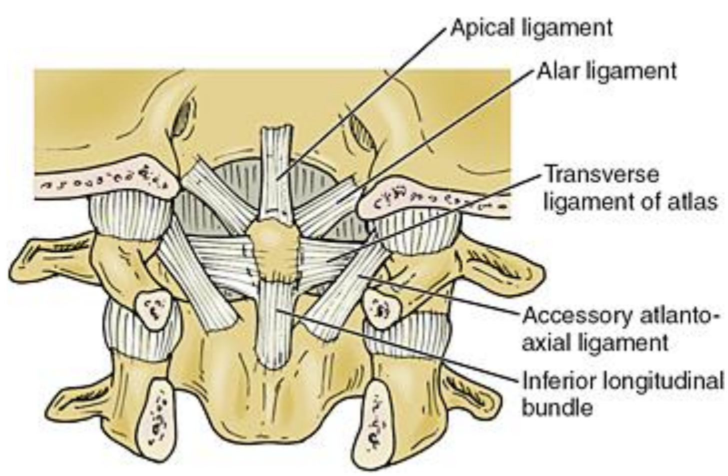

Figure 3. Ligamentous Structures of C1-C2 (Benzel 2012)

1.3 Assessing Craniocervical Characteristics

Empirical data has determined the influential role of the deep neck flexor group and neck pain disorders. Cervical impairments affect muscular strength and endurance, mobility, motor control, proprioception, and at times, evolve into a chronic and debilitating issue. By examining craniocervical characteristics, researchers and clinicians alike may further understand cervicogenic pathologies and implement appropriate assessment tools in an athletic population.

1.3.1 Muscular Strength and Endurance

It is essential for athletes to maintain muscular strength and endurance for optimal athletic performance and injury prevention. Due to intense training regimens for athletes, neck strength is generally greater in this population and males show greater neck strength measurements compared to female athletes.(Barton PM 1996, Naish R 2013) Cervical muscle strength measurements can be taken through a wide variety of devices and protocols such as hand held dynamometry or repeated isometric contractions to assess muscle endurance, but also report a vast range of performance values with minimal reliable research studies.

1.3.2 Cervical Segmental Mobility

Along with evaluating muscle strength, assessing segmental mobility in the cervical spine is a necessary aspect of a clinical evaluation. Segmental mobility could have the potential to influence cervicogenic components of concussion. Segmental joint instability is defined as the spine being horizontally displaced 3.5-mm or greater.(White, Johnson et al. 1975) Mobility may be assessed through special tests with varying reliability, cervical range of motion devices, or radiographic imaging such as biplane radiography with CT scans to assess dynamic joint movement. Mobility assessments can distinguish segmental instability and reduced range of motion. Hypermobility is indicative of segmental joint instability in result of an injury, various intrinsic abnormalities, or extrinsic pathologies. Furthermore, hypermobility of the cervical spine can be a direct result of a whiplash injury and potentially has a relationship with concussion, requiring future investigations.(Mathers SK)

1.3.3 Cervical Proprioception and Joint Awareness

Cervical sensory-motor function as well as its ability to orient the head and neck in spatial time is quite complex in nature. External forces causing high impact loads may alter an athletes motor control and proprioception depending on the damage and severity. Assessing joint position sense in the cervical spine can be done through special tests sensitive to proprioceptive deficits. Cervical proprioceptive information influences postural stability, head and neck orientation, and eye movement; special tests are designed to target these systems to discover underlying impairments. Joint sense deficits are observed in neck pain patients as well as concussed individuals. Treleaven et al found that patients with prolonged symptoms of dizziness had greater joint sense deficits indicating a significant amount of abnormal cervical afferent input.(Treleaven 1994)

1.4 Definition of the Problem

Due to the complexity of concussion injury, the investigators have yet to identify many critical diagnostic, prevention, and treatment variables with their underlying connections. Because of this, concussions require a multifaceted and targeted approach. However, there are minimal to no published clinical trials pursuing the involvement of the CCJ and concussion. The current consensus statement on concussion in sport calls for scientific evidence that evaluates diagnostic and evaluative measures for sports related concussion. This study seeks to add to the body of literature concerning a subset of the population suffering from symptoms after a concussion with cervicogenic components. The mechanism of injury in closed-head trauma related to contact and non-contact sports collisions involves forces to both the head and cervical spine. There is a gap in the literature pertaining to the evaluation of the cervical spine and CCJ in subset of population. Based on current studies and the data from previous pilot studies there are routine physical examination and radiographic procedures that have the potential advantage of being reliable and simple clinical tests to assess the cervical spine and the CCJ. It was our aim to investigate characteristics of the cervical spine utilizing simple clinical tests among National Collegiate Athletic Association (NCAA) Division I athletes and assess concussion history within these subjects. This then, allowed us to examine the relationship between test findings and duration of symptoms following an episode/s of concussion. This study may be useful to clinicians seeking to evaluate cervical characteristics in a concussed population. Additionally, this may serve as background information for a clinical trial involving treatment interventions for this subset of a population with latent symptoms following closed head and neck trauma.

1.4.1 Purpose of the Study

The purpose of this study was to explore neck musculature characteristics in an athletic population. The relationship of previous concussion history and cervical characteristics was investigated.

1.5 Specific Aims and Hypotheses

Specific Aim 1: To investigate cervical spine characteristics in competitive athletes with and without history of concussion.

Hypothesis 1: Significant differences will be demonstrated between groups of athletes with and without previous concussion.

Specific Aim 2: To gather normative data on neck muscle characteristics in a sample of competitive athletes.

Hypothesis 2: This hypothesis is strictly explorative.

1.6 Study Significance

Contemporary research has focused on contact-related head and neck injuries along with concussion in sports setting a focal point of research. Empirical clinical evidence has identified a subset of patients with a history of closed head and neck injury suffering from chronic neck pain, headache, and dizziness. Cervical confounding factors ultimately affect the clinical diagnosis and screening of this subset of population. A review of the literature reveals debate and controversy about the use of advanced diagnostic imaging procedures – such as CT and MRI – to assess the integrity of the CCJ soft tissues and the ability to make a clinical determination of CCJ hypermobility. Static images of CCJ anatomy produced from CT and MRI scans simply do not inform the clinician about the status of the functional movements of the joints in the CCJ region. Randomized controlled clinical trials have concluded that manipulative manual therapy simultaneously with an exercise program reduces cervicogenic headache symptomology and have identified structural and behavioral changes in patients with mechanical neck pain.(Jull, Trott et al. 2002) (Jull, Trott et al. 2002, Ylinen, Takala et al. 2003, O'leary S May 2009) Clinicians also use physical examination procedures such as palpation and orthopedic tests to determine mobility, neck muscle performance, or motor control of the cervical spine and cranio-cervical junction. There is evidence establishing the reliability of these procedures for evaluating the cervical spine and CCJ. This study can help to fill the gap in the literature regarding the validity and clinical applicability of these simple, safe and cost-effective screening procedures.

2.0 Literature Review

The following review of literature aims to highlight concussion epidemiology, risk factors, return to play criteria for an athlete post sport related concussion, and post-concussive trajectories. This review will also cover descriptive epidemiology of musculoskeletal injuries to the cervical spine, clinical evaluations post injury, and the cranial cervical junction (CCJ) pertaining to concussion. It is the author's intent that this review lay the foundation to establish a possible link between the presence of sports related concussion and potential suboptimal cervical characteristics.

2.1 Background of Sport Related Concussion

A concussion is a complex pathophysiological process that is caused by biomechanical forces affecting the brain.(Cheever, Kawata et al. 2016) The Center for Disease Control and Prevention estimates that 3.8 million sports related brain injuries occur yearly, being a "silent epidemic." (Prevention. 2007) An epidemiological study of collegiate sports related concussions revealed that concussions in baseball and softball contributed to 6-8% of injuries sustained in a game setting and 4-7% in a practice setting.(Daneshvar, Nowinski et al. 2011) Within the same study, basketball showed 3.4 times the rate of concussion incidence for women compared to men. Women were 8.5% more likely to sustain a concussion in a game setting and 4.7% in a practice setting. Interestingly, women's ice hockey had the highest incidence rate at .91 injuries per 1,000 AE, and women's soccer falling second at .41 per 1,000 AE.(Hootman 2007) Concussions account for 5.5% of injuries within men's NCAA soccer and 4.3% of injuries occur around the head, face, and neck.(Prevention 2009) The sole act of heading attributes to 8.4% of all soccer injuries.(Prevention 2009) Goalkeepers are more susceptible to concussion due to head collisions showing 21.7% of total goalkeeper injuries within the sport of soccer. Similarly, women's soccer sustained concussions due to head to head collisions, ground contact, and heading. During a take down in collegiate wrestling, concussions consisted of 42.6% of all the wrestling injuries combined.(Daneshvar, Nowinski et al. 2011)

Approximately 25% of the total patients who have sustained a concussion are between the ages of 19-28 years. (Zuckerman, Kerr et al. 2015) 116 116 116 116 114, 118,117 The overall frequency of sport related concussions is commonly defined in literature as an injury rate per 1,000 athlete exposures (AE). One AE is expressed as one student athlete's participation in an NCAA sanctioned game or practice setting. For the purpose of a study conducted by Zuckerman et al., they described the injury rate per 10,000 AEs. This five year epidemiological study of sport related concussions in NCAA athletes using the NCAA Injury Surveillance Program (ISP)(Zuckerman S 2015) and found that the overall concussion rate was 4.47 per 10,000 AEs. The same study identified that the competition or game concussion was 12.81 per 10,000 AE being larger than the practice rate (2.57 per 10,000 AEs). Of all the sport related concussions, 9% were recurrent.(Zuckerman S 2015) Sport activities that were highly associated with a greater number of sport related concussion were football, soccer, and basketball. In men's football, most of concussions occurred in the practice setting with a practice rate of 7.16 AE and 5% of those concussions were recurrent. Approximately 86.7% of football concussions in a game setting were due to player-to -player contact. In football, quarterbacks, wide receivers, running backs, and defensive backs are three times more at risk of a concussion compared to linemen.(Pellman EJ 2004) The largest incidence rates were in men's wrestling (10.92 per 10,000 AEs), men's ice hockey (7.91 per 10,000 AEs), women's ice hockey (7.50 per 10,000 AEs), and men's football (6.71per 10,000 AEs). Men's football resulted in the highest annual reported rate along with women's soccer, and women's basketball.

Within the same data set, another published study by Kerr et al focused on the symptom prevalence, resolution time, and return to play time.(Kerr 2016) Between 2009-2010 to 2013-2014 academic years, the most common symptoms reported were headache (92.2%) and dizziness (68.9%). Of those concussed, 8.9% required over four weeks of recovery before returning back to sport participation.(Kerr 2016) Likewise, a study by Teel et al.(Teel E 2017) found that baseline symptoms are associated with post-concussion symptom frequency and severity within collegiate and high school athletes. They found that athletes with a baseline headache, fatigue, sleeping issues, blurred vision, light/ noise sensitivity and mental fogginess reported higher symptom frequencies with greater severity post-concussion. Clinicians should understand factors that influence post-concussion symptoms in order to develop a sound recovery strategy.(Teel E 2017)

2.1.1 Sports Related Concussion Risk Factors

Sports participation is a risk factor for concussions; however high intensity, contact or collision sports have the highest incidence rate of concussion. In a study that investigated the injury rate per exposure based on sport in collegiate athletes from 1998 to 2004, (Hootman 2007) concussions were 5% to 18% of all reported injuries. Football had the highest number of reported concussions at 55%. Importantly, 2% of all collegiate athlete concussions reported restricted participation for 10 days or more. In all, concussions do occur less frequently compared other musculoskeletal injuries, but may have more significant health consequences.(Hootman 2007)

Preexisting conditions, previous history of concussions, family problems, history of migraines, age, psychiatric comorbidities and/or neurological problems are associated with prolonged symptoms and that these cases are considered to be “at-risk” individuals.(Broglio S 2014, Kania, Shaikh et al. 2016) Risk factors to prolonged symptoms also include learning disabilities, ADHD, adolescence, and sex.(Collins M 2014) Psychiatric comorbidities that can have a contributing factor to PCS may include: anxiety, depression, bipolar disorder, and autism.(Al Sayegh, Sandford et al. 2010, Nelson, Guskiewicz et al. 2016, Schwarzbold M 2008) Established prognostic indicators for extended recovery and negative outcomes have also been identified. Post concussive migraine symptoms such as headache with nausea or photo/phonosensitivity (sensitivity to sound or light), immediate dizziness, sub-acute fogginess, concentration difficulties, and imbalance are predictors of prolonged recovery. Evolving predictors are furthermore being established by sports medicine professionals.(Collins M 2014)

2.1.2 Consequences of Sports Related Concussion

Consequences of sport related concussions are subjective to the athlete. Recovery time differs for each athlete, however, by utilizing the information self-reported by the athlete and information provided by clinical assessment tools, a clinician may have a better understanding of the injury and a further grasp on a recovery period. Approximately 80% of concussed athletes recover within 3 weeks. (Iverson GL 2006) Risk factors such as previously sustained concussion or comorbidities have a strong influence on recovery outcomes. There are also prognostic indicators for a prolonged recovery with poor outcomes.(Collins M 2014) Researchers have found that post-traumatic migraine symptoms (headache with nausea and photo and/or phonosensitivity), instant dizziness, subacute fogginess, concentration difficulties, and numbness following a sports related concussion predict an extended recovery time period. (Lau BC 2011) Post concussive symptoms may manifest in many different symptom categories and it is the responsibility of the clinician to identify and treat these symptoms.

2.1.3 Sport Related Concussion Clinical Trajectories

Emerging clinical trajectories of concussion are divided into six categories. Traditionally, concussion symptoms have been divided into four categories; cognitive, emotional, physical, and sleep.(Pardini J 2004) These four categories have evolved into cognitive/fatigue, vestibular, ocular motor, post-traumatic migraine, anxiety/mood, and cervical trajectories.(Collins M 2014) The cognitive/fatigue trajectory established by Collins et al, is described as symptoms characterized by fatigue, decreased energy levels, non-specific headache, and sleep irregularities with all symptoms increasing at the end of the day. (Collins M 2014) Clinicians can use computerized neurocognitive testing along with targeted questions that focus on the ability to concentrate in order to distinguish this trajectory. The focal point of treatment is to reduce physical and cognitive demands and to establish behavioral regulation of daily habits.

The vestibular trajectory outlines symptoms of dizziness, fogginess, nausea, detachment, anxiety, and feeling overwhelmed in complicated environments. Quick head movements may aggravate symptoms. Symptoms may be triggered in various settings and clinicians should note any provoking stimuli. Neurocognitive testing can illicit general impairments in processing and reaction times along with memory performance. Vestibular oculomotor screening is necessary to target the vestibular trajectory. Comprehensive vestibular therapy by a trained professional is the most ideal for this subgroup. (Collins M 2014)

The ocular motor trajectory is characterized by localized, frontal headaches, fatigue, distractibility, difficulties with vision-based stimuli, pressure behind the eyes, and inability to focus. Complete school or work days can induce or increase symptoms. Smooth pursuits and saccades eye movements can reveal this symptomology; however, irregular near-point convergence testing may reveal a more targeted ocular motor deficit. A comprehensive evaluation from a neuro-optometrist is highly recommended for this category of individuals. Vestibular therapy can substitute neuro-optometry if one is unavailable.

The anxiety or mood trajectory is outlined as an over intensified feeling of anxiety with hypervigilance, overwhelming thoughts, sadness, or hopelessness. These individuals may have insomnia in result of anxiety. Anxiety may be masked as fogginess and it is important for the clinician to ask detailed questions to unveil underlying anxiety. Physical exertion may begin if the anxiety trajectory is recognized and may provide emotional release with reduced arousal levels. (Collins M 2014) Cognitive behavioral therapy with behavioral regulation can be a corrective route for anxiety related symptoms. (Al Sayegh, Sandford et al. 2010)

Post-traumatic migraine trajectories are termed as a unilateral, moderate to severe headache following head trauma with pulsating pain along with nausea, photosensitivity and/or phonosensitivity usually intensified by physical activity.(Society 2004) Clinicians should consider a previous history of migraines and/ or a family history of migraines. Treatment for post-traumatic migraines consist of pharmacologic interventions. Introducing a physical exertion protocol with cognitive behavioral therapy is highly recommended for this subgroup.(Collins M 2014)

Lastly, the cervical trajectory is one that requires extensive clinical research and is not fully understood. This subset of individuals presents with cervicogenic symptomologies and may not overlap with other trajectories. A patient can present with cervicogenic dizziness or headache, neck pain, or reduced range of motion. In cervicogenic dizziness, abnormal muscle activity can be a result of mismatched diverging cervical proprioceptive input into the CNS.(Broglio 2016) This can lead to impaired postural control, irregular eye movement, and cervical muscle imbalance. It is also imperative to characterize the presenting headache, whether it produces a dull, throbbing, or pressure headache in the frontal, temporal, or occipital region.(Collins M 2014) When a cervical injury is suspected, cervical range of motion, manual muscle testing, ligamentous instability, and palpation should be evaluated by a licensed professional. Treating the underlying cervical spine injury by increasing range of motion, manual cervical and thoracic mobilization, post injury re-education, biofeedback, therapeutic modalities for pain reduction, and or trigger point injections are suggested by clinical research.[12] Visual, vestibular, and oculomotor rehabilitation may be implemented to normalize proprioceptive input.(Broglio 2016) Within this comprehensive approach, there is no inclusion to specifically assess the CCJ along with any mentioned clinical tests that can be sensitive and specific to the CCJ or cervicogenic headaches.

2.1.4 Sports Related Concussion Evaluation and Treatment

Assessing a sports related concussion should combine a comprehensive clinical interview with concussion assessment tools. These assessments target multiple domains of concussion including complexity of the case, an athlete may require psychological, vestibular, and vision referrals.(Collins M 2014, Collins, Kontos et al. 2016) The clinical interview is the primary tool of communication and provides important information directly from the patient to the clinician. The interview considers the detailed history of the athlete and establishes the mechanism of injury with the presentation of signs and symptoms. (Collins M 2014) Initial signs and symptoms may include loss of consciousness, post- traumatic amnesia, ocular disturbances, dizziness, headache, or nausea. An assessment tool that provides pertinent information is the Sport Concussion Assessment Tool-5 (SCAT-5), which is a tool to evaluate signs and symptoms, balance, memory and a short cervical spine assessment. (Collins M 2014)

The occurrence of symptoms should be reported, and clinicians should identify whether symptoms are worsened with activity. Specific types of activity, the severity of symptoms, and the number of symptoms reported upon interview are indicated during the use of assessment tools.(Collins M 2014) It has been found that the primary symptom reported in 75% or patients during the first week post-concussion is headache. (McGrath N 2013) Additionally, 50% of high school athletes have reported dizziness within 7 days post-concussion. (Lovell MR 2004) Vestibular and ocular impairments may include unstable vision, difficulty focusing, motion discomfort, issues with busy visual stimuli, and dizziness. (Collins M 2014) Dizziness and migraine symptoms have been found to indicate poor outcomes and longer recovery, so it important to uncover these symptoms at the initial evaluation of injury. (Collins M 2014) Dizziness can have various etiologies and determining the pathology is quite important; dizziness can be caused by: migraine, cervicogenic dysfunctions, psychiatric, or central or peripheral vestibular dysfunction.(Collins M 2014)

Approximately 30% of athletes within the acute stage will experience ocular motor problems and 65% of athletes will have ocular motor dysfunctions post-concussion .(Capo-Aponte JE 2012, Kontos AP 2012) Ocular motor dysfunctions can present problems with vergence (simultaneous movement of the eyes toward or away during focusing), accommodation, and alignment.(Ellis MJ 2015) An athlete may experience blurred vision, diplopia (double vision), difficulty reading, eyestrain, headache, loss of place while reading, and scanning problems.(Collins M 2014)A reliable tool of assessment is the King-Devick to test ocular dysfunctions along with Smooth Pursuits and the Vestibular Ocular Motor Screen.(Collins M 2014)

Balance impairments have been subjectively reported by approximately 40% of athletes within the acute stage. (Capo-Aponte JE 2012) Balance issues have also been reported to extend out to 30 days.(Broglio SP 2007) Another reliable assessment tool that is warranted for balance impairments is the Balance Error Scoring System (BESS). (Collins M 2014)

Neurocognitive testing provides a comprehensive assessment for sports related concussion. The Immediate Post-Concussion Assessment and Cognitive Testing tool, or ImPACT, is a commonly used and most widely known tool for neurocognitive testing.(Collins M 2014) These examinations take up to 30 minutes for completion assessing the athletes demographics, concussion symptoms, and cognitive testing specifically attention, memory, processing speed, and reaction time.(Collins M 2014) Typically a baseline assessment of the ImPACT tool is implemented for all athletes in preseason to compare pre to post injury performance. Research on the ImPACT indicates a 94.6% sensitivity and 97.3% specificity in determining neurocognitive deficits in an asymptomatic population. (Schatz P 2012) Researches also found that athletes were 17.2% less likely to return to play within 10 days post- concussion when neurocognitive testing was used in comparison no implementation.(Meehan WP 3rd 2012)

A novel approach to the treatment of concussion stresses individualized care that is continuously developing and implemented in the field of sports medicine. (Collins M 2014) The "Statements of Agreement from the Targeted Evaluation and Active Management (TEAM) Approaches to Treating Concussion" in 2013 was held to discuss current diagnostic measures, evaluation, and active management of concussion. Key points on this approach to concussion were: no return to play on the day of injury, physical and cognitive rest until symptoms subside, work and school accommodations, and lastly, progressive aerobic exertion-based return to play solely dependent on patient reported symptoms.(Collins, Kontos et al. 2016) Active treatment guidance and research are limited, as well as any empirical evidence regarding randomized controlled trials for prescribed physical and cognitive rest post-concussion. Evidence has shown that active rehabilitation, not strictly rest, can alleviate concussion symptoms. Matched individualized treatments to recovery trajectories are suggested for more optimal results.(Collins, Kontos et al. 2016) There is a call for future research to support this clinical heterogeneity specifically; on recovery trajectories, benefits of prescribed active interventions, complementary and integrative therapies, multisite, and prospective studies of concussion treatments to assess concussion along with the effectiveness of possible treatments.(Collins, Kontos et al. 2016)

2.2 Concussion and the Craniocervical Junction

The evidence of cervical spine involvement in concussion is becoming increasingly more apparent, but there is a lack of empirical data and the prevalence of cervical spine involvement with concussion is unknown.(Cheever, Kawata et al. 2016) Craniocervical Junction (CCJ) involvement may affect cervical nerve roots, cervical musculature, trigemino-cervical nucleus, intervertebral discs, and cervical joints.(Piovesan EJ 2003, J. 2010, Cheever, Kawata et al. 2016, Makdissi, Schneider et al. 2017) Cervical levels C0-C1, C1-C2, C2-C3, and C3-C4 are associated with cervical symptoms post-concussion.(JS. 2004)

Whiplash-associated disorder (WAD) displays remarkable resemblance to concussion in mechanisms of injury and can present sensory disturbances, motor dysfunctions, and psychological issues similar to concussion presentation; warranting further exploration.(Smith

A. D. 2013, Schneider KJ 2014) During a whiplash injury, the forces exerted on the head and neck can cause a concussion, inducing symptoms that could be in result of either the head or neck region. Studies that collected data on high school and collegiate athletes found that concussion injuries resulted in linear impact accelerations between 60 to 160 G force (force of gravity). Contrastingly, mild strains to the cervical tissue can be demonstrated at 4.6 G force of acceleration.(Spitzer WO 1995, Broglio 2011)

Cervicogenic headaches (headaches origination from the neck) are well known amongst clinicians and may exist in concussion or cervical impairments. Amongst whiplash patients, researchers have found that up to 4.6% of patients will develop chronic headaches post whiplash injury and 2% will be on disability.(J. 2010) Investigators also found that a group of 12 concussed individuals with persistent post concussive headache (PCH) had simultaneous injuries to their cervical spine region. These individuals had cervical segmental joint dysfunction, limited neck flexor endurance, and stiff neck musculature.(Treleaven 1994) Another study found that within a cohort of junior hockey players who sustained both whiplash or concussion mechanisms, 100% of the hockey players presented with signs and symptoms of WAD and concussion demonstrating a concurrent phenomenon.(Hynes LM 2006) Table 1. provides an excellent visual which illustrates the similar symptoms of concussion and cervicogenic injuries created by Cheever et. al. (Cheever, Kawata et al. 2016)

Table 1 Commonality Symptoms of Concussion and Cervicogenic injuries (Cheever, Kawata et al. 2016)

Symptom	**Condition**	
	Concussion	Cervical Injury
Headache	**X**	**X**
Tinnitus	**X**	**X**
Irritability	**X**	**X**
Sleep Disturbances	**X**	**X**
Blurred Vision	**X**	**X**
Neck Stiffness	**X**	**X**
Balance Disturbances	**X**	**X**
Depression	**X**	
Cognitive Deficits	**X**	**X**
Memory Deficits	**X**	**X**
Attention Deficits	**X**	**X**
Decreased Cervical Range of Motion		**X**
Decreased Isometric Neck Strength	**X**	**X**

There are clinical diagnostic tests that are specific to the CCJ, but there are no readily available clinical tests that indicate a concussion as an injury to the brain. The pursuit of differentiating concussion from a cervical impairment within these patients in ways of clinical tests is a practical approach. There is a lack of evidence that attributes this cluster of symptomologies strictly to brain involvement.(Oliver 2013)

A case study series was published by Marshall et al. to discuss the pathophysiology of concussion along with positive outcomes after manual rehabilitation targeted to restore cervical spine function.(Marshall C 2015) The first case was a 25 year old martial arts athlete who had persistent PCS 4 months post injury. This patient reported four previously sustained concussions, all in which resolved within the acute stage. The patient complained of continuous headaches in the frontal and temporal regions, bilaterally. The cervical spine was restricted a C2-C3 with referral pain into the head during palpation of the longus colli, suboccipital musculature, sternocleidomastoid, and splenius capitis. The patient underwent soft tissue therapy, as well as active deep neck flexor endurance training. Manipulative therapy targeting joint restriction was completed and within the fourth visit of therapy, the patient was asymptomatic.(Marshall C 2015) The five cases all had similar scenarios and outcomes with complete alleviations of symptoms after cervical assessment and treatment.

A randomized controlled trail conducted by Schneider et al. determined that a combination of cervical and vestibular physical therapy successfully decreased time for medical clearance in sport for an adolescent and young adult concussed population.(Schneider KJ 2014) These patients presented with persistent dizziness, neck pain, and/or headache post-concussion and 73% of these cervicovestibular therapy patients were medically cleared at the end of the trial compared to 7% of the control group.

There are clear rehabilitation methods to reduce the cervical trajectory post-concussion. However, it is important for clinicians to establish procedures to surface early recognition of this cervical trajectory. Cheever et al. found specific clinical testing that has the potential to be utilized as an assessment tool after head and neck trauma to distinguish between a cervical mechanism versus a concussion.(Cheever, Kawata et al. 2016) Renecker et al indicated the primary reason clinicians do not incorporate cervicogenic tests into their concussion approach was due to lack of education and awareness of proper methods.(Reneker JC 2015) They also identified that the cervical joint-repositioning test, the cervical flexion-rotation test, and assessing of the deep neck flexors and extensors were among the clinical tests to possibly differentiate symptomology. Although, future research is required to establish clinical utility and validity of targeted concussion protocols and procedures. Effectively implementing cervical exams to a concussed populous has the potential to uncover further information for the cervical trajectory.

2.2.1 Sport Related Craniocervical Injuries

With the recent attention being given to cervical spine trauma within athletic populations, there is a growing urgency for injury management and prevention. A cervical injury can be defined as persistent impairments caused by dysfunction of the somatosensory system of the cervical spine.(Ellis MJ 2015) The cervical injury incidence rate has significantly decreased as a result of the implementation of strict rule changes and equipment regulations within sport such as eliminating spearing within football and improving helmet mechanics. The National Center for Catastrophic Sport Injury Research (NCCSIR) completed an incidence report between the years of 2005-2014 for total fatalities in high school and collegiate football due to traumatic brain injury or spinal cord injury. It was concluded that, over this time period, there were 24 deaths, 2.8 per year, which resulted from tackling or being tackled in a competitive setting.(Kucera 2017) In fact, cervical spine injuries account for 10-15% of all football players or injuries.(KS 1998 Jan. 17)

High impact, high energy sports such as hockey, soccer, rugby, wrestling, and gymnastics, are especially at risk for head and neck trauma. (KS 1998 Jan. 17, Swartz, Floyd et al. 2005, Bretzin A April 2017) Collisions with high velocity and acceleration during intensive play, coupled with axial loading, can be fatal or cause permanent damage to the brain or spinal cord, deformity, or paralysis. (Pho C 2018) Whiplash mechanisms involve acceleration and deceleration movements of the head and neck transmitting forces upon one another. Cervical spine involvement is generally suspected post whiplash injury and can cause a variety of musculoskeletal ailments specifically to important surrounding cervical structures. Cervicogenic headaches, being located at the occipital region to the frontoparietal and orbital regions, in particular are hypothesized to stem from nociceptors within the cervical spine. These headaches may be chronic or episodic with symptoms characterized as non-throbbing pain within the neck and triggered by neck movement, posture, dizziness unrelated to vertigo, pressure over the C0-C3, and reduced range of motion of the cervical spine.(Society. 2004)

Neck musculature strength has been found to be a significant predictor to cervical injuries along with concussion amongst young athletes. Additionally, Sex differences have been established for head-neck segment kinematics and neuromuscular control in reaction to external stimuli. Female subjects resulted in greater peak angular acceleration (505%) and displacement. They were found to have 50% less isometric neck strength than their male counterpart, 23% less neck girth, and 43% less head to neck circumference.(R. Tierney 2005)

Muscle impairments and inactivation are associated with neck pain disorders and chronic neck pain, as well.(Mathers SK) Cervical spine trauma has been identified as a primary medical condition responsible for the interruption of neck strength and the integrity of the transverse and alar ligaments.(Mathers SK) Hartman et al. investigated the mechanical effect of the alar ligament when undergoing various loads of stress. Cadaveric specimens were placed in three states, intact, unilateral and bilateral alar ligament resection. Clinical exams were also used to test for sensitivity and reliability for evaluating an alar injury. It was suggested that the damaged alar ligament caused hypermobility and latent symptoms post-concussion and/or whiplash mechanisms. This study was the first biomechanical study to simulate clinical mobility exams utilizing robotics to assess for sensitivity and specificity; warranting further exploration into clinical application.

2.2.2 Clinical Examinations and Methodological Considerations

One of the most important responsibilities for a clinician is to perform a comprehensive and thorough clinical examination for this population. Prior to the application of a clinical exam, there must be established reliability and validity for safety of the patient as well as to conduct evidence-based practices. The methodology of this study will use clinical tests commonly used in clinical practice that have shown consistent sensitivity, specificity, reliability and validity to cervical spine characteristics. Literature reviews have attempted to discuss the inclusion of a cervical injury assessment in the guidelines for managing and treating patients with concussion. In summary, these studies have highlighted the current absence of well-defined, universally understood clinical exams that may diagnose cervicogenic pathologies in the presence of a concussion. Research has concluded that further investigations towards clinical utility and validity of examinations designed to isolate these impairments is required. Systematic reviews aiming to choose clinical tests that may differentiate cervicogenic pathologies along with concussion have suggested an assortment of cervical spine assessments with clinical utility and validity for strictly cervical impairments, but not for concussion. These tests incorporate range of motion assessments, mobility testing, proprioception, physical and neurological examinations, along with palpation, manual therapy, and special tests. The possibility of incorporating cervical exams in concussion evaluation, but the continuing question is which clinical exams are the most appropriate.

The Deep Neck Flexor Endurance Test (DNFET) is a convenient and simple assessment technique that identifies cervical muscle weakness, inactivation, impairment, and/or injury. (Jull GA 2008, Domenech MA 2011 Feb.) There is growing evidence that identifies impaired activation of the deep neck flexors being a result of cervicogenic headache along with related neck disorders.(Jull GA 2008, Kim and Kwag 2016) The DNFET protocol is performed with the patient in supine crook lying with the cervical spine in neutral and resting on a treatment table. The patient is instructed to make a nodding movement and is asked to maintain an isometric contraction for as long as they can. DNFET inter-rater reliability and construct validity studies have shown to be highly satisfactory.(Harris KD 2005 Dec. , Jull GA 2008, Juul T 2013) There is only one established normative data set between the ages of 20 to 80 years old in healthy men and women, as well as patients with neck pain.(Domenech MA 2011 Feb.) These findings attempted to objectify deep neck flexor endurance impairments and suggested further research in patients with a history of neck pain or a muscular endurance deficit. The potential of collecting a physically active college aged data set may be beneficial for future studies on this population subgroup.

Assessing functional movement of the cervical spine serves as another important aspect of a clinical exam. Assessing mobility of the cervical spine can be done passively or actively. However, evaluating cervical hypermobility requires manual palpation and passive motion. An easily practiced clinical test to assess segmental motion of the C1-C2 is the Cervical Flexion-Rotation Test (CFRT). While the athlete is supine, the cervical spine is flexed to end range of motion and rotated bilaterally to a normative end range of 44 degrees. (Ogince M 2007) When movement is passively applied, onset of symptoms such as cervicogenic dizziness may occur, or restriction of the cervical spine could indicate asymmetry in range of motion and/ or afferent pathway deficits from cervical proprioceptors to the central nervous system. Studies have indicated that the CFRT is a valid clinical measure of cervical mobility and assesses cervicogenic dizziness.(al. 2011, Ogince M 2007) This exam shows 91% specificity and 90% sensitivity to cervicogenic headache.(Cheever, Kawata et al. 2016)

The Spinous Kick Test, also known as the alar ligament stress test, is widely accepted as an assessment for C2 ligamentous hypermobility. The Spinous Kick Test has shown substantial reliability and construct validity for hypermobility.(Osmotherly, Rivett et al. 2012) This procedure assesses the coupled rotation of C2 during cervical lateral flexion and rotation. Upon palpation of the C2 spinous process, passive rotation contralateral to the direction of side bending is considered normal; a positive test indicates a lack of C2 spinous process rotation during lateral bending upon palpation. (Osmotherly PG 2012, Osmotherly PG 2013)

Lastly, the Lateral Shear test is an examination that screens for the integrity of the alar ligaments. There have been minimal reliability studies performed for this physical exam. However, within the past year, a reliability study through the University of Pittsburgh, “Reliability of Craniocervical Ligament Testing” (Nelson 2013), established excellent reliability for the Lateral Shear test.

The Head Repositioning Test (HRT) is an assessment used to examine proprioceptive and motor performance in individuals who have sustained a whiplash injury. Specifically, it is utilized to determine one’s head and neck positional awareness. (Juul T 2013) An individual’s proprioceptive ability is indicative of functional sensory integration to perform dynamic stability. The HRT assesses the ability with eyes closed to reposition the head to a neutral position after maximally rotating in the transverse plane. If the patient is unable to create repositioning, this can indicate damage to afferent descending pathways (linking neural tracts from the brain to the body) within muscle spindles of the neck and decreased sensorimotor control. A recent systematic review has established various protocols for the HRT.(De Vries 2015) Studies have utilized CROM devices, electromagnetic tracking systems, to electro-goniometry, assessed cervical movement in the vertical or horizontal plane., and report different number of trials. (Sjolander P , Heikkila and Wenngren 1998, Treleaven 2003, Treleaven J 2006) Established criterion validity has showed significant differences between whiplash subjects and healthy controls. (Heikkila and Wenngren

1998) This exam has 82% sensitivity and 92% specificity to cervical pathologies.(Cheever, Kawata et al. 2016) Intra and interrater reliability shows moderate to perfect interrater and intra-rater reliability with interclass correlations of .0985. (Juul T 2013) (Loudon JK 1997)

In all, these examinations have proved to be clinically applicable to cervicogenic pathologies and have the potential to be useful for clinicians seeking to evaluate cervical characteristics in a concussed population.

3.0 Methodology

3.1 Experimental Design

A descriptive cross-sectional design was chosen to investigate the relationship between previous concussion and cervical characteristics in athletes.

3.2 Subject Recruitment

The study was approved by the Institutional Review Board (PRO18010446) at the University of Pittsburgh preceding the implementation of all research procedures. Subjects were healthy, physically active, competitive athletes at the University of Pittsburgh between the ages of 18-25. Competitive athletes within this study were defined in accordance with the American College of Cardiology, "One who participates in an organized team or individual sport that requires regular competition against others as a central component, places a high premium on excellence and achievement, and requires some form of systematic (and usually intense) training".(Maron BJ 2015) All recruiting activities were completed with approved recruitment flyers and an information session prior to testing. Prior to participation, the subjects completed informed consent in accordance with the University of Pittsburgh Institutional Review Board. The principal investigator informed all potential subjects about the study through an information session, to ensure that they were adequately informed about the overall parameters of the study and what to expect if chose are eligible and choose to participate. Interested participants were provided with a consent form. Subjects had the right to terminate the screening at any point in time and could elect not to answer any of the questions asked. The informed consent was in a physical printed form and the subject was given sufficient time to read the entire document. Subjects was encouraged to ask questions and the tester obtaining informed consent verbally provided clarification to any aspects of the study that seen unclear. Once the subject gave informed consent, inclusion/exclusion criteria was reconfirmed prior to study enrollment with the subject information form. Interested participants informed the study investigator. Prior to participation, interested participants underwent screening for inclusion/exclusion and were presented with informed consent documentation. Informed consent was in the accordance with the University of Pittsburgh Institutional Review Board. Qualification was furthermore determined by the following inclusion and exclusion criteria:

3.2.1 Inclusion Criteria

This study included both male and female student athletes 18 years or older. Participants were required to be NCAA sanctioned athletes and were required to be in current status of participation in competitive practice and game for the 2018 fall sport season.

3.2.2 Exclusion Criteria

Subjects were excluded if they had previous radiographic evidence of fracture, dislocation, or instability in the cervical spine. Competitive athletes who were pregnant were not included within this study as well as any athlete with a history of cancer.

3.3 Sample Size Analysis

To date, few previous studies have examined the relationship between cervical spine characteristics and concussion. Group sample sizes of 64 (concussed group) and 64 (non-concussed group) were calculated using PS-Power and Sample Size Calculations, Version 3.1.2; achieving 80.0% power to reject the null hypothesis of equal means, assuming a moderate effect size of d = 0.5, with a significance level (alpha) of 0.05 using a two-sided two-sample t-test. To account for subject attrition and data loss, approximately 20% more participants were recruited into the study with a sample size of 128 + 26 = 154; 77 in each group.

3.4 Instrumentation

A series of physical examination procedures were performed to assess cervical mobility, muscular endurance, and proprioception of the deep neck flexor muscles in competitive athletes. All these physical examination procedures were commonly used in the sports medicine setting and are considered safe with minimal to no risk to patients.

3.4.1 Demographic data and Concussion History

A survey was utilized to collect subject demographics, previous concussion history, sport participation, cervical injury history, confirmed inclusion and exclusion criteria, and recorded results from clinical examinations. The survey data was collected through a mobile platform survey by Qualtrics (Qualtrics, Provo, UT and Seattle, WA), licensed by the University of Pittsburgh.

3.4.2 Neck Circumference and Segmental Mobility Measurements

Neck circumference was measured with a retractable tape measure (Body Tape Measure, MVAP medical supplies Inc., Thousand Oaks, CA). The suboccipital region (rectus capitis posterior minor and major, obliquus capitis superior and inferior) were manually palpated to assess for tightness, tenderness, or pain. The CFRT was utilized to measure C1-C2 segmental motion and has demonstrated 91% specificity and 90% sensitivity to cervicogenic headache and movement impairments in the CCJ.(Osmotherly, Rivett et al. 2012) A modified Lateral Shear test was utilized to assess the integrity of the alar ligaments in the frontal plane (Mathers 2014), and has demonstrated reliability with moderate to excellent interclass correlations (ICCs) of 0.63 to 0.9.(Osmotherly P 2013) The C2 Spinous Kick test was utilized to measure the coupled rotation of the C2 spinous process during cervical lateral bending. This test has demonstrated moderate to excellent interclass correlations of 0.58 to 0.94. (Pho 2018)

3.4.3 Head Repositioning Test

The Head Repositioning Test (HRT) was utilized to assess cervical joint position sense. This test has shown moderate to almost perfect validity and reliability, by appropriately assessing cervical proprioceptive performance.(Loudon JK 1997, Lee 2006) Loudon et al. assessed the ability to reproduce head reposition in patients post whiplash injury. This study found ICC's of 0.972 interrater reliability and 0.975 intra-rater reliability. Lee et al. found that relocation to neutral in the transverse plan had greater reliability than in the sagittal plane.(Lee 2006, Anderst, Donaldson et al. 2013) Established criterion validity has shown significant differences between whiplash subjects and healthy controls, as well as, 82% sensitivity and 92% specificity to cervical pathologies. (Heikkila and Wenngren 1998) Validity has also been established in abnormal rotation of cervical joint position error.(Treleaven J 2006) Furthermore, high variability has been established in vertical testing for patients with cervical neck pain and has yet to be considered a valid measure for clinical use.(Treleaven J 2015) A CROM deluxe (Cervical Range of Motion Instrument) (Model 926649, Cary, NC) with a laser pointer (PintyGLS, Tempe, AZ) attached superiorly was utilized along with a 40 cm in diameter target (Longbow, Birkenhead, UK).

3.4.4 Neck Muscle Endurance Measurement

A stopwatch and a treatment table were required for the Deep Neck Flexor Endurance test. DNFET inter-rater reliability and construct validity studies have shown to be highly satisfactory.(Harris KD 2005 Dec. , Jull GA 2008, Juul T 2013) Inter and intra-rater reliability has proven to be excellent and is consistent within multiple findings.(K. 1994, Harris KD 2005 Dec.)

3.5 Testing procedures

All testing was coordinated through the University of Pittsburgh Department of Athletics Sports Medicine/ Athletic Training Staff. The sports included in testing were men’s soccer and men’s wrestling at the University of Pittsburgh.

3.5.1 Testing and Tester Proficiency

Subjects reported to the University of Pittsburgh's athletic training room at the Peterson Event Center or the Fitzgerald Field House. Subjects rotated through four stations that included a Qualtrics survey and physical exams. The total duration of testing for each subject was 10 minutes.

Tests were performed by certified athletic trainers and physical therapists who were proficient in the necessary safety and procedural skills needed to complete them.

3.5.2 Qualtrics Survey

Data was recorded through a Qualtrics mobile platform survey. Each subject had an assigned de-identified subject ID number and this number was given to each subject upon data collection. The survey included questions highlighting subject demographics (age (years), height (inches), weight (pounds), and then body mass index (BMI) was calculated post data collection), their primary sport, concussion history, number of concussions, and past cervical spine injuries. Exclusion criteria was solidified and then continued onto the physical examinations that were completed by the tester.

3.5.3 Neck Circumference, Suboccipital Palpation, and Segmental Mobility Measurement

Physical examinations were utilized to measure neck circumference, suboccipital palpation, and segmental mobility of the cervical spine. Subjects were instructed to lay supine on a treatment table during the neck circumference measurement, palpation, CFRT, modified lateral shear test, and the C2spinous kick test.

3.5.3.1 Neck Circumference

Neck circumference was measured with hand placement of the tape measure just above the Laryngeal cartilage. If a male subject had a visible laryngeal prominence or Adam's apple, the tape measure was placed inferior to the prominence. (Rezasoltani 2005)

3.5.3.2 Suboccipital Palpation

Suboccipital palpation was completed following neck circumference in supine position to assess for tense, tender, or painful extensor musculature. While the subject was laying in supine, the tester located the spinous processes of C2 and moved their fingers laterally to find the suboccipital region. Superiorly and laterally to the C2 spinous process, the rectus capitis posterior major sits as one of the suboccipital muscles that is most easily palpable. The tester palpated perpendicular to the muscle fibers. The tester felt for increased tonicity within the muscle bellies as well as asked the subject if the area was tender upon palpation and if the subject had general suboccipital pain.

3.5.3.3 Cervical Flexion-Rotation Test (CFRT)

The CFRT was administered following neck circumference measurement. The subject was lying supine in a neutral position. With both hands, the tester passively flexed the cervical spine and slowly rotated the head left and right. A positive test was defined as an observable asymmetry in range of rotation between both sides of the cervical spine with or without pain at end range and restricted end-feel. (Benzel 2012, Osmotherly 2013)

3.5.3.4 Modified Later Shear Test

The modified lateral shear test was administered following the CFRT. This procedure screened for integrity of the alar ligaments in the frontal plane. The tester palpated the transverse process of C1 with the distal phalanx of the second digit of both hands. Overpressure was applied to one side and a shift of the opposite transverse process was assessed using the opposite digit.(Mathers SK) Palpation of lateral translation of the C1 transverse process in relationship to C2 was considered a positive test.(Mathers SK)

3.5.3.5 C2 Spinous Kick Test

The C2 spinous kick test was administered following the Modified Later shear test. This screens for the coupled rotation of C2 during cervical lateral bending. The tester palpated the occiput with one hand and palpated the spinous process of C2 with the other hand. The subject's head was passively side bent to the left or right. Palpation of C2 spinous rotation contralateral from the direction of side bending was considered normal. A positive test was defined as when the examiner palpated a lack of C2 spinous rotation during lateral bending.(Osmotherly, Rivett et al. 2012)

3.5.4 Head Repositioning Test

The HRT was administered following the neck circumference and segmental mobility tests. The methodology of this test was patterned after Heikkila and Astrom33 and Treleaven et al.(Heikkila and Wenngren 1998, Treleaven 2003) The protocol developed by Treleaven, Jull, and Sterling has been replicated throughout literature most frequently and was replicated within this study.(Chen 2013) Each subject was instructed to sit in a chair positioned 90 cm in front of the target while maintaining a relaxed posture. The subject wore a head laser apparatus and was instructed by the tester, with eyes open for memorization, visual input, and practice, to rotate completely to the right maximally and reposition to neutral while attempting to position the laser at the 7 cm in diameter circle around the center of the target. Treleaven et al. has found that if a subject is 90 cm from the target, then a 7 cm error from the center of the target translates to a 4.5-degree error (Arctan or 7cm/90cm=4.5 degrees). Figure 4. indicates the target developed by Treleaven et al. and shows error greater than 4.5 degrees or 7cm is significant to cervical joint position error.(Treleaven 2003) Figure 5. displays the target used for this study. The red circle is the 7cm or 4.5-degree measurement for cervical joint position error. For the continued practice round, the subject was asked to rotate maximally to the left maximally and reposition to neutral while attempting to position the laser at the 7 cm in diameter circle around the center of the target. When the subject voiced that they were ready, the subject entered the trial rounds and was instructed to close their eyes and replicate this task on each side 3 times with a total of 6 trials at their own pace. Studies have reported that using a laser pointer provides significantly higher cervical joint reposition errors in people with neck pain than in controls and have also found that 6 or more trials provided significantly higher joint position errors in people with neck pain than in controls, similarly.(Revel 1994, Heikkila and Wenngren 1998, Chen 2013) If the repositioning was beyond the 7 cm circle within this study, this was indicated as global error and was considered a failed attempt. Previous studies have measured HRT outcomes by the differences of degrees, cm measurements, or a scoring system derived from Treleaven et al.(Revel 1994, Heikkila and Wenngren 1998, Treleaven J 2006) This study utilized the modified scoring system derived by Trevleaven et al. recording the number of successful attempts out of right and left trials used by Pham, Elder, and Wu. (T. Pham 2017)

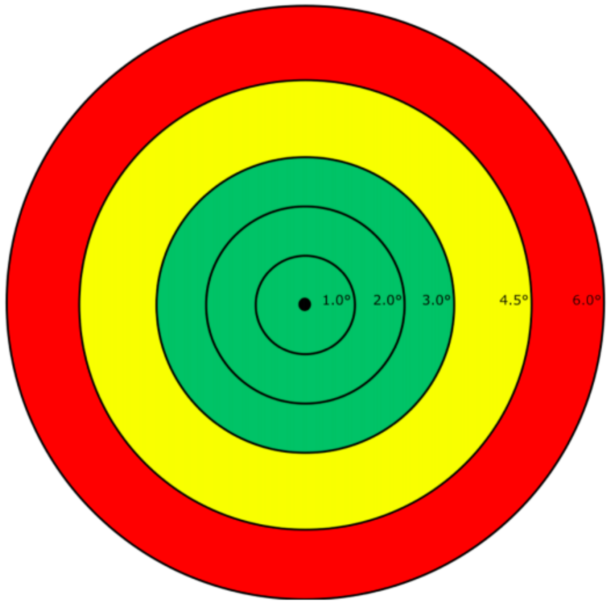

Figure 4. HRT Target Developed by Treleaven et al.

Figure 5. Head Repositioning Test

3.5.5 Deep Neck Flexor Endurance Assessment

The Deep Neck Flexor Endurance Test (DNFT) was performed with the patient in supine crook lying position with the cervical spine in neutral on an athletic training table. A tester sat at the head of the patient to assess musculoskeletal movements. The subject was familiarized with this exam and completed a practice trial, then three timed trials. The tester asked the subject to lift their head slowly off the table, so they were not touching the tester's fingers under the subject's occipital protuberance. Two finger widths were placed below the occiput. While holding an isometric contraction, the subject was instructed to perform a head nod position, tucking the chin towards their chest and lifting their head off the table. The patient was reminded to be precise and to minimize the use of their sternocleidomastoid. The familiarization allowed the subjects to recognize inappropriate or compensatory movements, particularly with the superficial cervical flexors, to be recognized.(Jull GA 2008, Juul T 2013, Kim and Kwag 2016) The subject was then asked to complete three timed trials with a 30 second rest period(Kristjansson E 2001)

3.6 Data Reduction

Two groups were determined by establishing history of concussion or no history of concussion. A history of concussion was determined if subject has been concussed within the past 2 years prior to the date of data collection. This operation definition was chosen due to the limited number of recruited subjects and will be described within the discussion.

Files were checked to ensure that all data points were present. Outcome measures were sub classified based on cervical characteristics: demographics, segmental mobility and sub occipital palpation, proprioception, and muscular endurance. A subject with history of concussion was defined as an athlete with sustained head trauma within the past 2 years. Data reduction for BMI was obtained and normalized (kg/m^2). Suboccipital palpation for pain and tenderness were combined for data processing purposes and scored yes or no. CFRT, Modified Lateral shear test, and C2 Spinous Kick test were recorded as positive or negative. These scores were converted into proportions, using the number of positive tests/number of subjects within the group = %. For the HRT, a percentage was calculated for trials passed in the left or right direction out of three trials performed. The DNFT trials were measured in seconds then combined and averaged out of the three trials.

3.7 Data Analysis

Statistical analysis was conducted using SPSS version 24. Data was tested for normality using the Shapiro-Wilk test. Descriptive statistics (mean, standard deviation, median), were calculated for all variables. Neck muscle performance data was described for subjects with or without history of concussion, and then stratified by sport. The Fisher's exact test was used to compare proportion of positive tests during the CFRT, Modified Lateral Shear Test, C2 Spinous Kick Test, and suboccipital palpation. A Mann-Whitney U test was used to compare percentage of successful HRT trials in the right and left directions as well as the average time for isometric neck flexion hold between groups in the DNFT. Neck Circumference was compared using an Independent Samples T test. Statistical significance was set a priori at alpha = 0.05, two-sided.

4.0 Results

4.1 Subjects

Demographic data of 46 participants are presented in Table 2. A priori analysis initially revealed that a sample of N=154 would be necessary to complete data collection, thus subject recruitment did not meet the necessary sample size.

The age range for the sample was 18-22 years old. All 46 subjects were male and were considered to have a healthy BMI. Fourteen concussed subjects were compared to 32 non-concussed subjects. Fifty percent (11 out of 22) of men's soccer subjects were in the concussed group and 50% (11 out of 22) were in the non-concussed group. Twelve-point five percent (3 out of 24) of men's wrestlers were in the concussed group and 84.5% were in the non-concussed group (21 out of 24).

Table 2. Subject Demographics

	Concussed		(N=14)	Non-Concussed		(N=32)
	Mean	**±SD**		**Mean**	**±SD**	
Age (years)	19.50	±1.09	14	19.94	±1.39	31
Height (cm)	176.66	±6.18	14	176.79	±6.92	31
Weight (lbs.)	163.57	±26.81	14	168.28	±23.06	32
BMI	23.78	±2.55	14	24.27	±2.28	31
Soccer	11/22=50.00%		11	11/22=50.00%		11
Wrestling	3/24=12.50%		3	21/24=87.50%		21

4.1 Comparing Cervical Spine Characteristics in Concussed and Non-concussed Athletes

Cervical characteristics were imported into SPSS for analysis. Descriptive statistics were computed for all variables. Fourteen concussed males and 32 non-concussed males were reported. Eight out of the 14 concussed males reported multiple concussion with six subjects reporting two concussions and one reported three concussions. HRT, DNFT, and neck circumference were tested for normality using the Shapiro-Wilk Test. Neck muscle characteristics, specifically neck circumference, were compared between athletes with or without a history of concussion using and Independent Sample T-test (Table 6). The Mann-Whitney U test was used for DNFT and HRT left and right rotation (Table 4 & 5). The Fisher's Exact test was used for segmental mobility examinations. (Table 3).

4.1.1.1 Neck Circumference, Suboccipital Palpation, Segmental Mobility

Neck circumference measurements were significantly greater in the non-concussed group (Table 6) $t(44)=3.000$, $p=0.004$. No subjects demonstrated tightness during suboccipital palpation. No significant group differences were demonstrated for proportion of subjects with positive tests for tenderness or pain during suboccipital palpation, motion restriction during CFRT, the alar ligament assessment during the Modified Lateral Shear Test, and the coupled rotation of C2 during C2 Spinous Kick Test.

4.1.1.2 Proprioception

A significantly greater percentage of successful head repositioning trials in the right direction was demonstrated in the non-concussed group (Table 4).

4.1.1.3 Deep Neck Flexor Endurance

No significant group differences were demonstrated for the DNFT timed trials in concussed and non-concussed groups (Table 5).

Table 3. Cervical Spine Characteristics in Concussed and Non-Concussed Athletes

	Concussed(N=14)	**Non-Concussed (N=32)**	
	Proportion	Proportion	Sig.
Suboccipital Palpation Tenderness or Pain	1/14=7.10%	4/32=12.50%	1
Suboccipital Tightness	0/14=0.00%	0/32=0.00%	
Suboccipital Palpation No pain or Tightness	13/14=92.90%	26/32=81.30%	0.413
Motion Restriction	3/14=21.40%	13/32=40.60%	0.316
CCJ Hypermobility	1/14=7.10%	11/32=34.40%	0.073
CCJ Instability	2/14=14.30%	12/32=37.50%	0.169

Fisher's Exact analyses were used to determine between groups differences in- percentage of positive tests

No Group differences among proportions

Table 4. Head Repositioning Test in Concussed and Non-Concussed Athletes

	Concussed (N=14)			Non-Concussed(N=32)			
	Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**	**Sig.**
RR	0.38±0.37	0.33	0.00,0.50	0.61±0.35	0.67	0.33,1.00	*0.043
RL	043±0.38	0.33	0.00,0.75	0.59±0.37	0.67	0.33,1.00	0.166

Mann-Whitney U test was utilized to determine between group differences in percentage of successful trials for concussed and non-concussed groups

HRR= percentage of head reposition trials passed in the right direction

HRL= percentage of head reposition trials passed in the left direction

Significantly greater group differences in neck proprioception in the right direction

Table 5. Deep Neck Flexor Endurance in Concussed and Non-Concussed Athletes

DNFT		Concussed (N=14)		Non-Concussed (N=32)		
Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**	**Sig.**
34.50±13.01	32.17	23.75,43.92	34.30±14.36	32.33	23.00,41.75	0.765

Mann-Whitney U test was utilized to determine between group differences in a three-trial -average from concussed and non-concussed

No Group Differences

Table 6. Comparing Neck Circumference in Concussed and Non-Concussed Athletes

Concussed (N=14)			Non-concussed (N=32)			
Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**	**Sig.**
38.41±2.45	38.5	36.75,39.63	40.46±1.99	41	39.25,42.00	0.004*

Independent T test was utilized to determine between group differences in concussed and non-concussed neck circumference measurements

Significantly greater differences were shown in the non-concussed group

4.2 Neck Performance in Concussed and Non-concussed Men's Soccer Athletes

Description of neck performance data stratified by sport is displayed in tables 6-9. Men's soccer athletes in the concussed and non-concussed group had equal proportions of suboccipital pain or tenderness with no suboccipital tightness. Segmental mobility examinations showed greater proportions for positive tests in the non-concussed group. A greater percentage of successful head repositioning trials in the right direction was demonstrated in the non-concussed group. Men's soccer DNFT resulted in lower mean timed trials in the concussed group. Neck circumference had greater mean measurements in the non-concussed group.

Table 7. Neck Performance in Men's Soccer Concussed and Non-Concussed

	Concussed(N=11) Proportion (%)	**Non-concussed(N=11)** Proportion (%)
Suboccipital Palpation- Tenderness or Pain	1/11=9.1%	1/11=9.1%
Suboccipital Tightness	0/11=0.00%	0/11=0.00%
Suboccipital Palpation No pain or Tightness	10/11=90.9%	10/11=90.9%
Motion Restriction	2/11=18.2%	5/11=45.5%
CCJ Hypermobility	0/11=0.00%	1/11=9.1%
CCJ Instability	2/11=18.2%	4/11=36.4%

Percentage of positive tests

Table 8. Men's Soccer Head Repositioning Test Concussed vs. Non-concussed

	Concussed (N=11)			Non-concussed (N=11)		
	Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**
HRR	0.36±0.35	0.33	0.00,0.33	0.54±0.37	0.33	0.33,1.00
HRL	0.36±0.38	0.33	0.00,0.67	0.51±0.35	0.33	0.33,1.00

HRT displayed as percentage of successful trials for concussed and non-concussed groups

HRR= percentage of head reposition trials passed in the right direction

HRL= percentage of head reposition trials passed in the left direction

Table 9. Deep Neck Flexor Endurance in Men's Soccer Concussed and Non-Concussed

Concussed (N=11)			Non-Concussed (N=11)		
Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**
35.12±13.20	38.0	24.00, 43.00	29.88±8.79	30.67	23.00, 35.67

DNFT of a three-trial average from concussed and non-concussed

Table 10. Neck Circumference of Men's Soccer: Concussed and Non-Concussed

DNFT	Concussed (N=11)		Non-Concussed (N=11)			
Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**	**Sig.**
37.73±1.95	38	36.00,39.00	39.27±1.84	40	38.00,40.00	0.071

4.3 Neck Performance in Concussed and Non-concussed Men's Wrestling Athletes

Description of neck performance data of male wrestlers is displayed in tables 11-14. Men's wrestling athletes in the non-concussed group had increased proportions of positive tests in suboccipital pain or tenderness and the concussed group had no pain or tightness upon palpation. All cervical examinations resulted in increased proportions of positive test percentages in the concussed group. A greater percentage of successful head repositioning trials in the right direction was demonstrated in the non-concussed group. Regarding the DNFT, the non-concussed group among had greater mean timed trials. Neck circumference had greater mean measurements in the non-concussed group, showing a 1 cm difference.

Table 11. Neck Performance in Men's Wrestling Concussed Vs. Non-Concussed

	Concussed (N=3)	Non-concussed (N=21)
	Proportion (%)	Proportion (%)
Suboccipital Palpation Tenderness or Pain	0/3=0.00%	3/21=14.30%
Suboccipital Tightness	0/3=0.00%	0/3=0.00%
Suboccipital Palpation No pain or Tightness	3/3=100%	16/21=76.20%
Motion Restriction	1/3=33.30%	8/21=38.10%
CCJ Hypermobility	1/3=33.30%	10/21=47.60%
CCJ Instability	0/3=0.00%	8/21=38.10%

Percentages of positive tests

Table 12. Men's Wrestling Head Repositioning Test Concussed vs. Non-concussed

	Concussed (N=3)			Non-Concussed (N=21)		
	Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**
HRR	0.44±0.51	0.33	0.00,0.33	0.61±0.35	0.67	0.33,1.00
HRL	0.67±0.34	0.67	0.33,0.67	0.63±0.38	0.67	0.33,1.00

HRT displayed as percentage of successful trials

HRR= percentage of head reposition trials passed in the right direction

HRL= percentage of head reposition trials passed in the left direction

Table 13. Deep Neck Flexor Endurance in Men's Wrestling Concussed and Non-Concussed

Concussed (N=3)			Non-Concussed (N=21)		
Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**
32.22±14.83	24.33	23.00,43.92	36.61±16.26	32.66	22.50,54.00

DNFT of a three-trial average from concussed and non-concussed

Table 14. Neck Circumference of Men's Wrestling Concussed and Non-Concussed

Concussed (N=3)			Non-Concussed (N=21)		
Mean±SD	**Median**	**IQR**	**Mean±SD**	**Median**	**IQR**
40.80±2.87	39.5	39.00,40.00	41.09±1.81	41	40.25,42.55

5.0 Discussion

The purpose of this study was to examine cervical spine characteristics between competitive athletes with and without previous concussion history. Previous history of concussion was reported through a Qualtrics survey and cervical characteristics were measured through assessments focusing on segmental mobility, proprioception, and endurance.

It was hypothesized that there would be significant differences in cervical characteristics between athletes with and without a history of concussion. This hypothesis was partially supported by the results of this study, as there were only significant differences between athletes with and without a history of concussion in neck proprioception and neck circumference. Furthermore, this study aimed to collect normative data on neck muscle performance in a sample of competitive athletes.

5.1 Relationship Between Previous Concussion History and Cervical Spine Characteristics in Competitive Athletes

5.1.1 Suboccipital Palpation

Results demonstrated a trend for increased suboccipital pain or tenderness in the non-concussed group. These results were not similar to previous studies that found, by using magnetic resonance imaging and neurocognitive testing, reduced cross sectional area of the suboccipital musculature was associated with increased symptom severity and prolonged recovery post-concussion.(Fakhran August 2016) This indicates that reduced cross sectional area or atrophy of the musculature can cause increased symptoms of pain and tenderness around the suboccipital region. Recent investigations have also identified the presence of fatty infiltration and muscle degeneration in chronic whiplash associated disorder (WAD) patients.(Elliott, Noteboom et al. 2009) The muscular atrophy observed in this population is not fully understood and the subjectivity to chronic patients has not been determined. Investigations on subgrouping these individuals based on clinical presentation post-concussion along with post WAD should be taken into consideration. With this current study, post concussive duration may have affected the results and any associated symptoms may have subsided by the time this data was collected. With the concussion history definition being any subject who had sustained a concussion within the past two years for this study, an injury to the cervical musculature most likely resolved within this time period.

5.1.2 Segmental Mobility Measurement

The present study had no clear pattern or significant differences and failed to detect any clinically relevant group implications. This may be in result of the heavily underpowered sample size. Another consideration would be that these concussed athletes may not have fallen into a cervical trajectory alone. This study was unable to classify the type of trajectory each previously concussed patient exhibited, and additional examinations should be implemented in future studies to attempt to place subjects in certain trajectory groups. For example, incorporating examinations that focus on vestibular, oculomotor, or cognitive symptoms such as the SCAT-5 or imPACT testing may target the cognitive, vestibular, ocular, post-traumatic migraine, or anxiety trajectories.

A study by Schneider et al. observed changes in measures of cervical spine function, vestibulo-ocular reflex, dynamic balance, and divided attention following sport-related concussion in elite youth ice hockey players.(Schneider KJ) Researchers collected baseline measurements and post-concussion measurements with a median post-concussive duration of 4 days. Alterations in measures of the Deep Neck Flexor Endurance Test, Flexion Rotation Test, suboccipital pain, dynamic balance and functional gait assessment, computerized visual acuity using a NeuroCom, and Head Repositioning tests following concussion compared to baseline scores were observed. Research demonstrated all measures significantly decreased following concussion, specifically the flexion rotation test which was positive in 1 participant (1/52, 1.9%) at the preseason evaluation and was positive in 9 of 52 (17.3%) players in the acute period following concussion. This implies that these subjects had dysfunctional C1-C2 motion segment post-concussion. The study also found that 23% of concussed athletes also failed all head repositioning trials.

The current study assessed CCJ hypermobility and instability, specifically screening for the integrity of the alar ligament using the Modified Lateral Shear Test and the C2 Spinous Kick test. Due to the concussive forces and whiplash associated mechanisms being of similar nature, this study intended to see significant differences between groups. This study found no significant group differences for either test. A possible cause could have been the duration between assessments and the actual incident of concussion. The question remains whether CCJ hypermobility is associated with concussion and should be further assessed with future prospective studies.

5.1.3 Neck Circumference

The non-concussed group demonstrated significantly greater neck circumference compared to the concussed group. However, the mean difference was two centimeters, which may not be clinically meaningful. The current study results are in agreement with results of previous literature demonstrating that decreased neck circumference, along with weak neck strength, can put an athlete at greater risk for concussion.[20] More specifically, as muscular strength and neck girth increase, concussion risk decreases.[20] Neck circumference, relative to muscle hypertrophy, could potentially be a modifiable risk factor for this population. For practical considerations, coaches or clinicians should investigate the benefits of neck hypertrophy training in populations at risk for head and neck injury. Future research should also investigate changes in neck circumference during different components of training and competition seasons.

The composition of athletes within the concussed and non-concussed groups may have confounded significant neck circumference results. The non-concussed group was primarily composed of wrestlers (21 of 32 athletes), whereas the concussed group was composed of three wrestlers and 11 soccer players. Additionally, within this study, there was a trend for higher average neck circumference in wrestlers compared to soccer players. These findings suggest that due to the specificity of training and the demands of the sport, wrestlers may have, on average, greater neck circumference than soccer players. Therefore, the results of the current study may have been due to composition of athletes within the groups rather than history of concussion. To determine if this variable was truly confounding, a larger same size should be implemented with a variety of athletes.

5.1.4 Proprioception

Neck proprioception was significantly better in right direction in the non-concussed group compared to the concussed group, which is supported by previous literature. Sterling et al. also found significant differences in whiplash injuries compared to healthy controls during neck rotation repositioning in the right direction. They also found neck rotation to left and neck extension were not significantly different from healthy controls. (Trevleaven 2015) The specific rotational deficit may be a result of an injury that caused a unilateral segmental dysfunction rather than a bilateral injury, affecting right or left rotation alone. Another possible application is that individuals may have a side dominance or preference when it comes to left or right contact. When an athlete has a preferred left or right dominance and an impactful force affects this side, neck proprioception may be altered. With this reason, neck proprioception could have shown significant group differences in a single direction regarding previously injured athletes.

Sterling et al. identified deficits in the motor system as well as persistent deficits in WAD patient's months after injury. (Trevleaven 2015) Another practical implication in the current study could be that the concussed groups may have sustained a WAD that had persistent motor dysfunctions but can only be suggested and it is imperative to investigate clinical subgrouping of symptomology post injury.

Regardless of the post-concussion duration, impaired proprioception has been demonstrated in previously concussed patients. There have been demonstrated changes in the control of head-on-neck motion secondary to altered processing of sensory input from the central nervous system. (Society 2004) Future research should further evaluate neurophysiological alterations in cervical spine function and recovery of proprioceptive deficits post-concussion.

The significant findings in neck proprioceptive outcomes within this study should be investigated further. The reduction of data for neck proprioception was not entirely adequate. The outcome measures lack quantitative measures that may add true validity or sensitivity to cervicogenic proprioception. Previous studies that have used the HRT have used outcome measures that are quantifiable. For example, the distance between zero point (center) and the point where the laser stopped, which is a more appropriate method in clinical research.(Revel 1994) It should be understood that the HRT has also been completed in vertical direction (flexion/extension) along with the rotational horizontal direction.(Heikkila and Wenngren 1998, Hides, Franettovich Smith et al. 2017) The vertical direction was not assessed within the current study. The vertical direction has uncovered greater cervical proprioception deficits within patients of chronic neck pain patients only and not WAD patients specifically. It was recommended that this measure was not appropriate for traumatic neck pain patients, but further research is warranted and the vertical component of the HRT could be implemented in the future. (Treleaven J 2015) De Vries et al. concluded in a systematic review that there are multiple protocols for HRT.(De Vries 2015) Although, the method used in this study could be seen as a quick and simple protocol, it lacks clinical validity. Another study by Chen and Treleaven suggested modifying the HRT further to determine a test that is a more definitive measure of cervical afferent dysfunction. They suggested incorporating the Smooth Pursuit Neck Torsion Test (SPNTT) along with HRT to establish a motor control, vestibular, or cervicogenic impairment.(Chen 2013) The current findings also should allow clinicians to understand that true importance of using consistent protocols and most importantly targeting cervical proprioceptive systems during the acute stage of injury and rehabilitation in cervical trajectory recovery, or concussion recovery as a whole.

5.1.5 Deep Neck Flexor Endurance

No group differences were demonstrated for deep neck flexor endurance. By reviewing each trial of neck endurance, results showed a lower performance mean in trials one through three. Future research may wish to investigate the influence of fatigue on performance of successive trials in neck flexor endurance, as well as investigate if neck flexor fatigue impacts an athlete's risk of head and neck injury. Previous findings have demonstrated altered activation of the deep neck flexor group with deficits in strength and endurance in patients with neck pain or muscular impairments. (Kontos 2012) However, limited literature has assessed the deep neck flexor group in a concussed population. Smith et al. assessed high school football players on clinical measures of deep neck flexor endurance and active range of motion who have a history of concussion. (Treleaven 2006) This study found no significant group differences in both the neck flexor endurance and active range of motion, similarly to the current study. This may indicate the true importance of collecting pre- and post-concussive assessments to observe significant differences. These findings may also indicate that deep neck flexor endurance assessments alone may not fully capture the neurodynamic elements of cervical musculature and additional assessments of the cervical spine that target all systems should be incorporated in further studies.

Further discussing muscular strength, the first and only normative dataset on healthy adults for the deep neck flexor isometric hold times are 38.9 ± 20.10 seconds. (Gessel 2007) The current study found within concussed male adults a mean hold time was 34.50±13.01seconds. Non-concussed male adults mean hold time was 34.30±14.36 seconds. These group means were 4.00 seconds lower in an athletic NCAA population in both concussed and non-concussed groups. This may suggest a revisit in normative data research on neck flexor endurance on healthy adults as well as athletic healthy adults. Reviewing temporal sequences of data collection once again, these athletes may have had a lower endurance due to mid-season testing as well as no information on whether the athlete participated in any work prior to testing was recorded which could have impacted the results.

5.2 Description of Neck Performance Within Sports

The second specific aim of this study was a descriptive aim, so trends in the data, instead of statistical inferences, were described. The two sports that were assessed were wrestling and soccer, which are two unique sports that require different muscular adaptations.

Wrestling athletes take on stressful loads to the neck during practice and competition on a regular basis. Interestingly segmental mobility examinations revealed a higher percentage of positive outcomes in the non-concussed group. Men's wrestling athletes, on average, had larger neck circumference mean values compared to men's soccer athletes. A study that assessed neck circumference and strength measures in wrestlers (aged 19-25 years old) identified significantly greater outcomes compared to a non-athletic population.(Rezasoltani A 2005) This study also found that among elite wrestlers, there are no significant differences in neck circumference between styles or weight and found an average of 41.58 ±2.81 cm.(Rezasoltani A 2005) Although no conclusions can be made, the larger neck circumference trends in the current study may complement previous findings. In the Modified Lateral Shear Test (10/21=47.60%) and the C2 Spinous Kick test (8/21=38.10%), there was a greater proportion of subjects with positive tests in the non-concussed group within men's wrestling. With no clear patterns in the results, it is difficult to observe any trends for mobility and joint instability. Future research is necessary to investigate cervical characteristics to assess CCJ hypermobility, instability, cervicogenic dizziness and neck pain in relation to concussion within sport. Regarding proprioception, wrestlers had greater proportions of successful trials and had greater mean values for the DNFT in the non-concussed group (36.61±16.26). These trends may provide insight for future investigation on wrestling athletes for neck strength and proprioception testing with and without a history of concussion.

Soccer athletes, alternatively, utilize the neck to intentionally head the ball during play and take on concussion risk during high velocity, repetitive impacts.(Bretzin A April 2017) In the current study, within men's soccer, neither subjects in the concussed nor non-concussed groups demonstrated suboccipital pain, tenderness or tightness. As previously mentioned, on average, men's soccer athletes had a smaller neck circumference than wrestlers. Average neck circumference measures have been previously described for male soccer athletes by Bretzin et al. (Bretzin A April 2017) They found an average of 35.90± 1.63 cm in NCAA Division I soccer athletes and also concluded that increased neck circumference, as well as strength, may be factors that limit head impact kinematics. Within this study, men's soccer also performed worse in the concussed group for the HRT trials and alternatively had greater DNFT mean values (39.27±1.84) in the concussed group, which may provide insight to further assess proprioception in soccer athletes only. Although results of the current study are strictly descriptive, due to the nature of each sport and physical demands, there is sport specific normative data that should be further evaluated and may be beneficial to inform coaches and clinicians about sport specific neck strengthening programs pre or post-injury.

5.3 Study Significance

This is one of the first studies to explore differences in cervical spine characteristics y to compare between athletes with and without a recent history of concussion. The results of this study provide insight to the complexities of concussion symptomology, particularly to the cervical spine, and provides evidence that clinical examinations need to be assessed further in their ability of diagnosing concussion trajectories. Normative data on neck muscle performance in competitive athletes are beneficial for clinicians who seek to further evaluate neck muscle performance in a concussed and non-concussed population for purposes of prevention, diagnosis, and rehabilitation.

Identifying specific concussion trajectories allows clinicians to develop individualized and unique treatment plans for concussed patients. More importantly, an active specialized therapy is required to fully treat and rehabilitate these patients. Determining clinical trajectories will provide more information on the pathology of the injury as well as what area of the brain the concussion has affected. Research is still in the early stages to produce guidelines and gold standard techniques to evaluate each trajectory, which is why a call to research is so imperative. If researchers find differences in cervical characteristics, these findings may attempt to open doors for future researchers and allows for further understanding of this population.

5.4 Limitations

This study has several limitations. The sample size was heavily underpowered; the required amount was 154 with 77 in each group. This study analyzed only 46 subjects, which likely affected statistical significance. It is important to recognize in the present study that the duration post-concussion was an impactful limitation to the results. The operational definition of previous concussion in the current study may have been clinically unacceptable. A concussive trauma occurring within the past two years of data collection was considered a concussed individual. It is known that 80-90% of concussions resolve within 7 to 10 days and any injury most likely resolved in this study showing no significance. (Capo-Aponte 2012) Due to the resolution of concussion symptoms occurring within the first week, it would have been more clinically appropriate to study clinically diagnosed concussed athletes in a time period closer to the concussive event. Self-reported concussion is a common method within youth and college level sports, these athletes may not be consistent in reporting medical information. A reliability study of self-reported concussion history found that a greater degree of inconsistency was associated with a greater number of concussions initially reported at baseline. (Covassin 2017) The sample size of this study was underpowered, however findings from this previous study may also indicate that measuring previous concussion history that is self-reported may not be the most appropriate method to detect previous concussion history.

Significant differences were found in proprioception. However, these results were qualitative measures (i.e. passing or failing head repositioning) and lack clinical sensitivity. Future studies should implement quantitative measures to add clinical sensitivity, validity, and applicability. This can be said for the Flexion Rotation Test as well. Previous studies that have found group differences in the Flexion Rotation Test using quantitative measures, assessing the degree of range of motion rather than using "positive or negative" measures. (Society 2004) They also reported whether the provocation of symptoms such as dizziness occurred. Additionally, there is a lack of validity data on clinical exams differentiating a concussion from a cervicogenic pathology, as well as an awareness of appropriate tests and methods for this population. If this study was able to establish a larger sample size and see any significance this could have had a substantial benefit to validity data research. Lastly, the inclusion criteria were restrictive. The population was strictly NCAA athletes. If this study were to include physically active adults, there may have been better recruitment outcomes.

Future studies should implement prospective methods with an appropriate sample size. Recruitment methods should be adjusted to a one-one match for concussed versus controls and a larger sample size with male and females with multiple sports, allowing for pre and post testing.

It is important to study subjects who have sustained a concussion with a shorter time period post concussive event to be more clinically applicable. Future studies should also consider additional clinical examinations that target cervicogenic impairments, along with the five other trajectories, with strong clinical utility.

5.5 Conclusions

This study was one of the first studies to examine previous concussion history and cervical spine characteristics measured during clinical examinations. Minimal between-group differences in cervical characteristics were demonstrated between concussed versus non-concussed groups, Clinicians should examine craniocervical characteristics to help further understand potential concussion trajectories and establish appropriate rehabilitation protocols. Comprehensive rehabilitation programs that incorporate neck proprioception protocols, including visual, vestibular, and oculomotor rehabilitation, (Broglio 2011) may be important for concussion patients exhibiting characteristics consistent with a cervical injury trajectory. Additionally, clinicians and coaches should further evaluate the importance of neck circumference and strength/endurance as modifiable risk factors for head and neck injury and to inform both strength and conditioning and rehabilitation protocols Overall, this study may provide important insight to clinicians investigating cervical function and cervicogenic symptoms related to a head-neck segment pathomechanical event.

Bibliography

Al Sayegh, A., D. Sandford and A. J. Carson (2010). "Psychological approaches to treatment of postconcussion syndrome: a systematic review." J Neurol Neurosurg Psychiatry **81**(10): 1128-1134.

al., T. e. (2011). "Normal kinematics of the upper cervical spine during the Flexion-Rotation test – In vivo measurements using magnetic resonance imaging." Manual Therapy.

Anderst, W. J., W. F. Donaldson, J. Y. Lee and J. D. Kang (2013). "Cervical spine intervertebral kinematics with respect to the head are different during flexion and extension motions." J Biomech **46**(8): 1471-1475.

Barton PM, H. K. (1996). "Neck flexor muscle strength, efficiency, and relaxation times in normal subjects and subjects with unilateral neck pain and headache." Arch Phys Med Rehabil. **77: 680-687. 10**.

Benzel, E. (2012). Spine Surgery(3rd Edition).

Bogduk N, M. S. (Novermber 2000). "Biomechanics of the Cervical Spine." Clinical Biomechanics **15(9)**.

Bretzin A, M. J., Tierney R, McDevitt J (April 2017). "Sex Differences in Anthropometrics and Heading Kinematics Among Division I
Soccer Athletes: A Pilot Study." Sports health **9**.

Broglio, S., Collins, M, Williams, Mucha, A, Kontos, A (2016). "Current and emerging rehabilitation for concussion: A review of the evidence." Clin Sports Med.

Broglio S, C. R., Gioia G, Guskiewicz K, Kutcher J, Palm M, Valovich McLeod T, (2014). "National Athletic Trainers' Association Position Statement: Management of Sport Concussion." Journal of Athletic Training.

Broglio, S., Surma, T, Ashton-Miller, J (2011). "High school and collegiate football athlete concussions: A biomechanical review." Ann Biomed Eng.

Broglio SP, M. S., Ferrara MS (2007). "Sensitivity of the concussion assessment battery. Neurosurgery."

Capo-Aponte JE, U. T., Temme LA, Tarbett AK, Sanghera NK (2012). "Visual dysfunctions and symptoms during the subacute stage of blast-induced mild traumatic brain injury. ."

Cheever, K., K. Kawata, R. Tierney and A. Galgon (2016). "Cervical Injury Assessments for Concussion Evaluation: A Review." J Athl Train **51**(12): 1037-1044.

Chen, X. a. T., J (2013). "The effect of neck torsion on joint position error in subjects with chronic neck pain." Man Ther.

Collins M, K. A., Reynolds E, Murawski C, Fu F (2014). "A comprehensive, targeted approach to the clinical care of athletes following sport-related concussion." Knee Surg Sports Traumatol Arthrosc.

Collins, C. L., E. N. Fletcher, S. K. Fields, L. Kluchurosky, M. K. Rohrkemper, R. D. Comstock and R. C. Cantu (2014). "Neck strength: a protective factor reducing risk for concussion in high school sports." J Prim Prev **35**(5): 309-319.

Collins, M. W., A. P. Kontos, D. O. Okonkwo, J. Almquist, J. Bailes, M. Barisa, J. Bazarian, O. J. Bloom, D. L. Brody, R. Cantu, J. Cardenas, J. Clugston, R. Cohen, R. Echemendia, R. J. Elbin, R. Ellenbogen, J. Fonseca, G. Gioia, K. Guskiewicz, R. Heyer, G. Hotz, G. L. Iverson, B. Jordan, G. Manley, J. Maroon, T. McAllister, M. McCrea, A. Mucha, E. Pieroth, K. Podell, M. Pombo, T. Shetty, A. Sills, G. Solomon, D. G. Thomas, T. C. Valovich McLeod, T. Yates and R. Zafonte (2016). "Statements of Agreement From the Targeted Evaluation and Active Management (TEAM) Approaches to Treating Concussion Meeting Held in Pittsburgh, October 15-16, 2015." Neurosurgery **79**(6): 912-929.

Covassin, T., J. L. Savage, A. C. Bretzin and M. E. Fox (2017). "Sex differences in sport-related concussion long-term outcomes." Int J Psychophysiol.

CR, W. (2015). "Wheeless' Textbook of Orthopaedics." Duke Orthopaedics.

Cramer, G., Darby, SA. (2005). "Basic and Clinical Anatomy of The Spine, Spinal Cord, and ANS." (2nd edition).

Daneshvar, D. H., C. J. Nowinski, A. C. McKee and R. C. Cantu (2011). "The epidemiology of sport-related concussion." Clin Sports Med **30**(1): 1-17, vii.

De Vries, J., Ischebeck, B, Voogt, L, Van der Geest, J, Janssen, M, Frens, M, Kleinrensink (2015). "Joint position sense error in people with neck pain: A systematic review."

Defrin, R. (2014). "Chronic post-traumatic headache: clinical findings and possible mechanisms." J Man Manip Ther **22**(1): 36-44.

Domenech MA, S. P., Dedrick GS, McGalliard MK, Brismee JM. (2011 Feb.). "The Deep Neck Flexor Endurance Test: normative data scores in healthy adults." PM R.

Dunkley, B. T., L. Da Costa, A. Bethune, R. Jetly, E. W. Pang, M. J. Taylor and S. M. Doesburg (2015). "Low-frequency connectivity is associated with mild traumatic brain injury." Neuroimage Clin **7**: 611-621.

Elliott, J. M., J. T. Noteboom, T. W. Flynn and M. Sterling (2009). "Characterization of acute and chronic whiplash-associated disorders." J Orthop Sports Phys Ther **39**(5): 312-323.

Ellis MJ, L. J., Willer B (2015). "Physiological, vestibulo-ocular and cervicogenic post-concussion disorders: an evidence-based classification system with directions for treatment.".

Fakhran, X. S. Q., X C, and Alhilali, X L.M. (August 2016). "Effect of the Suboccipital Musculature on Symptom Severity and Recovery after Mild Traumatic Brain Injury." AJNR Am J Neuroradiol 37:1556 – 60.

Gessel LM, F. S., Collins CL, et al. (2007). "Concussions among United States high school and collegiate athletes." J Athletic Training

Graham, R. (2015). "Sports-related concussions in youth: improving the science, changing the culture." Mil Med **180**(2): 123-125.

Harmon KG, D. J., Gammons M, Guskiewicz K, Halstead M, Herring S, Kutcher J, Pana, A, Putukian M,Roberts W (2018). "American Medical Society for Sports Medicine position statement: concussion in sport." Sports Medicine.

Harris KD, H. D., Roy TC, Santos DM, Whitman JM, Wainner RS. (2005 Dec.). " Reliability of a measurement of neck flexor muscle endurance.”." Physical Therapy.

Heikkila, H. V. and B. I. Wenngren (1998). "Cervicocephalic kinesthetic sensibility, active range of cervical motion, and oculomotor function in patients with whiplash injury." Arch Phys Med Rehabil **79**(9): 1089-1094.

Hides, J. A., M. M. Franettovich Smith, M. D. Mendis, N. A. Smith, A. J. Cooper, J. Treleaven, F. Leung, A. J. Gardner, P. McCrory and N. L. Low Choy (2017). "A prospective investigation of changes in the sensorimotor system following sports concussion. An exploratory study." Musculoskelet Sci Pract **29**: 7-19.

Hootman, J. M. D., R; Agel, J (2007). "Epidemiology of Collegiate Injuries for 15 Sports: Summary and Recommendations for Injury Prevention Initiatives " Journal of Athletic Training.

Hynes LM, D. J. (2006). " Is there a relationship between whiplashassociated disorders and concussion in hockey? A preliminary study." Brain Injury

Iverson GL, B. B., Collins MW, Lovell MR (2006). "Tracking neuropsychological recovery following concussion in sport.".

J., B. W. (2010). "Cervicogenic headache: evidence that the neck is a pain generator." Headache.

J.J. Leddy, J. G. B., B. Willer (2016). "Active rehabilitation of concussion and post-concussion syndrome." Phys. Med. Rehabil. Clin. N. Am.,: 437-454.

Jin X, F. Z., Mika V, Li H, and Y. K. Viano D (2017). "The Role of Neck Muscle Activities on the Risk of Mild Traumatic Brain Injury in American Football." JournalofBiomechanicalEngineering **139**.

JS., H. (2004). "Occipital nerve blocks in postconcussive headaches: a retrospective review and report of ten patients." J Head Trauma Rehabil.

Jull, G., P. Trott, H. Potter, G. Zito, K. Niere, D. Shirley, J. Emberson, I. Marschner and C. Richardson (2002). "A randomized controlled trial of exercise and manipulative therapy for cervicogenic headache." Spine (Phila Pa 1976) **27**(17): 1835-1843; discussion 1843.

Jull GA, O. L. S., Falla DL (2008). "Clinical assessment of the deep cervical flexor muscles: the craniocervical flexion test. ." J Manipulative Physiol Ther. **(7): 525-533.**

Juul T, L. H., Enoch F, Søgaar K (2013). "The intra- and inter-rater reliability of five clinical muscle performance tests in patients with and without neck pain." BMS Musculoskeletal Disorders.

Juul T, L. H., Enoch F, Sogaard K (2013). "The intra- and inter-rater reliability of five clinical muscle performance tests in patients with and without neck pain." BMC Musculoskelet Disord.

K., G. (1994). "Measuring the endurance capacity of the cervical short flexor muscle group." Aust J Physiother .

Kania, K., K. A. Shaikh, I. K. White and L. L. Ackerman (2016). "Follow-up issues in children with mild traumatic brain injuries." J Neurosurg Pediatr **18**(2): 224-230.

Kerr, Z., Yengo-Kahn, A. Wasserman, E. Covassin, T. Solomon, G. S. (2016). "Epidemiology of Sports-Related Concussions in National Collegiate Athletic Association Athletes From 2009-2010 to 2013-2014: Symptom Prevalence, Symptom Resolution Time, and Return-to-Play Time." Am J Sports Med. .

Kim, J. Y. and K. I. Kwag (2016). "Clinical effects of deep cervical flexor muscle activation in patients with chronic neck pain." J Phys Ther Sci **28**(1): 269-273.

Kisner, C., Colby, L, Borstad, J, (2018). "Therapeutic Foundations and Concepts." (7th Edition).

Kontos AP, E. R., Schatz P, Covassin T, Henry L, Pardini J, Collins MW (2012). "A revised factor structure for the post con- cussion symptom scale (PCSS): baseline and post-concussion factors. ." Am J Sports Med

Kristjansson E, D. A. P., Jull G (2001). "Cervicocephalic kinaesthesia: reliability of a new test approach." Physiother Res In **6: 224-235. 10.1002.**

KS, C. (1998 Jan. 17). "Epidemiology of Athltic Neck Injury." Clini Sports Med **1**: 83-97.

Kucera, K., Yau, R, Register-Mihalik, J, Marshall,S, Thomas, L, Wolf,S,Cantu, R, Mueller, F, Guskiewcz, K (2017). "Traumatic Brain and Spinal Cord Fatalities Among High School and College Football Players — United States, 2005–2014." Centers for Disease Control and Prevention, U.S. Department of Health & Human Services.

Langlois JA, R.-B. W., Wald MM (2006). "The epidemiology and impact of traumatic brain injury: a brief overview." J Head Trauma Rehabi.

Lau BC, K. A., Collins MW, Mucha A, Lovell MR (2011). "Which on-field signs/symptoms predict protracted recovery from sport-related concussion among high school football players? ."

Lee, H. Y., Teng,C. et al (2006). "Test-restest reliability of cervicocephalic Kinesthetic sensibility in three cardinal planes." Man Ther.

Lopez, A. J., J. K. Scheer, K. E. Leibl, Z. A. Smith, B. J. Dlouhy and N. S. Dahdaleh (2015). "Anatomy and biomechanics of the craniovertebral junction." Neurosurg Focus **38**(4): E2.

Loudon JK, R. M., Field E (1997). " Ability to reproduce head position after whiplash injury. Spine.".

Lovell MR, C. M., Iverson GL, Johnston KM, Bradley (2004). "Grade 1 or ‘‘ding’’ concussions in high school athletes." JP Am J Sports Med

Makdissi, M., K. J. Schneider, N. Feddermann-Demont, K. M. Guskiewicz, S. Hinds, J. J. Leddy, M. McCrea, M. Turner and K. M. Johnston (2017). "Approach to investigation and treatment of persistent symptoms following sport-related concussion: a systematic review." Br J Sports Med **51**(12): 958-968.

Maron BJ, Z. D., Kovacs RJ. (2015). "Eligibility and Disqualification Recommendations for Competitive Athletes With Cardiovascular Abnormalities: Preamble, Principles, and General Considerations: A Scientific Statement from the American Heart Association and American College of Cardiology." J Am Coll Cardiol **66:2343-9.**

Marshall C, V. H., Leddy, J, Baldwin B (2015). "The role of the cervical spine in post-concussion syndrome." Phys Sportsmed.

Martin, M. D., H. J. Bruner and D. J. Maiman (2010). "Anatomic and biomechanical considerations of the craniovertebral junction." Neurosurgery **66**(3 Suppl): 2-6.

Mathers SK, S. M., Timko M "Occult Hypermobility of the Craniocervical Junction: A Case Report and Review." journal of orthopaedic & sports physical therapy **41**: 444-457.

McCrory P, M. W., Aubry M, Cantu B, Dvorák J, Echemendia RJ, Engebretsen L, Johnston K, Kutcher JS, Raftery M, Sills A, Benson BW, Davis GA, Ellenbogen RG, Guskiewicz K, Herring SA, Iverson GL, Jordan BD, Kissick J, McCrea M, McIntosh AS, Maddocks D, Makdissi M, Purcell L, Putukian M, Schneider K, Tator CH, Turner M (November 2012). "Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich,." Br J Sports Med.

McCrory P, M. W., Dvořák J, Aubry M, Bailes J, Broglio S, Cantu RC, Cassidy D, Echemendia RJ, Castellani RJ, Davis GA, Ellenbogen R, Emery C, Engebretsen L, Feddermann-Demont N, Giza CC, Guskiewicz KM, Herring S, Iverson GL, Johnston KM, Kissick J, Kutcher J, Leddy JJ, Maddocks D, Makdissi M, Manley GT, McCrea M, Meehan WP, Nagahiro S, Patricios J, Putukian M, Schneider KJ, Sills A, Tator CH, Turner M, Vos PE (2017 Jun; 51). "Consensus statement on concussion in sport-the international conference on concussion in sport held in Berlin, October 2016." Br J Sports Med. **(11):838-847.**

McGrath N, D. W., Collins MW, Lovell MR, Elbin RJ, Kontos AP (2013). " Post-exertion neurocognitive test failure among student-athletes following concussion. ."

McLeod, T. C., & Leach, C. (2012). "Psychometric properties of self-report concussion scales and checklists. ." Journal of athletic training **47(2), 221-3.**

Meehan WP 3rd, d. H. P., Collins CL, Taylor AM, Comstock RD (2012). "Computerized neurocognitive testing for the management of sport-related concussion. ."

Mihalik JP, G. K., Marshall SW, et al. (2011). "Does cervical muscle strength in youth ice hockey players affect head impact biomechan- ics?" Clin J Sport Med.

Naish R, B. A., Burrows S, et al. (2013). "Can specific neck strengthening programs decrease cervical spine injuries in a men's professional rugby union team? A retrospective analysis." J Sports Sci Med.

Nelson, L. D., K. M. Guskiewicz, S. W. Marshall, T. Hammeke, W. Barr, C. Randolph and M. A. McCrea (2016). "Multiple Self-Reported Concussions Are More Prevalent in Athletes With ADHD and Learning Disability." Clin J Sport Med **26**(2): 120-127.

O’leary S, F. D., Elliot JM, Gwendolen J (May 2009). "Muscle Dysfunction in Cervical Spine Pain: Implications for Assessment and Management." journal of orthopaedic & sports physical therapy **39**(5).

Ogince M, H. T., Robinson K. (2007). "The diagnostic validity of the cervical flexion-rotation test in C1/2 related cervicogenic headache. ." Man Ther.

Oliver, L., Neil, C, (2013). "Concussion: Purely a Brain Injury?" Clinical Journal of Sport Medicine **23**(5): 331-332.

Osmotherly P, R. D., Rowe L. (2013). "Toward understanding normal craniocervical rotation occurring during the rotation stress test for the alar ligaments.".

Osmotherly PG, R. D., Rowe LJ. (2013). "Toward understanding normal craniocervical rotation occurring during the rotation stress test for the alar ligaments." Phys Ther. **93(7):986-92**.

Osmotherly PG, R. D., Rowe LJ. (2012). "Construct validity of clinical tests for alar ligament integrity: an evaluation using magnetic resonance imaging." Phys Ther **92(5): 718-25**.

Osmotherly, P. G., D. A. Rivett and L. J. Rowe (2012). "Construct validity of clinical tests for alar ligament integrity: an evaluation using magnetic resonance imaging." Phys Ther **92**(5): 718-725.

Pardini J, S. J., Lovell MR, Collins MW, Moritz K, Fu F (2004). "The post concussion symptom scale (PCSS): a factor analysis [abstract]." Br J Sports Med.

Pellman EJ, P. J., Viano DC, et al. ;54:81–94; discussion 86–9 (2004). "Concussion in professional football: epidemiological features of game injuries and review of the literature—part 3." Neurosurgery**;54:81–94; discussion 86–9**.

Pho C , G. J. (2018). "Management of Whiplash-Associated Disorder Addressing Thoracic and Cervical Spine Impairments: A Case Report." Journal of Orthopaedic & Sports Physical Therapy.

Piovesan EJ, K. P., Oshinsky ML (2003). "Convergence of cervical and trigeminal sensory afferents." Curr Pain Headache

Prevention, C. F. D. C. a. "Concussion Signs and Symptoms Checklist."

Prevention, N. D. C. f. S. I. R. a. (2009). "Men's Soccer Injuries."

Prevention., C. f. D. C. a. (2007). "Nonfatal traumatic brain injuries from sports and recreation activities—United States, 2001-2005." Morb Mortal Wkly

R. Tierney, M. S., B. Swanik, K.Swanik, M. Higgins, J. Torg (2005). "Gender differences in head-neck segment dynamic stabilization during head acceleration." Med. Sci. Sports Exerc.

Reneker JC, C. M. M., Cook CE (2015). "The diagnostic utility of clinical tests for differentiating between cervicogenic and other causes of dizziness after a sports-related concussion: An international Delphi study." J Sci Med Sport.

Revel, M., Minguet, M, Gergoy, P, Vaillant,J, Manuel, J (1994). "Changes in Cervicocephalic Kinesthesia After a Proprioceptive Rehabilitation Program in Patients With Neck Pain: A Randomized Controlled Study " Arch Phys Med Rehabil Vol 75, .

Rezasoltani A, A. A., Nehzate-Khoshroh M, Forohideh1, F Ylinen J (2005). "Cervical muscle strength measurement in two groups of elite Greco-Roman and free style wrestlers and a group of non-athletic subjects."

Schatz P, S. N. (2012). "Sensitivity and specificity of the online version of ImPACT in high school and collegiate athletes." Am J Sports Med.

Schmidt J, G. K. and M. J. Blackburn J, Siegmund GP, Marshall SW, (2014). "The Influence of Cervical Muscle Characteristics on Head Impact Biomechanics in Football." The American Journal of Sports Medicine **42**.

Schmidt JD, G. K. and M. J. Blackburn JT, Siegmund, GP, Marshall SW (2014). "The Influence of Cervical Muscle Characteristics on Head Impact Biomechanics in Football." The American Journal of Sports Medicine **42**(9).

Schneider KJ, M. W., Nettel-Aguirre A, Barlow K, Boyd L, Kang J, Emery CA "Changes in Measures of Cervical Spine Function, Vestibulo-ocular Reflex, Dynamic Balance, and Divided Attention Following Sport-Related Concussion in Elit Youth Ice Hockey Players." Journal of Orthopaedic & Sports Physical Therapy.

Schneider KJ, M. W., Nettel-Aguirre A, Barlow K, Boyd L, Kang J, Emery CA (2014). "Cervicovestibular rehabilitation in sport-related concussion: a randomised controlled trial." Br J Sports Med.

Schwarzbold M, D. A., Martins ET, et al. (2008). "Psychiatric disorders and traumatic brain injury. ." Neuropsychiatric Disease and Treatment.**;4(4):797-816.**

Sjolander P, M. P., Jaric S, Djupsjobacka M. "Sensorimotor disturbances in chronic neck pain-Range of motion, peak velocity, smoothness of movement, and repositioning acuity." Man Ther

Smith A. D., J. G., Schneider G., Frizzell B., Hooper R. A., Sterling M. (2013). "A comparison of physical and psychological features of responders and non-responders to cervical facet blocks in chronic whiplash." BMC Musculoskeletal Disorders.

Society, H. C. S. o. t. I. H. (2004). The international classification of headache disorders, 2nd edition. .

Society., H. C. S. o. t. I. H. (2004). "The international classification of headache disorders." 2nd edition. Cephalalgia **24:suppl 1.**

Spitzer WO, S. M., Salmi LR, Cassidey JD, Duranceau J, Suissa S, et al. (1995). "Scientific monograph of the Quebec Task Force on Whiplash-Associated Disorders: redefining whiplash and its management." Spine.

Swartz, E. E., R. T. Floyd and M. Cendoma (2005). "Cervical spine functional anatomy and the biomechanics of injury due to compressive loading." J Athl Train **40**(3): 155-161.

T. Pham, A. E., A. Wu (2017). "Dystonia Gravidarum Improved After Joint Position Error Training."

Teel E, W. E., Register-Mihalik J, Mihalik J (2017). "Baseline symptoms are associated with post-concussion symptom frequency and severity in college and high school athletes."

Treleaven, J., ,Jull, G,,Sterling,M. D (2003). "Dizziness and unsteadiness following whiplash injury: characteristic features and relationship with cervical joint position error." Rehabil Med.

Treleaven J, J., G, Lowchoy, N (2006). "The relationship of cervical joint position error to balance and eye movement disturbances in persistent whiplash.".

Treleaven, J., Jull, G, Atkinson, L. (1994). "Cervical Musculoskeletal Dysfunction in Post-Concussional Headache." Departmnet of Neurosugery **14**(4).

Treleaven J, T. H. (2015). " High variability of the subjective visual vertical test of vertical perception, in some people with neck pain - should this be a standard measure of cervical proprioception?" Man Ther.

Van Mameren, H., J. Drukker, H. Sanches and J. Beursgens (1990). "Cervical spine motion in the sagittal plane (I) range of motion of actually performed movements, an X-ray cinematographic study." Eur J Morphol **28**(1): 47-68.

Viano, D. C., Casson, I. R., and Pellman, E. J. (2007). "Concussion in Professio- nal Football: Biomechanics of the Struck Player—Part 14." Neurosurgery.

WF, W. (1980). "The Spinal Cord and Its REaction to Traumatic Injury." Anatomy, Physiology, Therapeutics. .

White, A. A., 3rd, R. M. Johnson, M. M. Panjabi and W. O. Southwick (1975). "Biomechanical analysis of clinical stability in the cervical spine." Clin Orthop Relat Res(109): 85-96.

Ylinen, J., E. P. Takala, M. Nykanen, A. Hakkinen, E. Malkia, T. Pohjolainen, S. L. Karppi, H. Kautiainen and O. Airaksinen (2003). "Active neck muscle training in the treatment of chronic neck pain in women: a randomized controlled trial." JAMA **289**(19): 2509-2516.

Zuckerman S, K. Z., Yengo-Kahn A, Wasserman E, Covassin T, Solomon G (2015). "Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms." Am J Sports Med.

Zuckerman, S. L., Z. Y. Kerr, A. Yengo-Kahn, E. Wasserman, T. Covassin and G. S. Solomon (2015). "Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms." Am J Sports Med **43**(11): 2654-2662.