Neck Strength-Endurance Assessment: Potential Utility in Sport-Related Concussion

by

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Abstract

Neck strength may modify the risk of sport related concussion by controlling head acceleration during high risk impacts. The majority of literature evaluates maximal neck strength leaving other parameters less-explored. Thus, the purpose of this study was to assess neck strength-endurance in male and female athletes. We hypothesized: (1) females would perform poorer on the neck assessment compared to males; (2) athletes with a history of concussion would perform poorer than those with no history of concussion. Neck strength-endurance (flexion, extension, left and right flexion) was assessed in ninety-seven (n = 97) interuniversity athletes. The majority (68%) of participants failed one or more directions of the neck assessment, and most often in flexion (38%) and bi-lateral flexion (33%). There were no significant differences in neck strength-endurance between participants with and without history of concussion or between sexes. These results support assessing neck parameters in an attempt to reduce direction-specific deficits.
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Introduction

Concussions are one of the most common sport injuries across all ages and level of competition. In the United States, 300,000 sport-related concussions (SRCs) are reported annually, representing 5.8% and 8.9% of all collegiate and high school injuries, respectively (1). In Canada, injury rates of 15-20% have been reported in youth and inter-university sport (2). These reported incidence rates of concussion, however, are believed to be underestimated due to under-reporting and/or self-management (3). Regardless of actual frequency, there is growing uncertainty surrounding participation in contact and collision sports due to the increased awareness of potential short- and long-term neurological consequences of SRCs (4).

A concussion is a form of mild traumatic brain injury (mTBI) induced by biomechanical forces transmitted to the head, from direct or indirect inertial forces inflicted on the body (5). The linear and rotational acceleration of the head results in a combination of compressive and diffuse axonal strain at the level of the brain tissue (5,6). This induces a pathophysiological process within the brain resulting in neurological, vestibular and somatic signs and symptoms (5,6). There is no definitive head acceleration threshold for concussion; however, in vivo head accelerometer data on athletic concussive events have reported ranges of 31.8 g-112.1g for linear and 2911.0-6174.2 rad/s² for angular accelerations (7).

Research to date has primarily focused on management and recovery of concussion, leaving preventative strategies less explored. Nonetheless, implementation of preventive initiatives in sport have increased in recent years, including rule and policy changes, equipment modifications,
and advised playing techniques(5,8). Eliminating all potential situations to high-risk head impact is likely not possible, as the inherent nature of many contact and collision sports involves some level of impact. However, targeting specific high-risk situations in sport has proven effective by eliminating certain actions and maneuvers(9), as well as improving education about recognition and management of concussion(5).

Hypothetically, improving one’s ability to mitigate head acceleration after impact by specific muscular strengthening may be a viable preventive initiative. Preliminary evidence has identified an association between neck strength and reduced head acceleration in sport(10–19), which may reduce risk of concussion(20). The neck is comprised of the cervical vertebrae, musculature and connective tissues, which all contribute to reinforcement the spine(21) and connect the head and torso. It is postulated that absolute strength of neck muscle reflects a capacity to dissipate and resist impulsive forces placed on the head(14,22,23). Consequently, researchers have evaluated maximal voluntary contraction (MVC) (or maximal strength) of neck musculature and its association to post-impact head kinematics. Early evidence supports the hypothesis that greater MVC is associated with attenuated post-impact linear and rotational acceleration, velocity, and displacement of the head(10–13,16,17,20,24,25). However, these associations may only apply to anticipated, low-velocity impacts, as they are not observed in unanticipated or sport-specific events(11,14,19,26). Despite a promising area for injury prevention, only one study has prospectively examined the relationship between MVC of the neck and incidence of SRC. Specifically, Collins and colleagues(20) reported that high school students reduced their risk of SRC by 5% with every 1-pound increase in neck MVC strength.
Strength ratios across flexion and extension have also been explored; Dezman and colleagues observed more severe head acceleration in soccer players with a larger flexion:extension discrepancy in strength, irrespective of absolute neck strength values (13).

Beyond MVC of neck muscle, alternative neck characteristics have been explored as potential correlates to head stability. Using a dropped load cell, neck stiffness has been evaluated as a potential modulator of head stability. Theoretically achieved by proper spinal alignment, greater surrounding muscle mass, cervical spine compression, and pre-impact muscular co-activation, neck stiffness is directly related to reduced angular displacement and change in velocity of the head after loading (11, 12, 16). Furthermore, cervical muscle fatigue, weakness, or delayed muscular activation may also be a concern as it places forces other tissues to absorb energy and counteract impulsive loads from accelerating the head (17, 25, 27–29). This may lead to further pathology, fatigability and weakness of the neck segment (17, 25, 27–29).

Impacts experienced in sport are highly variable and may not always be expected by the athlete. In situations where the athlete is unable to anticipate or brace for impact, greater neck tissue stiffness may help to absorb and resist post-impact head acceleration. Additionally, impacts can occur in any direction resulting in a combination of linear and rotation forces placed upon the head (6). It is theorized that training of multi-directional neck musculature will improve an individual’s capacity to reduce impulsive forces transmitted to the head.

Although recent experimental evidence holds promise for future concussion prevention initiatives related to neck musculature, there remains no standardized neck assessment strategy that effectively evaluates multiple neck parameters in account of sport-specific scenarios. Therefore, the purpose of the present study was to comprehensively evaluate neck strength in a cohort of interuniversity athletes and investigate the relationship between neck parameters and
previous concussion and sex. The present study provides insight on neck characteristics of interuniversity collision and contact sport athletes and takes initial steps in developing a practical and effective neck assessment for athletes at risk of SRC.

1.1 Literature Review

1.1.1 Concussion

1.1.1.1 Definition of Concussion

Concussion is derived from the Latin term *concussus*, meaning “to shake violently” (30), traditionally characterized by transient, functional disturbances without detectible structural damage to the brain tissue. The lack of objectivity in the signs and symptoms of concussion has created a challenge for detection, diagnosis and management of this injury. As our understanding has evolved, concussion has become known as a form of mild traumatic brain injury (mTBI), involving a unique set of symptoms as a result of injury to the brain. The physical and neurological pathologies of concussion can be detected through neurocognitive testing and self-reported symptomology, which are presented as cognitive, physical and somatic symptoms (5). Developing an understanding of the complexity of this injury is still in its infancy; only within the past 20 years have experts in this field generated a clear consensus on the utility and interpretation of the term: Sport-Related Concussion (SRC).

The first of four Concussion in Sport Group symposia took place in Vienna, Austria in 2001, where the formal definition of SRC was developed. This was followed by four subsequent symposia in Prague, 2004, Zurich, 2008 and most recently, Berlin, 2016. In Vienna, the operational definition of SRC was set forth stating that a concussion is a form of mild traumatic
brain injury, defined as a “complex pathophysiological process affecting the brain, induced by mechanical forces.” This definition went under minor revisions, leading to the most updated definition of SRC:

1) SRC may be caused by either a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head.

2) SRC typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, signs and symptoms evolve over a number of minutes or hours.

3) SRC may result in neuropathological changes, but the acute clinical signs and symptoms largely reflect a functional disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.

4) SRC results in a range of clinical signs and symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive features typically follows a sequential course. However, in some cases symptoms may be prolonged.

The clinical signs and symptoms cannot be explained by drug, alcohol or medication use, or other injuries (such as cervical injuries, peripheral vestibular dysfunction, etc) or other comorbidities (eg, psychological factors or coexisting medial conditions).

Epidemiology of concussion

It is estimated that the United States sees 1.6-3.8 million SRC cases annually(34), which may be a large underestimation due to high rates of underreporting(3). Nearly a quarter of all sport-related emergency visits by Canadian youth involve a TBI, and nearly over half of 500,000 TBI-related annual visits in the US are related to sport(35).
Among intercollegiate and interuniversity athletics, SRC rates are highly sport-specific. In the National Collegiate Athletic Association (NCAA) and Canadian University Sport (USports) football, women’s soccer, wrestling, men’s and women’s ice hockey and rugby show the highest rates of SRC consistently throughout surveillance literature(2,31,32). In Canadian USports, there is a considerably higher incidence of SRC in female (13.08%) compared to male (7.53%) athletes, which is a common observation in many sex-comparable sports(2,33–35). Furthermore, a greater number of SRCs occur in games and competition (66-71%) compared to practices and training (29-36%)(2,33–35).

Self-reported symptoms of concussion resolve in 7-10 days in approximately 80-90% of adults(5), but in some cases symptoms persist well beyond the 10-day mark, which is often the case in pediatric and other vulnerable populations(5). Computerized neurocognitive testing has become more sensitive and specific which has identified a discrepancy in symptom cessation and cognitive recovery in those recovering from concussion. Cognitive deficits tend to persist beyond symptom resolution, suggesting that underlying function may still be impaired after resolution of self-reported symptoms(2,4,5). As such, RTP times have slightly increased over recent years, but this may be a product of improved management rather that increased severity of injuries(33,34).

1.1.1.2 Pathophysiology of Concussion

A concussion, as a form of mTBI, is characterized by a pathophysiological process within the brain, initiated from rapid linear and rotational acceleration of the head(6). This damage presents itself through functional deficits, signs and symptoms experienced by the individual, which occur without detectible microscopic neural damage(36). Immediate mechanical deformation of brain tissue causes shearing of blood vessels, neurons, glial cells, and axons within the brain instigating chemical and mechanical alterations(6). There is a rapid increase in excitatory amino
acids (EAA), specifically glutamate, which increases the calcium (Ca$^{2+}$) and sodium (Na$^+$) influx and potassium (K$^+$) efflux to pathological levels, leading to depolarization at the cellular level. As K$^+$ is more negative than Ca$^{2+}$, a “diffuse spreading depression” crosses the extracellular membrane(37). As a result of altered Ca$^{2+}$ flux, a greater number of Ca$^{2+}$ enter the mitochondria causing mitochondrial dysfunction, leading to oxidative metabolism disturbances that further augment the cellular energy crisis(36). Recent findings support this connection to oxidative stress and altered intracellular redox state, placing stress on the system by free radical expression and metabolic pathway changes(36). These features can lead to longer lasting impairments to the brain and may be partially responsible for cellular vulnerability to subsequent concussion(38).

Shortly after the initial event, energy-dependent sodium-potassium (Na$^+$/K$^+$) pumps are working in over-drive to pump K$^+$ intracellularly and Na$^+$ extracellularly in attempt to re-establish homeostasis(37). This requires high levels of glucose metabolism, demanding excessive aerobic workloads of the already-damaged intracellular mitochondria, which produces excess lactate and depletes glycogen stores. Initial insult can also cause a reduction of cerebral blood flow of up to 50%, reducing energy delivery to the brain(37). Collectively, these metabolic events lead to an uncoupling of energy demand and supply within the brain, which may also present a state of heightened vulnerability to further damage(37,38). Animal models replicating these pathological states have informed assumptions that 3 days in rodents and 10 days in humans is the approximate window of neurobiological vulnerability to second injury(38). The pathophysiology of concussion in humans is still not well delineated and further research is required to gain a more complete understanding of these events in the human brain.

There is much discussion among academic and clinical literature of the heightened susceptibility of pediatric populations to concussion compared to adults. A contributing factor may lie in
pathological characteristics of this populations. Immature brains have less myelination of fibers, which have been shown in fluid percussion models to have a greater vulnerability to concussion(39). Although the immature brain is believed to have greater neuroplasticity in responsive to injury, impairment of glutamate subunit receptor after injury compromises that ability(40). Together with other physical and anthropometric differences discussed later, this physiological characteristic may predispose the pediatric population to injury.

There are many theoretical connections between neurobiological characteristics of concussion and post-concussion symptomology. Migraines, headaches and sensitivity to light are believed to be linked with the ‘spreading depression’ of ionic flux(37), however concomitant neck injury may also contribute to post-concussive headaches(41). Diffuse axonal dysfunction in the form of damaged white matter can be linked to slowed cognition present in many cases of concussion(36). It has been proposed there is a “window of vulnerability” where an individual is more susceptible to secondary injury due to the metabolic dysfunction(37); this knowledge has provided support for conservative management principles such as removal from play if a concussion is suspected, as well as gradual step-wise return-to-play (RTP) guidelines to limit exposure to head impact during this timeframe(5). Axonal injury and impaired neurotransmission collectively lead to impaired cognition, slowed processing speed and reaction time(36) which can be indirectly measured by neurocognitive examinations, often guiding RTP decisions by healthcare professionals(5).

Furthermore, the underlying changes responsible for chronic neuronal atrophy and persistent impairments lies in the activation of proteases, altered cytoskeletal proteins and neurotic cell death, both consequences of serious concussive events(36). This lingering damage is what can lead to long-term health problems.
Additionally, the fear of a second injury prior to pathophysiological resolution from the initial injury (42,43) has led to regulation changes that encourage athletes to withdraw from play if they exhibit any sign or symptom suspect of a concussion (5). Similarly, a RTP within the period of neurometabolic crisis predisposes the individual to injury at the level of brain tissue and as a matter of physical function, such as impaired reaction time and balance problems (37). This above information suggests returning within 10 days after injury places the individual at risk, and RTP guidelines must be designed and implemented accordingly to ensure a full resolution of all associated issues involved with concussion, experienced or as detected by sensitive NP testing (36,44).

This injury has gained a lot of attention from the media and sport communities as it is being linked to long-term neurological disorders, psychological health issues and decline of overall wellbeing in professional and amateur athlete populations (45). Although concussions are not often accompanied with visible damage, discovery of Chronic Traumatic Encephalopathy in deceased NFL players has improved our recognition of potential structural damage involved with this injury (45). Other highlights in sport media are the cognitive and behavioural consequences of concussion, which have come to light as former NFL (46) and NHL (47) players have come forward and discussed the detrimental aspects of this injury in sport and life. This lends support to the importance of both injury management and prevention by means of eliminating modifiable risk factors.

1.1.1.3 Sport Injury Risk Factors

Certain trends emerge when examining the nature and frequency of injury in sport. External and internal factors play integrative roles in determining those variables. A dynamic, recursive model of sport injury was developed to better understand the factors at play in a real-life sporting
environment. In this model, Meeuwisse and colleagues (48) propose that the incorporation of repeated participation with and without injury is an important influence of both susceptibility and adaptive resiliency to injury. Taking this into account alongside the traditional internal and external factors related to injury, this model captures the complex interaction of factors leading to injurious or non-injurious events. Extrinsic factors, outside the control of the individual such as turf conditions or game rules, are important targets for modifying risk of sport. These factors alone may not be enough to make the sport safe (49), and intrinsic risk factors may also need modification in improving the safety of sport. Intrinsic factors are characteristics within an individual athlete (ie. strength, hip width, genetics, etc.) that may predispose or protect a participant in sport. Understanding the interplay between intrinsic and extrinsic factors along with exposure, adaptations, and damage that may be shaping overall risk of injury at the individual level is difficult. At this point, it is important for researchers, clinicians and other stakeholders to ensure the most modifiable and influential factors are controlled for, preparing the individual for safer participation in sport. Identification of prevalent risk factors is the first step in combating concussion prevention and reduction in sport. With specific interventions documented, this body of literature can be assessed to dissociate effective and ineffective interventions to direct future research efforts and implement risk reduction strategies.

### 1.1.1.4 SRC Risk and Risk Reduction Factors – External

#### 1.1.1.4.1 Rules and Regulations

Rules and regulations can be a very effective avenue for implementing injury-reduction strategies in sport. Gabbett and colleagues (50) documented injury rates before and after
implementation of the limited interchange rule in rugby, demonstrating a considerable decrease of all injuries sustained due to fatigue throughout a session. Following this success, the concussion interchange rule was introduced to the National Rugby League(8), requiring the mandatory removal of any player suspected of having sustained a concussion. Despite promise, compliance to these regulations was inconsistent, and a retrospective analyses of game video revealed that up to 23.5% of players returned to play in the same game after showing visible signs of loss of consciousness(8), which is considered a definitive removal from play according to these guidelines. These findings highlight the importance of buy-in from player, coaches and other staff to ensure success of regulatory interventions.

Strategies to limit head impact in youth hockey have also been explored. These began with regulating body checking by age(5,51). The youth brain is more susceptible to concussion and with the wide ranges of body mass at a young age, this can increase vulnerability to some of the smaller athletes, placing this population at heightened risk(52). As most impacts and injuries occur from body-to-body impact(8,35,53,54), it makes sense that limiting this exposure will result in a reduction in injury(53). Conversely, a recent study demonstrated an increase in risk and severity of SRC in PeeWee- and Bantam-aged hockey players after implementation of “Zero-Tolerance” body checking rule(51). However, during collection of this data, SRC awareness was improving and benefit of the rule may have been masked by improved recognition of SRCs. Overall, the general consensus shows that reducing body checking in youth hockey (under 13 years) has led to a significant reduction in SRC risk(5). Likewise, limiting contacts in practice, such as body contact in American football and heading in soccer, has had a positive influence on impact exposure reduction and prevention of SRC(5).
Specific rules have been implemented to target over-aggressive and dangerous behavior and/or maneuvers in sport. Hockey, rugby and American football rules such as the elimination of head-first (spearing), head-directed, blind- or rear-sided hits/tackles and over-aggressive behaviour (roughing, fighting, etc.) have been implemented to limit injury risk (5,55). A recent review highlighted that SRCs in rugby accounted for 29% of injuries sustained during illegal play and only 9% in legal play (8). These findings suggest that although new rules are in place, dangerous play is still occurring, and both rule changes and culture changes of the sport need to be established in order for these interventions to be effective (5,8). This highlights the importance of not only implementing risk-reduction strategies but also disseminating the appropriate injury risk and management education and encouraging “buy-in” from all stakeholders of sport including coaches, players, referees and parents.

1.1.1.4.2 Education

Education is viewed as one of the most influential and cost-effective concussion prevention initiatives. Awareness of the risk and short- and long-term consequences of concussion have been publicized, demonstrating encouraging reception and versatility in the sport community (56,57). Online resources, pamphlets, posters, seminars, and presentations collectively spread awareness and understanding to those involved with sport, in hopes of a global exposure and implementation of proper recognition and management of this injury (56–58).

The role of education in recovery is also very important. It includes awareness of those involved with return to sport, school and life in step-wise protocols implemented in the respected environments and discouraging self-management (5,57–59). As these guidelines have only recently been established they have yet to be adequately evaluated in the literature, and failure to
completely comply or adopt these guidelines and programs is reported in some studies(60). Understanding the severity of actions that tend to lead to concussion may help shape cultural changes necessary to see full effect. Engaging in risky or illegal play is in the end, the decision of the athlete, and with proper understanding of the serious risk, unnecessary, aggressive, gladiator-like cultures in sport may be over-ridden with common sense and restraint.

1.1.1.4.3 Equipment

Other risk reduction strategies at the level of the athlete have been developed through protective equipment in various sports that present a high risk of head and musculoskeletal injury. Mouthguards are effective in preventing dental and orofacial injuries(49,58), however the theoretical prevention against head injury remains unclear(49). The purpose of mouthguards are to facilitate clenching of the jaw to promote bracing(61,62) and to aid in absorbing the “jolt” after impact by absorbing force transmitted through the head(61,62). Despite promise, clinical trials fail to demonstrate significant reductions in impulsive loading to the head, which negates the protective role of mouthguards against concussion(49,61).

Helmets and headgear are other pieces of equipment that can lead to significant reductions in severe TBI and skull fracture. That being said, helmets cannot be considered “concussion proof”(63). In theory, the foam layer surrounding the inside of a helmet dissipates head impact force, reducing head acceleration to below brain injury tolerance levels; This is achieved by attenuating impact energy and distributing impact force applied to the head(62). In non-contact sports such as cycling, cricket and skiing/snowboarding, helmets serve to significantly reduce head injury in adults and children by 56% and 29%, respectively(52,64). In some cases, however, wearing a helmet may impose additional risk(10,11,65). Weight of headgear increases the total head mass, therefore, head mass-to-neck strength ratio. This, in turn exaggerates the
requirements of the neck to stabilize the head which may increase post-impact head acceleration. This becomes a significant issue when the head mass-to-neck strength ratios are already high, such as in youth and female populations (10). In support of these concerns, Tierney (10) demonstrated that although male soccer players benefited from the addition of head gear by dissipating forces generated from head-to-ball contact, female soccer players actually increased their severity of head acceleration while wearing this equipment.

The psychology of wearing a helmet may also impose risk. Athletes have been found to use helmets as injuring tools or engage in more aggressive behaviour because they feel less vulnerable, known as risk compensation (62, 66). These consequences of wearing headgear may contribute to a more dangerous game compared to similar un-helmeted sports. This is seen when comparing Australian rules football and American football, where the un-helmeted collision sport in Australia shows significantly lower head accelerations than American football (67) despite the similar tackle and running style of play.

1.1.1.5 SRC Risk and Risk Reduction Strategies – Internal

Many characteristics that lie within an individual may impose additional risk to SRC. Some characteristics contributing to internal risk factors have been identified in the literature as potentially modifiable in the sport environment. Identifying which factors are most modifiable is an important step in targeting effective interventions. In sport, some of these factors include playing style, skill, and/or muscular strength which may be receptive to intervention-based strategies to reduce activity-specific risk.
1.1.1.5.1 Genetics

Genomic factors may play a role in predisposition to concussion. Recent work has identified an association between concussion and variations in apolipoprotein E (APOE) promotor and the brain derived neurotropic factor (BDNF) genotypes(68). In theory, APOE and BDNF may be linked to attention and executive function deficiencies related to concussion and may increase vulnerability to concussion by lowering injury threshold and/or amplifying consequences of trauma. Alternatively, these genes may correspond with brain anatomical characteristics that are vulnerable to injury(69). However, much of the current work in this area is comprised of exploratory, low-powered studies and cannot yet provide prognostic value(68,69).

In the NCAA, men’s sports have higher rates of concussion compared to women’s, which is logical given that men’s sports have much higher impact exposure frequency and severity(33,34). Football consistently reports the highest rates of SRC(33,34), yet what is most interesting is that women’s soccer holds the second highest predicted rates of concussion across the NCAA(34). This is surprising given the vast disparity in head impact exposure between the two sports. In Canadian University Sports (USports), there is a considerably higher incidence of concussion in female (13.08%) compared to male (7.53%) athletes, the highest rates in women’s rugby(2). Similarly, female hockey players experience fewer and less severe impacts(70) compared to male hockey players yet show similar if not greater rates of SRC(70,71). Mirroring NCAA trends, female soccer players sustain 3 times as many concussions as male soccer players despite almost identical frequency and magnitude of head impacts, style of play, and injury mechanisms(2,72,73). It has also been documented that youth girls’ soccer players experience head accelerations that surpass similarly-aged football and rugby players(74). It has been postulated from these findings that females may possess a lower biomechanical threshold of
concussion compared to males(70,75). This prompts many questions concerning internal differences across sex and age that may lead to biomechanical vulnerability to post-impact head injury.

1.1.1.5.2 Age

Youth experience nearly double the number of concussions than that of adults(60). During normal human development, the brain matures structurally and functionally in a non-linear pattern until adulthood. The structural changes over this period include unmyelinated grey matter growth which is more vulnerable to injury and result in slower processing speeds compared to myelinated neurons(76). Thus, with an underdeveloped protective layer of myelin, the pediatric brain is predisposed to short- and long-term neuronal damage and altered recovery times(39,76). Another key feature of development is the solidification of the skull, and pediatrics with softer skull bones may be less resilient to direct head damage, unable to provide protection of the brain(44). Furthermore, larger head-to-neck strength ratios (i.e. weak musculature required to stabilize a full-sized adult skull and brain) predisposes the head to high accelerations in response to impulsive loading(77). This ratio can be exasperated with the addition of headgear such as football/hockey helmets and soccer/rugby headgear, increasing responsibility of the neck to maintain stability of the heavier load(10). The kinematic consequences of large head mass-to-neck strength ratios may be a factor contributing to how youth experience similar post-impact G-forces as their older counterparts despite the much lower game speeds and collisions(78). Collectively, these features increase the risk of concussion for pediatrics to nearly double that of adults despite much lower impact burden of their counterparts(54).
1.1.1.5.3 Previous Concussion

The strongest predictor of SRC is history of a previous concussion, whereby those with a previous concussion are 3-6 times more likely to sustain a subsequent concussion(2,79,80). One study reported 21-29% incidence of repeat concussion over a single season, and 33-50% over five seasons(79). The underlying mechanism of this risk factor, however, is still unclear. It has been proposed that previous concussion may lower the biomechanical threshold for subsequent concussion(s)(81). Various theories attempt to explain this phenomenon, yet there remains no universal consensus on the mechanism. Pathologically, the brain may have lingering cellular and metabolic dysfunction that make the brain susceptible to injury(36,38). Functionally, the individual may have slower reaction time and/or declined awareness, making them more vulnerable to injurious situations(36). On a psychological standpoint, having experience of a previous concussion may increase the chances of a subsequent injury to be reported. This may be due to the individual being more aware of and adept in recognizing their symptoms, increasing the likelihood to report and seek medical attention of their injury(82).

Lingering pathophysiological consequences of concussion may be accompanied by physical detraining and/or musculoskeletal injury compounding the deficits(83). There is evidence demonstrating that musculoskeletal, vestibular and oculomotor systems can be impaired even after acute and subacute concussion symptoms have resolved, presenting vulnerability to future concussive events(69). Specifically, neck injury or deficit often accompany SRC(41). There are often many undistinguishable similarities between concussion and whiplash-like injuries that occur in sport(29,84). As such, treatment of the neck often accompanies post-concussion rehabilitation. It is suggested based on these correlations that lingering neck pathology after concussion may be one factor contributing to an increased risk of subsequent injury(85), as it
places one at an even greater disadvantage in stabilizing and compromising range of motion of the head.

Using computerized neuro-psychological examinations (ie. IMPACT®, ANAM®, C3Logix®) tools, practitioners can monitor cognitive function of individuals after concussion. Performance on these assessments can be compared to a pre-injury score or a population norm, which acts as one of multiple tools used to determine recovery status after injury. These, with symptom ratings, RTP exercise tolerance models, and other clinical assessments, serve to inform decision making athlete as they return to full participation in sport. It is imperative, however, that the concussed athlete fully achieve his or her physical and cognitive baseline (or population-matched norm) before a safe and successful RTP.

1.1.1.5.4 Neck Strength

Recent literature exploring neck strength in athletes has identified a modest relationship between neck strength and head stability. Greater neck strength and stiffness is believed to represent greater capacity for static head stability and control(10,12,16,86,87). Subsequently, neck strength has been investigated as a potential modifiable risk factor for concussion, yet the findings across the literature are equivocal. Pre-activation of neck muscle such as “bracing for impact” is effective in reducing head kinematics post-impact. In these scenarios, MVC is associated with a reduction in post-impact head accelerations(11,14,17,88). In contrast, greater neck strength does not correlate to better head stability in unanticipated conditions or in within-game analyses(26). This suggests that when an individual is unable to contract superficial musculature, MVC does not aid influence head motion reduction(13,17,26). As head kinematics are believed to drive mechanism of concussion(6), the preventative role of MVC for SRC requires further investigation. Despite these trends, an epidemiology study found a relationship between neck
strength and risk of SRC. In this study, Collins and colleagues (20) found that for every 1-pound increase in peak isometric neck strength, there was a 5% reduction in risk of sustaining a concussion. This group evaluated peak isometric neck strength of 6,662 high school basketball, soccer and lacrosse high-school athletes using a portable hand-held dynamometer (HHD). The authors surveyed the incidence of concussion for the following school year, reporting 179 concussions (2.7% incidence rate). During this time, neck strength remained a significant predictor of concussion after adjusting for sex and sport ($p=0.004$). Although this was a high-powered study, it is important to consider that these authors failed to provide a clear definition of concussion, nor outline how reporting was attained.

Neck-strengthening interventions have also been evaluated in a range of sport and professional cohorts that run the risk of neck or head injury. Collectively, these interventions show little effectiveness of neck MVC in attenuating post-impact head kinematics related to concussion mechanisms (12,13). Despite improving MVC to a greater extent than whole body resistance exercise, these interventions failed to improve head stability in a variety of testing mechanisms. This dilemma warrants further investigation into protective role of the neck as it pertains to concussion and explore alternative strength parameters that are associated with dynamic head stability.

As previously discussed, neck musculature dysfunction can influence head stability and symptomology. Recent evidence suggests that symptoms traditionally defining a concussive injury are not clearly distinguishable from non-TBI related cervicogenic and/or vestibular symptoms (41). This association is important when determining appropriate diagnosis, rehabilitation and injury prevention strategies for each of these injuries. Interestingly, neck pain and whiplash-like symptoms are common complaints of those suffering from a concussion (29),
and rehabilitation treatments often involve the neck after head injury (29, 84). Weak and fatigable neck musculature accompanies chronic and/or acute neck pain (89), and whiplash patients experience coordination, oculomotor and vestibular dysfunction after injury (41). Furthermore, post-concussion patients present with lower neck strength-endurance compared to healthy controls (41). These similarities suggest that whiplash and concussion may have similar underlying pathologies which may linger beyond cognitive recovery (29, 41). With this in mind, it is postulated that compromised neck strength and/or neuromuscular activation may result in a decreased ability to statically and dynamically stabilize the head, increasing susceptibility to head accelerations and risk of concussion. This may be one factor contributing to a heightened risk of a subsequent concussion, and strategies to screen for these deficits would be beneficial in this context (41).

The risk factors for concussion are highly complex and integrated. Factors that can be effectively manipulated to control a portion of risk of the predisposed athlete must be targeted for detection and intervention. Despite knowledge of the dangers associated with high or repeated impact, high levels of collision and contact are an inherent part of many sports, and complete elimination of SRC is unrealistic; Instead, research efforts must center around reducing incidence and severity of this injury from factors that can be internally and externally controlled.

1.1.2 Biomechanics of Concussion

The mechanical etiology of concussion involves a wide range of impacts and assaults leading to multi-directional head motion. Both direct and indirect inertial forces are involved with concussion; In the absence of a direct blow to the head, inertial forces transmitted from elsewhere on the body can cause acceleration of the skull and brain (6). There are two main
mechanical forces contributing to concussion – compression and shear-strain– which arise from linear and angular acceleration, respectively(6).

The brain is the softest tissue in the body, moves non-linearly and un-uniformly when under varying load frequencies and velocities(90). The brain is over three-quarters water, making it resilient to transient, low velocity compression(6). Conversely, when responding to high velocity rotation, the complex microstructures of the brain including dendrites, axons and astrocytes, are highly susceptible to shear and strain(6).

Although the brain may be more resilient to compression, there are reports showing that peak linear acceleration of the head is positively associated with concussion diagnosis(91,92). However, as detection and biomechanical measurement techniques have advanced, rotational acceleration has revealed a more proximal association with concussion, as shearing of brain tissues following rotational accelerations is believed to be the most related to concussive events(93). There remains debate over whether resultant linear, angular, or combined accelerations have the highest predicative value of concussion, but they likely do not occur in isolation and collectively contribute to the injury(6).

The magnitude of impact also plays an essential role in concussion tolerance and severity.

Traditional impact-severity measures include the Wayne State Tolerance Curve (WSTC) the Gadd Severity Index (GSI), and Head Injury Criteria (HIC). The WSTC and GSI are more informative for focal head injuries, whereas HIC has been developed to capture the long-term effects of diffuse brain injury missed by the previous measurements. These measures were calculated using replicated impacts of dummy and animal models in early TBI biomechanical research(6,17).
There is evidence demonstrating that greater total brain damage is predictive of overall experience of transient and/or persistent post-concussive symptoms(90). Recent technological advancements allow for cumulative brain damage to be estimated using finite element (FE) modelling, identifying specific sport scenarios that have the greatest potential for injury(15). Maximal principal strain of grey and white matter in the brain has been identified as a variable that closely approximates concussion, mirroring the severity of rotational acceleration(90,94). Thus, it is assumed that less rotational and linear acceleration will result in less brain damage and identifying a means of reducing this head acceleration in sport is of high priority. The direction of force applied to the head is also important, as impacts that are lateral, frontal or rear- dominant all result in different peak resultant accelerations with identical force application(94). Impacts from the lateral direction seem to be most vulnerable to head acceleration(94), thus, may be most susceptible to concussion.

1.1.2.1 Head Impact Biomechanics

Biomechanical model-based studies provide opportunity to evaluate various body segments systematically. The head-neck segment has been evaluated in multiple ways to analyze the relationship between muscular strength, range-of-motion and tissue capacities, as well as evaluate the effectiveness of strengthening programs and responses to acute trauma or loading.

1.1.2.1.1 Laboratory Analysis of Head Impact Biomechanics

Traditional experimental designs used to evaluate head trauma involved dummy and animal models, both providing milestones in this area of research. Researchers using dummy models to replicate human body and brain movement pioneered exploration of the basic understanding of brain physical and biological response to trauma(95). Animal models have also been used to help
develop our current understanding of TBI, providing a basis to systematically explore the cause and effect of traumatic events to the brain in a living being (37, 81). Hypotheses regarding brain injury can be tested in living animals to understand the physiological dynamics of this predominately functional injury (81).

Denny-Brown and Russell in 1940 (95) were pioneers in the study of “experimental cerebral concussion”, consolidating the current biomechanical understanding of head injury and conducting their own isolated experiments. Using animal models (i.e. cat, dog, monkey), these authors conducted a series of experiments by dropping a mass on a pendulum on to the animal’s head, causing concussive events. They documented key features of these concussive events including loss of consciousness and alternations in respiration, blood-pressure, and corneal reflex. These researchers concluded that acceleration of the head reaching 28.3 feet/second was necessary to elicit a concussion. Key limitations exist, however, as the operation definition of concussion at this time was inconsistent to our current understanding (ie. loss of consciousness was a requisite) and the units of acceleration are not currently accepted, making these threshold estimates difficult to apply. Holbourn (96) built upon Denny-Brown & Russel’s research, noting the resiliency of the brain to compression yet vulnerability to rotational acceleration. These authors concluded that the shear-strain of brain tissue from rotational accelerations caused the most severe trauma to the brain and is the primary cause of injury. Ommaya (97) further supported these claims using experimental primate models, discovering that linear acceleration of the brain resulted in focal injury, and angular acceleration led to a combination of focal and diffuse injury. Current understandings suggest that rotational and linear accelerations after impact are not exclusive and collectively lead to variable severities of concussion (6, 93, 98).
Although there are considerable neurobiological discoveries from non-human models, these findings must be interpreted with caution. The mild nature of mTBI presents a challenge to researchers when accounting for the differences across species. Specifically, differences in anatomy, temporal pathophysiologial profiles, and functional deficits make it difficult to replicate concussive events (81,99).

Knowledge and technological resources have improved over time, leading to the development of comprehensive computerized models of human brains that can mimic responses to real-life concussive events. FE modelling is a method used in this field to reconstruct brain tissue within the skull (94). This computerized model can determine the maximal principal strain and compression of brain tissues under certain scenarios, such as a SRC event (27). These models can be artificially designed (ie. a car accident creation) or can be recreations of specific concussive events made possible due to accurate game video and documented injury biomechanics (15,53,100). One challenge faced by researchers searching for a definitive concussion mechanism lies in the sizeable variation of injury-eliciting events (6). Using reconstructions of real game situations, researchers are able to quantify these variations that cannot be predicted using traditional laboratory models (17,27). There are still significant limitations in FE designs, as there is only partial understanding of the movement of the brain, estimations are based on 50th percentile male cadavers, and limited types of sport video can be recreated (17). Irrespective of the limitations in these designs, these methods present an important step in understanding specific SRC events.

1.1.2.1.2 Game Analysis of Head Impact Biomechanics

A wealth of knowledge has emerged as a result of the surveillance of in-competition injurious situations. Combining video and accelerometry provides a comprehensive understanding of
impact biomechanics specific to individual sports. Video analysis provides valuable information on the sport-specific mechanism behind injury; these include typical maneuvers, movement patterns, and game scenarios related to injury(8,53,100). Game events that lead to a diagnosed concussion can be retrospectively evaluated to collect metrics used to quantify kinematic data of the player(s) involved in the collision.

Pellman and colleagues(15), were the first group reconstruct head impacts of diagnosed concussions and comparing them to non-concussion events using game video. They found that the average peak head acceleration was 98g in concussed events, and 60g in non-concussed events, which led to the development of a NFL concussion threshold(15). Following this work, Viano and Pellman conducted a series of football related head biomechanical analyses by reconstructing helmet-to-helmet and helmet-to-ground impacts captured by NFL game video (ie.(17,101)). Head kinematics of both the striking and struck player were determined, calculating HIC to estimate impact severity by means of brain damage. In professional football, the struck player experienced more severe impacts than the striking player, with peak accelerations of 102.5g and 70.9g and change in head velocity of 7.1m/s and 5.6m/s, respectively.

Recognition of these variables has driven policy changes to limit exposure to vulnerable game situations(53). After rigorous examination of video data, certain professional leagues such as the Rugby Union, NHL, and NFL now govern an observational recognition tool of high-risk events(102). Specialists identified as “concussion spotters” observe the game in real-time and using systematic reporting they are able to identify players who demonstrate behaviours or actions that represent a risk of concussion they then have the authority to pull that player out of the game for evaluation(102).
More recently, game video has been advanced with the development of head accelerometry. Helmets, mouth pieces and other wearable devices equipped with accelerometers provide an opportunity to capture linear and rotational accelerations and impact location to determine head impact severity metrics\(^{(93)}\). Real-time accelerometer data capturing head kinematics has been used to model head impact exposure in many sports. This technology is designed to represent the movement of the athletes’ heads as represented through movement of the helmet, mouthpiece, head band, etc. Head impact telemetry (HIT) system captures impact frequency, magnitude and location to calculate overall impact exposure\(^{(7,103)}\). To improve the accuracy of the scoring estimates, Greenwald et al.\(^{(93)}\) developed the HIT severity profile (HITsp), which is the principal component score containing linear acceleration, rotational acceleration, and impact duration, which is also weighted by impact location\(^{(104)}\). This metric has been used to quantify head impacts \textit{in vivo}\(^{(103)}\) demonstrating greater predicative validity than impact severity alone\(^{(93)}\). Despite the initial promise in this technology, clinical utility of HIT and HITsp may not be feasible. In an eight-year prospective study using helmet-mounted accelerometers, the positive HITsp predictive values of concussion were less than 2\%, with linear and rotational accelerations highly variable across diagnosed concussion and non-injury conditions\(^{(103)}\). Additionally, numerous assumptions have been made in algorithms to form meaningful output data which needs to be considered when making interpretations. Although these metrics cannot be used for diagnostics at this time, they have provided in-depth analysis of real-time sport events to characterize various impacts, informing policy and future research.

\textbf{1.1.2.1.3 Sport-Specific Trends in Head Impact Biomechanics}

Collision and contact sports have the highest rates of SRC\(^{(2,33,34)}\), generally resulting from player-to-player impacts\(^{(15,53,58,104,105)}\). Surveillance data indicate that SRCs occur in games
more often than practices, and in games that have higher frequency and magnitude of head impacts(2,33,34). In professional hockey and football, SRCs were most often sustained after lateral hits to the head caused by player-to-opponent contact(34,54,106,107). These trends align with laboratory recreations of head impact studies finding that lateral helmet impacts have greatest potential of diffuse brain injury and concussion(94,108).

In amateur sports, diagnosed concussions result from impacts ranging from 31.8 g-112.1g linear and 2911.0- 6174.2 rad/s² angular acceleration(7). In attempt to identify a threshold for concussion, various values were proposed ranging from 80-100g(109,110). Attempts, however, have been invalidated as literature documents that 99.65% of impacts above 90g do not result in a diagnosed concussion, and some concussions occur at forces as low as 30.7g(74).

Unfortunately, these inconsistencies do not allow for clinical utility of head impact measures to determine a concussion diagnosis(5,7)

Head kinematics and injury rates in football are highly dependent on playing position and location of head impact. Type, frequency, and magnitude of impacts experienced by linemen and skill players vary significantly. Linemen have more frequent impacts(103) which often occur to the front of the helmet (49%) causing linear accelerations. Comparatively, skill players experience fewer total impacts yet experience a greater number of lateral, rear and unanticipated impacts causing greater angular acceleration and impact severity(111). Brain tissue tolerance to shear force is lowest under axial plane rotation(6), and hits to the lateral aspect of a helmet produce the greatest injury levels(94). Therefore, it is speculated that with greater impact severity, and greater number of lateral impacts, skill players are at a much higher risk of sustaining a SRC compared to linemen(112). These characteristics provide valuable information
to address certain modifiable factors, such as neck conditioning, to dissipate variable forces specific to sport and position on an individual level.

The most common event leading to injury in ice hockey is body-to-body contact, which often leads to impulsive or direct loading to the head(55,105). In youth, there is a three-fold increase in SRC risk in ice hockey leagues that permit body checking compared to leagues that do not permit body checking(55,105). Similar to American football, impact type also plays an important role, where SRCs occur most often after impacts to the lateral aspect of the head in professional hockey (NHL)(31,53,75). These impacts are often categorized as “blind-side” hits where the recipient of the hit is unaware and unprepared for the hit, as the opposing player is outside of their field of vision.

Rugby is another collision sport with a high incidence of injury. Head impacts experienced in rugby are unique compared to hockey or American football, as rugby players are not permitted to wear equipment nor required to wear headgear, and it involves specific tackling techniques (i.e. rugby requires that the player be tackled to the ground with play continuing, verses football tackle causing a pause in play, changing the height and purpose of the hit)(113). Despite these discrepancies, post-impact head kinematics are relatively similar(107). Amateur youth rugby players show linear (22.2g) and rotational (3902.9 rad/s²) impacts that are comparable to North American youth contact sports, however the mean impact severities leading to SRC are lower than North American counterparts(107). Young rugby players, 8-10-year-old, are exposed to high angular accelerations with a mean of 3500-4050 rad/s² and the top 5% reaching 11,384 rad/s² (113), which highlights the innate risk of this sport even at a young age.

Although soccer (synonymous in the literature with international football) is not a collision sport, it presents its own inherent risk of SRC, representing 33% of all injuries in this sport(112). This
sport involves a large number of lower velocity intentional headers, as well as unintentional impacts and collisions(114,115). The average header results in approximately 20g and 1247 rad/s² (74), which can be categorized as sub-concussive(25). The most concerning impacts in soccer may be unanticipated player-to-player collisions such as elbow- or head-to-head impacts(72,115). The mean peak linear and rotational accelerations across all events range from 17-34g and 2458 and 5974 rad/s² at the collegiate level(72), which is more severe than that of simply heading the ball. Surprisingly, however, youth female soccer players show peak angular accelerations of 8869.1 rad/s² from simply heading the ball(74), which has led to regulation changes restricting of headers at certain ages and during practices.

1.1.2.1.4 Sex and Age Differences in Head Biomechanics

Although collegiate football has the highest North American estimate of concussion(27), women’s soccer is a close second, almost doubling the estimates of men’s soccer despite the similar style of play(37) and overall head impact burden(72). This brings to light the potential influence sex has on anthropometric dimensions and concussion risk. Age and sex are significantly correlated with neck strength, whereby youth and females have weaker, less stable head-neck segments compared to matured, male counterparts notwithstanding other anthropometric variables(20,116,117).

No differences in the biomechanics between youth and adults have been observed(70,78), however, female and youth experience nearly double the risk of SRC compared to males and adults(2,33,34). Additionally, head accelerations appear to be relatively consistent across popular sports(2,34,118) even though different sports vary considerably in impact momentums and inertial forces as a result of game speeds, rules, and player mass. Considering these similarities,
weakness in the neck may be a predominant factor contributing to how the populations that experience less-severe impacts experience head kinematics similar to that of their counterparts. Youth American football players experience similar post-impact linear and rotational accelerations as their high school and collegiate counterparts(78,119), yet at a lower frequency ranging from 9-12 impacts per session and 252-520 per season compared to over 14 per session and 950-1353 per season at the collegiate level. Although average impact severity is similar across ages, frequency of high impacts (>80-98g, or 95th percentile) are much greater in high school (3x) and collegiate football (5.4x) compared to youth(112).

These patterns also exist in some sex-comparable sports, such as ice hockey and rugby. Impact mechanics are relatively similar across female and male hockey players and across skater positions(54,75), demonstrating similar impact severity of 95th percentile peak linear accelerations of 40.8g and 41.6g, and of average concussion inducing linear accelerations of 30-56g(70). However, males experience a much greater frequency of all impacts and greater number of 95th percentile angular accelerations and HITsp scores than female hockey players(70,71). This comes with no surprise as men’s hockey involves legal body checking after the age of PeeWee (11, 12 years old)(52), and women’s does not. Direct body checking is illegal in women’s hockey, yet there is still a high level of contact involved in the game(70). Despite the discrepancy in head impact exposure, reported SRC rates in women’s hockey are on par, or even higher than males(2,34,70).

A similar sex comparable sport is lacrosse, the men’s game involves high intensity and frequency of body contact whereas the women’s game involves little or no contact. Another notable difference is that men wear full equipment including a helmet and shoulder pads, whereas women wear only eye protection and mouth guards. In contrast to men’s and women’s
ice hockey, SRC risk amongst men (85%) and boys (73%) is greater than that of girls (40%) and women (41%)(120). These trends may be explained due to the highly variable styles of play, as SRC mechanism is player-to-opponent contact in male and stick or ball contact in female lacrosse(120). Overall, these trends beg numerous questions about the anatomic and physiological differences that may exist across sexes that may influence responses and consequences to impacts and vulnerability to concussion.

1.1.3 Neck and Cervical Spine

1.1.3.1 Basic Muscle Mechanics

Human skeletal muscle is involved with mobility, stability and general function of the body. This muscle is categorized into type I, type IIa and IIb fiber types; Generally speaking, type I fibers are small, produce lower force, and are fatigue resistant. They are also the first recruited in neuromuscular adaptation(121), yet have slower contraction and relaxation times. In contrast, type IIb fibers are larger, produce greater force, are highly fatigable, and are more difficult to recruit(121). These fibers have also fast contraction and relaxation qualities. Type IIa are similar to type IIb yet are generally less-fatigable and have lower maximal force generation capacity. Targeting specific muscle groups requires understanding of the location and movement direction, as well as strength properties that the muscle possesses. Throughout the body there are many muscles that act synergistically to achieve a common movement, and it is often unrealistic to isolate a specific muscle in vivo, but rather assess the contribution of muscles to specific static and dynamic conditions. There are prime mover muscles that act to deliberately move specific body segments (ie. the biceps brachii flexes the arm at the elbow joint). Another role of muscle is to act synergistically
to maintain an equilibrium across joints both reflexively and voluntarily maintaining physiological stability(121); Unbalanced strength or fatigue between muscle groups can result in unequal moment about a joint, causing issues with joint functionality(122). In these cases, there may be changes in energy usage or compensation by other tissues to maintain balance, both of which can be harmful and often become problematic after repetitive use(123).

Internal fiber properties are not the only aspect contributing to performance of a muscle. Skeletal muscle geometry plays a crucial role in determining performance of muscle or muscle group(124). Fiber orientation, pennation angle, number, resting and active length all contribute to the amount of force that a specific muscle is able to produce p(124).

The human body is extremely complex, and the groups of muscle used to stabilize or move a joint involve a large number of muscles all working in different capacities and orientations to achieve an end goal. This is the main reason why isolation of muscles is not only difficult, but also unproductive at assessing the capacity of a system. Instead, targeting specific functional capacities is a more appropriate approach.

In order to target specific muscle capacity, testing parameters (ie. force application) must match the specific strength and fatigability of the desired trait(121). For example, testing endurance capacity of a muscle group must involve force applied over an extended period of time, or repetitively, at moderate to low magnitude to elicit contribution from the endurance properties of a muscle(121). If the force is applied for a short period of time, or at too high of a load, the endurance properties of muscle will not be evaluated. In this sense, testing a muscle group under maximal capacity does not necessarily reflect what that muscle group can produce repetitively or under sustained loads, thus, having an inaccurate representation of all contributing factors of a segment.
1.1.3.2 Anatomy of the Neck and Cervical Spine

The neck is comprised of the cervical vertebrae, musculature and connective tissues, which all contribute to reinforcement the spine(21). The cervical spine extends from the Occiput (C0) connected to the skull, to the thoracic spine (T1). The cervical vertebrae (C1-C7), permit physiological flexion, extension, rotation and side flexion, reinforced by ligaments, disks, and muscle that run along or within the spine(125). Ligaments are uniaxial structures that generally resist tensile and distraction forces. Intervertebral disks respond most frequently to compressive forces placed on the spine by the weight of the head. This being said, disks hold the capacity to respond to multi-directional vectors if necessary(125). The musculature of this region is categorized into deep and superficial muscles, on either the posterior or anterior aspect of the neck. The categorization published by Blouin and colleagues(126) divide these muscles into superficial (sternocleidomastoid, upper trapezius, levator scapulae, splenius capitis and semispinalis captis) and deep (scalenes, erector spinae, longus capitus and colli, and splenius/semispinalis cervicis muscles) muscle groups. Similar to other areas of the spine, the superficial muscles are larger with greater maximal force generation capacity, and the deep musculature is smaller and run along the spine while providing continual postural support of the cervical spine(126,127).

1.1.3.3 Stiffness of the Neck Segment and Cervical Tissues

The neck is comprised of the cervical vertebrae, musculature and connective tissues, which all contribute to reinforcement the spine(21). The cervical spine extends from the Occiput (C0) connected to the skull, to the thoracic spine (T1). The cervical vertebrae (C1-C7), permit physiological flexion, extension, rotation and side flexion, reinforced by ligaments, disks, and
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Stiffness also varies within the tissues, playing an intricate role in the function of segments they are a part of. There is yet to be a direct measure of intramuscular stiffness, however using a combination of multiple proxy measures (ie. EMG) and biomechanical models (ie. cross-bridge calculations) estimates can be made to describe the nature of stiffness within mammalian tissue(30). Musculo-tendinous stiffness is defined as the combination of tendon, connective tissue, and actin-myosin cross-bridge interaction(87). The concomitant action of passive and reflexive properties serves to provide involuntary regulation of joint stiffness by resisting impulsive loading and allow for greater transfer of force through the rigid body.

Measurement of this stiffness is complicated yet can inform estimates of segment stability in situations that require active and passive resistance to perturbations(128). The tissues of the cervical spine are comprised of a combination of elastic and connective tissues, discs, facet joints.
and muscle that collectively contribute to an overall stiffness of the segment connecting the head with torso(128). The tissues of this region follow the same passive stress-strain curves as other tissues of the body. Although related, there is a non-linear relationship between muscular force capacity and muscular stiffness(128).

One contributor to stiffness within the muscle is human resting myofascial tone (RMT). RMT is a passive tonus that has elastic properties present in static situations(129). In other words, this property helps in providing a rigid support to otherwise soft, compliant tissues supporting a joint. This underlying tone is involved in stabilizing the spine during balanced postures as well as mitigating post-impact accelerations(86). An example of this is when you unintentionally step off a curb, the ligaments of the ankle will be protected by greater underlying muscular tone and feedforward muscle activation provided by RMT(30). This is beneficial as it adds additional stability to the passive tissues. In response to impact, the contractile component of muscle is unable to generate force immediately, leaving tendon, connective tissues and underlying muscular tone to absorb initial impulsive loading(30). In anticipated situations in sport, players are able to “brace” for impact in football or hockey, or purposefully stiffen their neck to head a soccer ball(12,25,28). In contrast, unanticipated situations do not allow for pre-contraction of these muscles, relying on underlying RMT and musculo-tendonous stiffness(30). In theory, greater muscle fiber cross-sectional area of neck muscle will improve passive muscle tone, adding resistance to perturbing forces(30). Therefore, muscle volume may be another desired outcome of resistance training separate from maximal neck strength.

This being said, a primary function of the cervical spine is to perform dynamic, controlled motion of the head, where too much stiffness may impede this performance. There may be an
ideal stiffness beneficial in contact or collision sport, resisting head acceleration after impulsive loading, leading to a functional and stable joint segment.

1.1.3.4 Stability

In a qualitative sense, stability is the ability of a system to withstand perturbation with minimal change in position or trajectory(130). Stability occurs in both static and dynamic conditions, maintaining an equilibrium or moving with time, respectively. A system can be stable - no detectible change from original position or trajectory, asymptotically stable – detectible change in position or trajectory with a return to the original position or trajectory, or unstable – a significant change in position or trajectory(131). Oscillations in response to perturbation are normal and required to meet a more complex definition of stability(131). The ability to change the range in which these oscillations occur by applying variable intensities of perturbation is an indication of a healthy and functional system(131). The absence of this range is an indication of an unstable system. Stability is highly context-specific and multi-factorial when assessing the human body and intentional movement; it must be evaluated based on the goals and intentions of a task, often assessing joints and segments exclusively. A system is either stable or not, there is no spectrum of this definition, thus, a term more appropriate for human performance and training of a system is robustness. To be robust, a system is stable over a wide range of disturbances or able to tolerate internal states such as changes in muscular stiffness. In training targets such as core or neck muscular training to stabilize the spine, robustness is a more appropriate term to describe the desired outcome.

Following a perturbation, the system will respond with a certain level of accuracy and speed, eliciting an energy cost to maintain stability or asymptotical stability(131). The body’s regulation of this robustness can be depicted through the use of an input feedback parameter. Input, which
can be viewed as the perturbation, must be countered by a feedback response of the body, such as muscular contraction\(^{86,132}\). If the feedback response is accurate enough to return the system to its original behaviour, then this system is robust and is stable\(^{131,132}\). Feedback control in the body are driven by neuromuscular receptors that detect changes in velocity, position and pressure of tissues, eliciting an appropriate response. These responses happen both reflexively and voluntarily through the peripheral and central neurological systems, respectively. The oscillatory response to the load is called damping, which mimics loads to maintain an equilibrium or constant behaviour\(^{131}\).

1.1.3.5 Neuromuscular Control of the Head and Neck

Cervical muscle and ligamentous tissue mitigate impulsive loading on the cervical spine and motion of the head-neck segment\(^{133}\). Although muscle volume and strength contribute to this capacity, peak force (PF) may not capture requirements for head-neck stabilization\(^{134}\) as the time before contact may not be sufficient to produce PF, which also may not be reproducible over time\(^{101}\). More meaningful variables in head-neck segment stability situations may be rate of force development (RFD) and peak short-latency strength. These variables are novel, however present a very important quality to be assessed and trained in the neck. In other skeletal muscle, heavy resistance training results in marked increases in RFD and impulsive PF from improved neural drive\(^{135}\), suggesting that isolated training of neck musculature may augment this quality.

Almosnino\(^{24,134}\) took a novel approach of testing force development of the neck musculature. These authors measured the force-time variables of isometric contractions of 26 male collegiate athletes (21.6y) using a custom-built neck-strength testing device, similar to previously discussed studies\(^{77,164}\). The participants were instructed to push as quickly and as forcefully as they could for
a duration of 4 seconds in 5 testing directions: flexion, extension, lateral flexion, and protraction. PF (N), RFD (N/s) and time to 50% PF (ms) were determined in each direction. These parameters were theorized to represent the responsive ability of head stability; however, these methods lack a direct measure of the responsiveness to load. Although these tests are informative in the voluntary reactive properties of the neck, administering this test to a large number of athletes would not be feasible, nor does it consider head stability in conditions with an applied perturbation such as a hit or tackle in sport.

1.1.4 Neck and Cervical Spine: Clinical and Performance Considerations

The neck connects the head to the torso, controlling head motion and force transmission between the two segments(87). Complex deep and superficial neck musculature combine with intervertebral ligaments and disks to provide static and dynamic stability of the spine. Provided these tissues maintain physiological function, they act to maintain a state of postural equilibrium of the head relative to the torso(136).

1.1.4.1 Musculoskeletal Injury Risk Assessments

Strength assessments are an effective way of identifying weaknesses that may predispose an individual to injury. Common themes across strength-based assessments demonstrate that strength balance is necessary for proper force distribution across a musculoskeletal joint, therefore, proper static and dynamic function(137). Likewise, neck flexion and extension ratios have shown to correlate with head stability during heading in soccer(13), warranting exploration of distribution and interaction of multi-directional strength about the cervical spine.

Identifying risk in common musculoskeletal injuries is a highly researched field. Injuries such as hamstring muscle strains, anterior cruciate ligament (ACL) tears and low back pain (LBP), to
name a few, are often targeted by muscular strength and mobility assessments (138). Peak strength, strength-endurance, and strength ratios are targets for assessment. Balanced forces applied to either side of a joint is often closely coupled with stability and strain avoidance after repetitive contractions or impacts (137). The ACL, for example, is placed at high risk when hamstrings and quadriceps muscle groups have disproportionate strength (138). In non-contact ACL injuries, constant weakness on one side of the knee leads to strain of the ligament after repetitive impact of running and agility maneuvers (137). This mechanical discrepancy may be avoidable with appropriate identification and strength training.

Although mobility is permitted, the spine functions best when it is properly aligned and evenly compressed by deep and superficial muscles, ligaments, discs and facet joints (139). With unbalanced muscle activity, this can be compromised. Extensive unilateral fatigue may lead to similar mechanisms as ACL injury mechanisms, causing connective tissue and joint capsule strain, contributing to LBP or neck pain (130,140). These theories are supported clinically, demonstrating that training both deep and superficial muscle for strength and endurance capacity often results in a significant reduction of pain, and increased mobility and function (141–143).

Depending on the targeted muscle groups, different strength measures should be conducted. For example, MVC ratios of hamstrings and quadriceps are informative for of ACL injury risk (138), yet deep postural muscle endurance capacity is best informative of lumbar stability (144,145).

Strength tests must be designed to assess the physiological function of that specific joint. The lumber spine needs to be constantly supported, with little pathophysiological movement, therefore assessing isometric (static) strength makes sense. Similarly, if the goal is stabilization of the head, strength in that stable position should be assessed.
Isometric strength, in theory, reflects the capacity to generate force capable of coupling the head and torso as well as absorb force otherwise applied to the boney and ligamentous structures of the spine\(^{(146, 147)}\). Neck strength has therefore been explored in various activities pertaining to head control specifically in fighter pilots\(^{(148)}\), collision and contact sports\(^{(12, 73, 149, 150)}\), and sports that involve extended end-range postures of the neck such as cycling\(^{(151)}\). Within these non-clinical cohorts, the neck may be explored as a modifiable internal risk factor for injury prevention.

1.1.4.2 Assessment of the Neck and Cervical Spine

A range of neck assessment tools have been used to evaluate the many strength parameters of the cervical spine in non-clinical populations. Handheld and fixed frame dynamometers (HHD, FFD) used to measure maximal and submaximal force generation of the cervical musculature are well-validated in the literature\(^{(20, 152, 153)}\), however limitations do exist. Hand held testing devices are limited by the force generation capacity of the administrator, which may limit the maximal value as well as consistency across evaluators\(^{(154)}\). The FFD is a more reliable tool, where force generation is developed by the participant alone, against the immovable force recorder of the device. One limitation of FFD is that other limbs or posture of the head and neck must be regulated by the evaluator, as the tool itself will only capture force generation\(^{(154)}\).

Because of this, other rules or restrictions need to be set in place to ensure accurate, reliable, and repeatable measures of neck strength. Contribution from other areas of the body including legs or arms, must be eliminated, which has been achieved in different ways across the literature; Chest strap, hands placed on thighs, and feet on a collapsible box are common techniques used to isolate neck musculature\(^{(153, 155)}\). Instances that may compromise this is when participants grip a stationary object at different angles, have solid foot support, or if they are able to lean in any
direction away from neutral during measurement (24). Just as importantly, the participant must have a neutral neck, head and spine posture throughout the duration of the test in order to ensure appropriate and consistent muscular contribution (134), which should be operationally defined and required throughout neck testing. These inconsistencies across posture and limb position make it difficult to compare data across studies.

Practicality of these devices also differ. FFD are not ideal for a S&C or clinical environment nor are they cost-effective (156). HHDs on the other hand, are portable and more affordable, but as mentioned above, strength of the administrator can greatly affect the result (24). Neither device allows for adjustment of resistance, only measuring the force applied against the device. These two methods primarily measure MVC in flexion, extension and side bending, but some also involve axial rotation. Endurance properties have also been assessed (157), collected by producing force at 20-70% MVC for either repeated contractions, or longer intervals of 3-10 seconds (153, 158). Furthermore, neck strength in various rotated postures has been collected, using an adjustable chair and head piece to test MVC to determine force generating capacity of different muscle groups and orientations (156, 159).

Preliminary testing of cervical neuromuscular properties such as electromyography (16), rate of force development (24, 155), and time to 50% peak MVC (24) have all been investigated. These measurements provide insight of neuromuscular properties and dynamic strength in situations requiring head stabilization, however, are limited to the laboratory environment.

As highlighted earlier, maximal neck strength does not relate to head stability in conditions that do not allow for pre-activation (ie. unanticipated, game conditions). This being said, the underlying deep musculature of the neck when appropriately activated, provides postural stability that acts independent of muscular activation. Assessing this parameter may provide
important information regarding one’s ability to stabilize their head(30,87,129), reducing head acceleration below relative tolerance levels of concussion after impact. Estimation of head-neck segment mass has led to better estimates of head kinematics which may be used to determine these strength-endurance requirements(87). There remains no standardized neck screening protocol that effectively evaluates multiple neck parameters under sport-specific conditions across a wide range of athletes.

1.1.4.3 Posture and Alignment of the Head-Neck Segment

The deep flexors are identified as key modulators of head posture and are closely linked to neck pain(136,160,161). Testing the strength and endurance of this muscle group has become standard practice in many clinics as these parameters are associated with neck pain(142,160). Training to improve strength-endurance of this muscle group is effective in reducing and neck pain in these patients(160). A subtle, yet important, feature to neutral head posture is the degree to which the head is tilted forward. If the subject has a forward head posture, measured craniovertebral angle, muscle contribution to the movement could be compromised and lead to invalid measurement of cervical strength(162). Achieving a “tucked chin” aligns the head on top of the vertebrae and facilitates engagement of the deep cervical flexor muscle groups that play a key role in cervical spine stability(141). Another consideration of appropriate alignment and muscular activation of the head-neck segment is shoulder posture. It is common practice for individuals to have shoulder elevation or forward flexion in many tasks or posture. Specifically, rounded shoulder posture is related to neck pain and dysfunction(163), and elevation of the shoulders involves trapezius musculature which may take over in neck rotation and extension movements with elevated shoulders. As such, it is important to encourage scapular depression and retraction...
during neck training or testing tasks to promote appropriate distribution of muscular contribution(162).

1.1.4.4 Neck Characteristic Population Norms

Using the assessment tools described above, population norms of typical neck strength parameters have been established in the literature. Normative values indicate that within a healthy individual, the force generating capacity of flexor, extensor and lateral flexor muscle groups differ significantly(158,164–166); In order for athletes to maintain cervical stiffness under multi-directional perturbations, the neck must be appropriately balanced across these directions(13). Post-training values demonstrate that extensor group is the strongest, followed by bi-lateral flexion (80-85% extension) and frontal flexion (50-60% extension) (158,164–166).

Men exhibit significantly greater strength then women, even when controlled for anthropometric variables(10,14,158,165). Age is not a consistent predictor of neck strength in the general adult population, however, when homogenizing the population, a trend begins to appear such that younger individuals with less neck-specific exposure have weaker necks(116,117,157). For instance, elite rugby players under the age of 18 show a mean neck strength that is significantly lower than that of the adult population, despite similar anthropometric and whole-body strength parameters(166). This is an interesting finding, as weight and peripheral strength were previously assumed to represent neck strength within an individual(166). In this cohort, the only variable that correlated with neck strength was years of playing experience in the front row – a very tackle-based position in rugby – suggesting exposure to situations involving neck maximal contractions and withstanding force may lead to muscular adaptations of the neck muscle(166).

Younger athletes are generally smaller, have less developed muscle mass and demonstrate greater risk of post-impact head displacement and acceleration(14,167). In high-school and
college athletes, body mass and age are positively correlated to neck strength\(^\text{(20)}\), suggesting smaller and younger athletes are comparatively weaker.

Females in both athletic and general populations have smaller and weaker neck muscle, with strength of 40-70\% of that of males\(^\text{(10,13,14,152,158,165)}\). In a cross-sectional study conducted by Catenaccio and colleagues\(^\text{(152)}\), peak and average neck strength of 157 (M=84, F=73) healthy young adults (27y) were measured using a FFD in flexion, extension and bi-lateral flexion. Neck girth, body mass index, body weight and neck volume were all predictors of neck strength in females, yet only neck volume for males. These trends are consistent across the literature showing an absolute and relative strength discrepancy between males and females\(^\text{(10,13,14,152,158,165)}\).

Another muscular property that contributes to neck responses to head loading is passive stiffness of cervical tissues. One study measured passive cervical stiffness of university-aged cohort\(^\text{(133)}\). In this cohort, extension stiffness was significantly greater than flexion stiffness, and flexion was greater than bilateral flexion. Men exhibited greater overall passive neck stiffness and elasticity compared to women, suggesting that they are more resilient to injury of this segment\(^\text{(133)}\). These results are important as they align with general neck strength trends and may have important implications for unanticipated impacts. As discussed above, women tend to me more vulnerable to acceleration of the head, which may in addition to muscular strength be influenced by passive stiffness. This suggests that assessing maximal strength may not encapsulate all modifiable neck tissue that is involved with head stability.

1.1.4.5 Evidence Linking Neck Parameters to Head Biomechanics

All tissues of the neck work in conjunction to absorb energy and produce force to withstand and respond to impulsive loading; passive and active properties of these tissues play a significant role
in mitigating acceleration of the head in response to impact(133,147). Of these properties, maximal neck strength has been the most investigated in the role it plays in head stability. Newton’s second law states that force is a product of mass and acceleration, whereby greater mass requires a greater force to accelerate it. In practical terms, the head as a single mass will accelerate to a greater extent than the head coupled to the torso, and force is more efficiently transferred through a rigid segment. In theory, greater neck strength would outperform weak strength in achieving this coupled segment.

*In vivo* and *in vitro* studies support these theories, demonstrating that anticipation and pre-activation of neck musculature significantly reduces post-impact head kinematics(10–14,16). Specifically, Mansell et al.(12) reported a 21% reduction in head acceleration with anticipated ‘bracing’ compared to the unanticipated conditions using a quick-release load cell. This same study, however, did not find any improvements in head stability after an 8-week isotonic training regime despite a concomitant increase in neck girth and strength.

In a similar design, Eckner et al.(14) used a load cell proportional to body weight (2.5% BW when released) attached to participants’ heads. The quick-release force application created impulsive loading to the head in a “known” and “unknown” condition. Participants’ performances were then correlated with sex (male vs. female) and age (younger vs. older). During known anticipated conditions, younger subjects demonstrated 26-38% greater angular and linear velocity in forced flexion, extension, lateral flexion and rotation, representing a greater risk of injury. Likewise, average MVC in flexion, extension, lateral flexion and rotation ranged from 34-54% less in the younger group, and SCM cross-sectional area was 26%-41% less in younger compared to older.
Showing similar trends, Tierney et al (11) conducted a study on male and female soccer players, finding that females exhibit less neck strength and greater head velocity and displacement after application of an impulsive load to the head. Overall, these subjects demonstrated considerably less head motion in anticipated conditions compared to unanticipated conditions suggesting that bracing and muscular pre-activation is an effective means to stabilize the head.

Schmidt (16), examined forty-nine high school and intercollegiate football players to investigate the relationship between multiple neck variables and concussion risk. Peak isometric strength in flexion, extension and bi-lateral flexion was measured using a HHD, and UT, SCM and SSC muscle fiber cross-sectional area was determined using ultrasound. Similar to Eckner, these authors used a 2.5% BW load cell drop to measure neck stiffness (Nm/ rad). Head displacement and neck stiffness were calculated and normalized to player height and weight. After collection, athletes were binned into high and low performers on all neck measures and compared to observational head kinematics. To assess head impacts experienced in sport, the participants’ helmets were equipped with HIT systems. Using HITsp, impacts were binned into mild (HITsp<11.7), moderate (11.7-15.7) or severe (>15.7). When comparing cervical strength scores with head accelerations, high performance of peak isometric strength did not influence the odds of sustaining moderate or severe head impacts (OR 1.02, 0.96). In contrast, linemen who were high performers in muscle strength and size experienced greater overall head acceleration. The authors explain this phenomenon as a product of playing position and risk compensation, whereby athletes who believe they are bigger and stronger are more likely to involve themselves in higher risk situations under the impression that they are less vulnerable than their counterparts.

As discussed earlier, other reports demonstrate that front-line players experience a much greater number of impacts compared to skill players. These occur predominantly to the front of the
helmet causing linear accelerations(15) which may be influencing these values. Overall, Schmidt and colleagues conclude that neck stiffness and head displacement measured in the laboratory setting are good predictors of sport-induced head acceleration, however, isometric strength and muscle size, are not.

In line with these findings, Mihalik et al.(26) contradicted their hypothesis proposing that cervical strength predicted head acceleration in elite youth hockey players. Using a HHD, resistance was applied to the head until the subject no longer could withstand the force (“break-test”). Peak strength (kg) was assessed in flexion, extension and rotation and the scores were averaged to a composite measure of total neck strength. These were categorized into strong, medium or weak tertiles. A HIT system was equipped to the participants’ helmets, recording post-impact linear and rotational head accelerations greater than 10g. HITsp was calculated in 37 players over 98 games and 99 practices, totaling 7770 recorded impacts. Between the three neck-strength tertiles, there was no significant difference between HITsp or incidence of concussion in this population. These results further negated the predictive influence of static isometric neck strength for SRC risk.

Although most conversation in the literature has centered around the concussion-inducing impacts in sport, only a small percentage of impacts in sport actually result in a concussion. In contrast, the majority are sub-concussive impacts which occur at relatively low velocities and force. These situations, however, may play a role in overall brain health, and mitigating sub-concussive impacts may also help to reduce head injury burden. Neck tissues play a critical role in controlling low-grade, anticipated impacts(14,129), therefore, lessening loading to the brain. Heading a soccer ball is an example of these types of impacts. Pre-activation and stiffness of the neck prior to a header significantly reduces head displacement and peak velocity after head-to-
ball impact(12,13,18). Due to the high-frequency of heading the ball, these low-grade impacts are of concern in athletic populations, and neck properties play a crucial role in dampening these impacts is crucial.

Bauer et al.(28) provided a comprehensive analysis of the head kinematics and role of the cervical muscle activity in soccer headers. To do so they recorded EMG of the UT and SCM in female soccer players. They determined that pre-activation of UT and SCM improved neck stiffness and decreased head displacement and peak velocity after impact, factors believed to be most related to risk of concussion(15,17). Dezman et al.(13) also assessed neck characteristics of soccer players, determining that mean difference, or ratio, between flexion and extension strength was positively correlated with post-impact angular head acceleration in this cohort.

Expanding on these concepts, Shewchenko and colleagues(19) used FE models to reconstruct the biomechanics of controlled headers while adjusting direction and magnitude of neck stiffness. Impact severity was quantified using Head Impact Power derived from ball speed, muscular activation, and head and torso kinematics in each scenario. Spinal stiffness was calculated from muscle force activation, axial compression and shear force about the junction of the head and cervical spine (C0-C1) determining the influence of variable cervical muscle activation on the spine. From this design, the researchers determined that increased spinal stiffness and axial compression from muscular activation and spinal alignment coupled the head and torso during soccer headers. This in turn reduced peak head acceleration of up to 7%. Heading the ball is primarily anticipated and occurs at a low-velocity which on average causes accelerations well below estimated concussion-inducing values (20g and 1247 rad/s²)(74). This suggests that head impact mitigation techniques used in these events may not apply to other sport scenarios.
involving higher and more dangerous impacts. Nonetheless, this research further highlights the importance of neck properties and head control.

Similar to other muscle groups, training age may be largely indicative of strength, and exposure to neck-specific training at an early age may be particularly beneficial to prepare for high levels of play. Overall, the results summarized demonstrate that in sport, youth and females exhibit considerably less head stability compared to adults and males, respectively. This provides one explanation of how young athletes experience similar head accelerations to high school and university-level athletes despite having less impact severity in their respective levels of play(1,34,75). Lastly, to our current knowledge, an association between maximal isometric neck strength and concussion beyond the acute stage post-concussion has yet to be established.

1.1.5 Rationale

Preliminary evidence has identified an association between neck strength and reduced head acceleration in sport(10,16,20,27), which is thought to reduce risk of concussion(20). Currently, the literature is limited to maximal isometric neck strength, which is found to only provide stability of the head under anticipated loading conditions at low velocities(10–12,14,16,27). This does not encompass the variety of impacts experienced by collision and contact sport athletes, which occur from multiple directions, under altered anticipatory states, and on a repetitive basis. As such, investigation into alternative neck parameters is warranted. Although reaction-based strength, neck stiffness and neck girth have been explored, the current designs evaluating these metrics are experimental, place the subject at a heightened risk, and/or are difficult to replicate in environments with fewer resources or with large groups such as sport teams.

This gap may be adequately filled by assessing strength-endurance properties of the neck. The musculature surrounding the cervical spine is highly complex and is categorized into segmental
stabilizers and prime movers by moment-generating capacity of each muscle(168). Generally speaking, deep muscles along the cervical spine provide stability and more superficial muscles perform prime movements(168). Although prime movers generate the greatest force and moment, they require central activation which takes time to respond to a stimulus. The reaction time of this muscle may be too slow to adequately respond to unanticipated loading of the head(134). Stabilizing musculature on the other hand provides constant stability of the head-neck segment(136) that may play a role in providing support in unanticipated perturbations. It is likely that previous examinations of maximal neck strength mainly assessed the capacity of the prime movers, leaving the stabilizing muscles and endurance properties unevaluated. As opposed to the maximal strength properties, fatiguability of a muscle will influence a muscle’s ability to maintain force and/or provide stability over time(121). Contact and collision sports involve numerous impacts in a given session(70,91) thus, exploration of both strength and endurance capacity of the neck is required to account for repetitive, moderate external loading.

Moment generating capacity of a muscle can be used to quantify passive and active function of a musculoskeletal segment. This property can be influenced by muscular moment arm, architecture and neural activation(127). The latter two are modifiable and dictate the isometric force capacity of specific muscle. Therefore, modifying a muscle’s isometric strength and endurance properties will influence moment generating capacity. Strength-endurance, which consists of the moment generating capacity of the neck, represents the capacity to produce or resist force over sustained and/or repetitive loading(121). Specific to neck muscle, strength and endurance have been examined in individuals with neck pain and/or dysfunction and is closely associated with instability and improper neuromuscular activation(141,161). Specifically, overactivity of the sternocleomastoid and/or hindered strength of deep muscle is associated with instability and neck
pain(140). Patients with neck pain also show significant improvement in local pain, deep cervical muscle strength and head stability following endurance training(144,160,169). In the context of SRC, a number of studies have found lingering cervical dysfunction in those with acute or persistent concussive symptoms(170–173). In accordance with the neck pain trends, it has been suggested that those with a history of concussion are at greater risk of sustaining a future SRC(5,174) potentially due to dysfunctional neck parameters(171,175). The requirements of the neck in sport-specific scenarios are unique, involving multi-directional impacts under various states of attention. As discussed above, maximal neck strength does not reflect head stability capacity to unanticipated or sport-specific impacts. In contrast, the unexplored characteristic of strength-endurance may better encapsulate the strength requirements of the neck to provide continual resistance to impulsive loading in sport.

Thus, the purpose of this study was two-fold. First, to characterize and quantitate athletes’ neck strength-endurance. Second, to examine potential differences in performance between sexes and those with a history of concussion by using both an independent rater and OptiTrack motion capture technology.
2.1 Abstract

Background:

Identification and implementation of effective risk reduction strategies for sport-related concussion (SRC) remain a high priority. There is evidence to suggest that maximal neck strength may be a modifiable intrinsic risk factor for SRC, where greater neck strength may decrease head acceleration during high risk impacts. Furthermore, females have been reported to have weaker neck musculature and potentially an increased risk of SRC than males. Maximal neck strength may not encapsulate all muscular properties of the neck contributing to head acceleration and there is a void of research examining strength-endurance capacity in male and female athletes.

Purpose:

The purpose of this study was to assess the neck strength-endurance properties in male and female athletes. We hypothesized: (1) females would perform poorer in a neck assessment
compared to males; and (2) athletes with a history of concussion would perform poorer than athletes with no history of concussion.

Study Design:

Cross-sectional design.

Methods:

The ability to maintain a submaximal static flexion, extension and left and right lateral flexion moment about the neck was assessed in ninety-seven (n = 97) collision and contact sport athletes. An external load of 15%, 12% and 10% body mass in forced-flexion, extension and left and right lateral flexion, respectively was applied to participants’ heads at the level of their foreheads. Head motion relative to the torso was used as the indicator of neck performance and was measured in two ways (1) head distance and displacement derived from an optoelectric motion capture system, and (2) by an independent rater using generic video. The independent rater determined each trial as a pass or fail by observing head motion relative to neutral posture. A secondary analysis comparing failed trials with matched passed trials was conducted to determine agreeability between the results of motion capture and individual rater analyses.

Results:

The majority (68%) of participants failed on one or more directions of the neck muscle strength-endurance assessment. The participants failed most often in flexion (38%), followed by lateral flexion (33%), then extension (11%). In both independent rater and motion capture analyses, there were no significant differences in neck strength-endurance in any direction between athletes with and without history of concussion. Similarly, there were no significant differences
in performance between males and females. Motion capture data revealed that participants exhibited the greatest head motion in the flexion trial of the neck assessment. There were no differences in peak head displacement between trials. Using a matched analysis, mean head motion of those who failed was 46% greater on average than in those who passed.

Conclusion:

The present study measured head motion under custom loading to represent strength-endurance of neck musculature in collision and contact sport athletes. Out of the four directions assessed, performance of the neck was poorest in flexion and left and right lateral flexion directions. Performance of the neck in this assessment did not significantly differ between males and females nor athletes with or without a history of concussion.

Clinical Relevance:

Strength-endurance of the neck is a novel parameter that differs from maximal neck strength in male and female collision and contact sport athletes. It is possible that strength and conditioning efforts may improve direction-specific strength-endurance of the neck, and future studies evaluating modifiable risk factors of concussion should further investigate the utility of neck strength-endurance.

**Keywords**

Concussion, Sport Related Concussion/SRC, Neck Strength, Cervical Muscle, Resistance Training, Prevention
2.2 Introduction

A concussion is a form of mild traumatic brain injury that results from biomechanical forces being transmitted to the head(5). This results in linear and rotational acceleration of the brain within the skull, causing compression, shear, and strain of brain tissues(6). These mechanical loads trigger a pathophysiological response within the brain leading to a transient disruption of brain function(5,176).

In response to the high frequency of and potential disability from sport-related concussions (SRC)(177), identification of effective prevention initiatives is a priority. Headgear and mouthguards were regarded as a reasonable approach to prevent SRC, however, researchers have failed to find overwhelming benefit in their use(62). More recently, maximal neck strength has been identified in the literature as a potentially modifiable intrinsic risk factor for SRC. The strongest evidence in support of this hypothesis was reported by in Collins et al.(20) who determined that every 1-pound (~0.45kg) increase in neck strength reduced risk of concussion by 5% in high school athletes. Apart from initial findings by Collins and colleagues, the link between neck muscle function and head biomechanics related to concussion has not been fully supported(26,85,183). One potential reason for the conflicting findings is that although maximal neck muscle strength improves head stability in anticipated, low-velocity impacts its effect in sport-specific situations (e.g., hockey game impacts(54) and tackles in football(16)) or unanticipated loading(10,11,14) remains debatable. Beyond maximal strength there are numerous ways to examine neck muscle structure and mechanical function as potential modifiers of head kinematics and concussive injury. The most frequently explored parameters are neck girth, stiffness, and maximal strength. Neck girth and stiffness are found to be closely related to head stability(10–12,14,16), however these neck parameters present a challenge to collect in a
clinical or strength & conditioning (S&C) environment(153). They require fixed and expensive equipment(153), involve abrupt loading of participant’s heads and/or require skilled operators outside of the scope of S&C professionals(11,14), making it difficult to evaluate large sport teams.

Assessing neck strength-endurance is a potentially attractive parameter in sport concussion prevention initiatives. This parameter has yet to be fully explored and the potential deficits are modifiable(124,148,149,150). Generally speaking, stability of the spinal column is achieved through coordinated contributions of surrounding passive and active tissues of the neck(180). Deep muscles lining the cervical spine provide constant postural support (136), whereas the superficial muscles act as prime movers of the head-neck segment (169). The larger superficial muscles theoretically hold the greatest capacity for stabilizing the head and neck given the muscles’ anatomical (morphological) and functional (mechanical) characteristics, yet they may exhibit a delayed response, or reaction time, to a stimulus(134). It is possible that the contribution of deep cervical muscle may aid in stability of the head neck segment beyond that of isolated superficial muscle partially due to the feedforward activation of the deep muscle(136). Furthermore, the resting myofascial tone of deep and superficial layers of neck muscle may be the main contributor for head control in instances where full muscle contraction is absent, such as in unanticipated loading. Previous examinations of maximal neck strength may only assess the maximal voluntary force-generating capacity of the muscles and not reflect the muscular role in unanticipated conditions. Furthermore, maximal neck strength may not reflect the muscle’s capacity to sustain force production. As opposed to maximal strength, fatiguability of a muscle will influence a muscle’s ability to maintain force and provide stability over time(121). Contact and collision sports involve numerous impacts in a given session(70,91); thus, exploration of
both strength and strength-endurance properties of neck muscle may be required to account for repetitive external loading. 

Both the passive and active properties of a muscle-tendon complex contribute to its moment generating capacity(181). For instance, the static moment generated by a muscle-tendon complex can be influenced by its moment arm, effective line-of-action, muscle size and architecture, and neural activation(127), several of which are modifiable (e.g., via [de]training). Strength and endurance of neck musculature has been examined in individuals with neck pain. In these populations, neck pain has been linked to poor head posture, neck muscle activation magnitudes and patterns (141,161). Specifically, using electromyography and craniovervical endurance assessments, associations have been identified between overactivity of superficial muscle and/or hindered strength of deep muscle and instability and/or neck pain(140). Improvements in local pain, deep cervical muscle strength and head posture are observed following endurance training(144,160,169). In the context of SRC, a number of studies have found lingering cervical dysfunction in those with acute or persistent concussive symptoms(170–173). In accordance with the neck pain trends, it has been suggested that those with a history of concussion are at greater risk of sustaining a subsequent SRC(5,174) which may in part be due to cervical dysfunction(171,175). The requirements of the neck in sport-specific scenarios are unique, involving multi-directional impacts under various states of attention. As discussed above, maximal neck strength does not necessarily reflect head stability in response to unanticipated loading(10,14) or sport-specific impacts(16,26). In contrast, the unexplored characteristic of neck strength-endurance may better encapsulate the strength requirements of the neck to provide continual head stability in sport.
Females have 30-60% less maximal neck strength (11,164,165), lower head-neck segment mass(14,18), and less neck girth than males(14,18). Females also show greater head accelerations after impact or loading(10,167). Furthermore, Reports indicate that females have greater relative risk of SRC in sex-comparable sports(2,70,85). As such, it has been suggested that females may be more vulnerable to concussion due to neck parameters, yet the association has yet to be established.

Thus, the purpose of this study was two-fold. The first purpose was to characterize and quantify athletes’ neck strength-endurance. The second was to compare neck strength-endurance between sexes and between those with and without a history of concussion. We hypothesized: (1) females would perform poorer on the neck assessment compared to males; and (2) those with a history of concussion (Hx) would perform poorer than those with no history of concussion (No).

2.3 Methods

2.3.1 Participants

Ninety-seven (n = 97) athletes were recruited between February 2018 and May 2018 at a single institution from 12 interuniversity male (M) and female (F) sport teams. These included soccer (M/F), ice hockey (M/F), basketball (M/F), football (M), volleyball (M/F), field hockey (F), and rugby (M/F). Athletes were ineligible for the study if they were experiencing or recovering from any shoulder, head or neck injury at the time of recruitment. All study participants provided written informed consent prior to enrollment, and all study procedures were in accordance of the declaration of Helsinki, and approved by the Health Sciences Research Ethics Board, University of Toronto (protocol reference #31568).
2.3.2 Neck Strength-Endurance Assessment

For the purposes of this study, strength-endurance represents the ability of active and passive tissues of the neck to produce and maintain sub-maximal force output under static (isometric) and/or dynamic loading (127,182). To evaluate neck strength-endurance of the neck, previously-reported maximal isometric strength values were scaled using time-under-tension principles to represent a 15-second isometric force value. Prior research in athletic(166) and general(164,165) populations have contributed to our understanding of maximal neck strength capacity in collision and contact sport athletes. The resulting loads that were used to apply an external load to the head were 15% body mass (BM) in forced flexion (extension strength), 12% BM in left and right lateral flexion (right and left strength), and 10% BM in forced extension (flexion strength). These percentages were used to calculate resistance applied to the head for each participant. The goal of this assessment was to maintain a neutral head and torso posture under the external loads for 15 seconds which is achieved through the contribution of both active and passive tissues of the neck. For the purposes of this study, the directions will be referred as the internal moment polarity required to equilibrate the external (demand) moment imposed (e.g., flexion strength is assessed under the load of 10% BM).

To ensure that this protocol was suitable for collision and contact sport athletes, multiple (n = 10) pilot tests were undergone to assess feasibility and address any potential adverse effects. The multi-directional nature of this assessment was important, as research has provided strong evidence suggesting that angular accelerations pose a heightened risk of concussion in comparison to linear accelerations(183). Since the muscles involved with axial rotation are involved with lateral flexion, flexion and extension(127), it is reasonable to assume that the
testing procedures above capture the capacity of axial rotation in a safe, effective and practical manner.

The neck assessment consisted of a single session lasting approximately ten minutes for each participant. The equipment comprised of an Elieko (Chicago IL, USA) 20kg power lifting bar, a 30cm generic metal box, and Rogue (Rogue Fitness CA, USA) power rack which anchored the custom-designed pulley system. The pulley system was built of a 200cm and a 100cm piece of wood (5 x 10cm) bolted to the power rack, supported by two grounded cords (Figure 2a).

Attached to this was a generic metal pulley, rope, custom weight basket (1.3kg) and head harness (Figure 2a) used to apply force to the head. Metal plates ranging from 0.1kg to 5.0kg were used to attain individualized force requirements. One evaluator operated the camera systems while another applied resistance to the participant’s head using the pulley system.

A six-camera OptiTrack Flex-13(NaturalPoint, Corvallis, OR) motion capture system operating at 120 Hz was used to measure kinematics of the participant’s head and torso (Figure 2b). These data were garnered using AMASS/Capture2D (C-Motion, Germantown MD, USA) software.

The participants were outfitted with 17 reflective markers (Figure 2c) attached to the head and torso, which allowed for detection and quantification of the participant’s position and motion. Two generic video cameras (Logitech©, Newark CA, USA. C90 HD Pro Webcam 1080p/30fps) were time-synchronized and captured the entire testing procedure from sagittal and frontal plane perspectives. Using these videos, an independent rater classified each of the participant’s four trials as a pass or fail. The following criteria was used in evaluation: 1) maintaining a neutral head position for 15 seconds; 2) keeping the torso pressed against the restraining device at all times; 3) no change in foot or upper body posture as determined by pressure detection devices under the feet and/or movement of hands from thighs. If one or more of these conditions were
not met, the trial was deemed a fail. Using the dual screen, pause, and time recording features of Kinovea® (Version 0.8.26, France) the time at which the harness was released was used to begin the 15-second trial (0 seconds) and was recorded to the time a failure occurred, or if the participant completed the trial (15 seconds).

2.3.3 Motion Capture Data Processing

Motion capture data were analyzed using AMASS and Visual3D (C-Motion, Germantown, MD). The markers positions acquired using Capture2D were labeled in AMASS before being exported to Visual3D for processing and kinematic analyses. Head center of mass (CoM) was determined using an eight-marker representation of the head segment (Figure 4) with the origin at the seventh cervical vertebrae. The thorax was also created using a six-marker representation (Figure 4). The position of the head relative to the thorax coordinate system (torso) at the beginning of the trial was “zeroed”. From the initial position (0.00m), motion of the head was tracked over time and used to generate kinematic variables to assess neck strength-endurance. Euclidean distance of the head segment relative to the torso was calculated to quantify the total distance covered in all planes. These values were used to determine outcome measures of head distance (m) and displacement (m) relative to time(s).

Three kinematic variables were used to characterize and quantify performance in each of the four directions of the neck assessment. These included peak head displacement (PD)(m), time of PD(s), aggregate head distance (AD)(m) and absement (AB)(m*s). AD was calculated by summing the change of distance from 0 to 15 seconds. AB was calculated as the area under the distance-time curve for each motion capture trial to quantify time the head spent outside of neutral position. Collectively, these measures enabled a comprehensive evaluation of neck isometric properties during the trials.
2.3.4 Statistical Analysis

Participants’ characteristics (mass, height, age, concussion history) and dependent variables (four-directional head kinematics) were evaluated for normality using Shapiro-Wilk tests. Parametric tests ($t$-tests) were employed to assess normally distributed data and non-parametric tests (Mann-Whitney $U$ and Wilcoxon Signed-Rank tests) were employed for data that was not normally distributed. Significance was corrected for multiple comparisons using Bonferroni post-hoc tests.

Participants were also categorized into pass (if they passed all directions) or fail (if they failed one or more directions) based on independent rater decisions. Using these categories, analysis was completed in two ways. First, a two-by-two Chi Square goodness-of-fit test ($\chi^2$) was employed to assess the frequency of pass or fail between sexes and concussion history. Second, to further compare the relationship between motion capture and observational results, participants’ failed trials were matched with another participant’s passed trial in that specific direction who was similar mass (<3kg), sport (collision/contact) and sex (M/F). Their direction-specific AD at the time at which the failure occurred was compared using Wilcoxon Signed Ranks test with Bonferroni correction.

Twenty participants returned for a second session during the same time of day, at least 1 week (7-14 days) after the initial session to evaluate test-retest reliability of the neck assessment. Reliability of independent rater was calculated by Chi Square goodness-of-fit test ($\chi^2$), and motion capture data was calculated using Spearman’s correlation.

All statistical analyses were completed in R (RStudio, version 1.1.456, Boston MA, USA).
2.4 Results

2.4.1 Participant demographics

The mean ± standard deviation of participants’ age was 21.9 ± 1.7 yr for M and 21.7 ± 1.2 yr for F. Height and mass differed between M and F (Table 1), however history of ≥1 concussion(s) did not ($\chi^2 = 0.188, p=0.665$) (Table 1).

2.4.2 Neck assessment protocol test-retest reliability

In the follow-up session there was moderate consistency in pass and fail decision making by the observer; on average 68% of decisions were the same ($\chi^2 = 0.016, df = 1, p= 0.900$). Extension was the most consistent (76%), followed by flexion (69%), left flexion (64%) and right flexion (60%). The test-retest reliability of the quantitative data was moderate for flexion ($r=0.436$) and extension ($r=0.341$), but low for left ($r=0.105$) and right ($r=0.287$) lateral flexion.

2.4.3 Performance based on kinematic variables

Mean head absment (AB) relative to the torso was used to quantify performance. Figure 5 illustrates head AB over 15 seconds of the athletes who passed that respected direction, depicting a successful performance under the conditions of the assessment.

Average PD values were similar in each of the four directions (Figure 6), however, time to PD was earlier in flexion (Mean ± SD = 8.34 ±5.1s) when compared to the other three directions (Ext = 10.8 ±5.6s, Left = 11.45 ±5.5s, Right = 10.98 ±5.5s).

Participants experienced the greatest AB (i.e. the head was a greater distance away from the torso for the longest time) in the flexion condition, which was significantly greater than left
lateral flexion and extension, but not right lateral flexion, which was also significantly greater than extension (Table 2 & Figure 6).

Participants were dichotomized into history of concussion (Hx) and no history of concussion (No), and M and F. There were no differences in PD, AB or time to PD between either of these comparison groups (Tables 3 & 4).

2.4.4 Performance based on independent rater classification

Participants had the lowest percentage of failures in extension (Fail %, time to failure) (11%, 5.3s). In contrast, participants had considerably higher failures rates in flexion (38% at 4.0s, 
\( p<0.001 \)), left flexion (33%, 4.8s, \( p<0.001 \)) and right flexion (33%, 6.4s, \( p<0.001 \)). Overall, 68% of the participants failed one or more directions. There were no significant differences in failure rates of the strength-endurance assessment between M and F athletes (M: 66%, F: 68% \( \chi^2 = 0.022 \ p=0.881 \) ) or Hx and No (Hx: 68%, No: 61%, \( \chi^2=0.786 \ p=0.375 \) ). However, when categorized by 1, 2, or 3 failed directions, females failed in 3 directions twice as often as males (M: 6%, F:14%, \( \chi^2 = 2.722, p=0.099 \) ).

2.4.5 Matched analysis

Participants had 46% greater AD at the time of failure compared to the matched control who passed that specific direction (extension: \( p=0.037 \), flexion: \( p<0.001 \), left flexion: \( p<0.001 \), right flexion: \( p=0.003 \)).

AB in those group of individuals who failed according to the “coach’s eye” was averaged to depict a poor performance on the assessment. There was a statistically significant differences in each of the trails between the AB of the individuals who passed and those who failed in the
matched analysis (extension: \( p<0.001 \), flexion: \( p=0.001 \), left flexion: \( p=0.001 \), right flexion: \( p=0.003 \)).

2.5 Discussion

The main finding of the present study was that a high percentage of contact and collision-sport athletes performed poorly on the neck strength-endurance assessment. Contradictory to our hypotheses, performance was not significantly influenced by sex or history of concussion. Strength and endurance of neck musculature is modifiable\(^{(148,149)}\) and may be trained to address individual differences such as those identified in this study. Hypothetically, strength-endurance may be important for protection against concussion, yet it remains unclear whether this intrinsic factor effects the risk of concussion in sport.

2.5.1 Direction-specific neck strength-endurance

We observed differences in performance between neck flexion, bi-lateral flexion and extension. Participants exhibited the largest AD and reached PD the earliest in the flexion trial compared to the other three conditions. Participants failed most frequently during the flexion trial, followed closely by bi-lateral flexion. These results are aligned with previous work evaluating maximal neck strength that report flexion and bi-lateral flexion strength to be significantly weaker than extension\(^{(10,12,20,117,164,166)}\). However, the discrepancies between these two indices in the present study may be more significant. Our neck strength-endurance assessment involved scaled force application of 10\%, 12\% and 15\% BM in flexion, bi-lateral flexion and extension, respectively. This scaling, based off of previous maximal strength reports\(^{(149,164,165)}\), was designed to normalize the difficulty across the four directions. The results indicated that when external load was applied the posterior head forcing flexion, extension neck strength-endurance
was the strongest of the four directions. This may be explained in multiple ways. Participants in
the current study regularly took part in general resistance training involving the shoulders and
upper back. These exercises may predominantly increase trapezius and erector strength, thereby
contributing to neck extension but not flexion or bi-lateral strength(73,127). Additionally,

anterior and posterior aspects of the cervical spine serve different functions of the neck(184).
The vertebrae and musculature of the anterior neck are designed for mobility whereas these of
the posterior neck are designed for loading and supporting the head(184). The vertebrae and
musculature of the anterior neck are designed for mobility and head control whereas the posterior
cervical vertebrae and musculature are designed for loading and supporting the head(184).

Additionally, muscle girth has previously been associated with neck strength and head

stability(11,12,73), and posterior neck consists of approximately 75% of the total physiological
cross-sectional area(133,152), whereas the anterior aspect of the neck consists of only 25%. This
discrepancy in muscle mass may have implications for moment generating capacity in the
flexion and lateral directions due to lower passive neck stiffness, viscosity and isometric
force(30,86), giving the posterior neck an advantage on this assessment. Overall, the anterior
cervical spine may not be designed to withstand impulsive loading from impacts involved in
contact and collision sports, inherently increasing the risk of instability and injury in flexion and
bi-lateral flexion directions.

2.5.2 Neck strength-endurance trends and risk of concussion

We observed a large discrepancy between participants’ flexion and extension neck strength-
endurance. Muscular strength imbalance about a joint may pose a risk of injury in
musculoskeletal joints such as the knee(185) and neck(13). This injury risk may be influenced by
biased joint loading after muscular contraction, limiting rigidity and reducing coupling between
two body segments. Specific to the neck, a flexion-extension strength ratio may influence head stability. For instance, Dezman and colleagues(13) report that a flexion-extension strength ratio closer to one is protective against head acceleration after heading a soccer ball, yet maximal neck strength is not. In application to the field of strength and conditioning, these findings highlight the importance of identifying neck strength-endurance ratios in addition to isolated values in each direction. Subsequent training should be designed with the focus of reducing strength gaps between directions.

Flexion and bi-lateral flexion strength-endurance may be of particular concern for collision and contact sport athletes. In these sports, kinematic and observational data show that concussive events occur largely from impacts to the frontal and/or lateral aspects of the head(15,35,53,100) resulting in a combination of linear and rotational forces(55). The mechanisms of impacts vary considerably, either directly (body-to-head impacts, heading a soccer ball), or indirectly (“whiplash” response to a body blow, tackle to the ground, or body check into the boards(7)). In scenarios where impacts occur directly to the head, forces may be mitigated with a coupled head-torso segment(12,30). We know that neck musculature in each of these directions can be adequately trained(125,148,149), yet the role of neck strength-endurance in controlling sport-specific loading is unknown. Our results warrant future investigation into the role of neck strength-endurance in head stability and prospective risk of SRC.

2.5.3 Concussion history and neck strength-endurance

Our original hypothesis derived from the findings of Collins et al.(20) was not supported in the present study. However, our findings align with recent literature which report no relationships between history of concussion and deep cervical flexor endurance in healthy youth football players(178) or peak multi-directional neck strength in asymptomatic pediatric athletes(186).
Despite acute changes in cervical flexor endurance (178) and cervical spine dysfunction (175) after concussion, there appears to be no long-term deficits in neck strength after this injury. There are numerous reasons why a relationship between concussion history and neck strength-endurance was not observed in this cohort. It is possible our conservative exclusion criteria (i.e., not experiencing head, shoulder or neck pain, dysfunction or injury in the past 6 months) are why we did not find any differences between athletes with or without prior concussion. It is also possible we did not observe differences in failure rates between these subgroups because of the high failure rate (68%) among all participants. It is also possible that there no relationship between concussion and neck strength-endurance, yet further research is warranted in this area. Future studies should consider using different percentages of body mass in an attempt to examine a relationship between prior concussions and neck strength-endurance. Additionally, the cross-sectional design did not allow for prospective evaluation of concussion incidence that the work by Collins et al. (20) did. This may be one reason for inconsistent findings between studies, eluding to the importance of prospective evaluations of neck properties and incidence of concussion. Assess how neck strength and/or endurance changes over the course of a game or training event may also be helpful in understanding the requirements of strength-endurance in addition to absolute neck strength in contact and collision sport athletes.

It is also important to consider the different biomechanical consequences of body verses head impacts in sport, and the role the neck plays in each. Specifically, forces applied to the head from direct head impacts may be mitigated by a coupled head and torso from a stiff neck, as there is an increased segment mass. In theory, this may be the opposite for forces transmitted to the head during a body hit, as a stiff neck may result in more efficient force transmission from the body to head. If this is the case, greater neck-strength endurance – which may reflect greater neck
stiffness capacity – may not truly be a protective factor for concussion. These are important features that need to be addressed in future biomechanical analyses of SRC.

2.5.4 Sex differences in neck strength-endurance performance

In contrast to our second hypothesis, neck strength-endurance was not significantly different between males and females. Our results are contrary to the majority of literature that report females to have 30-60% less maximal neck strength than males(11,164,165). However, in the present study we assessed strength-endurance relative to body mass, accounting for the difference in muscle mass between males and females, potentially contributing to our null findings. Furthermore, compared to males, females typically have greater relative endurance capacity than relative maximal strength capacity(187,188). Specifically, females have superior endurance profiles in spinal stabilizing musculature compared to males(188). Thus, neck strength-endurance properties may be less-disparate than maximal neck strength when comparing males and females.

2.5.5 Strength-endurance verses maximal neck strength

The primary purpose of this study was to assess strength-endurance of the neck musculature, however, the design allowed for examination of both absolute strength and endurance deficits. For instance, if an individual failed at 2 seconds, it is likely that they have an absolute strength deficit in that direction. In contrast, a participant who failed at 13 seconds is more likely to have an endurance deficit. The direction-specific strength and/or endurance identified in this neck assessment may be subsequently targeted in training interventions. Future research should continue to explore this parameter and its relationship to SRC.
2.5.6 Limitations

The study must be interpreted in the context of its limitations. The neck assessment used was limited to the standardized resistance and time domains in the design. Because of the novel nature of this study, steps had to be taken to establish a “starting” point to inform future investigations into neck strength-endurance. The evidence-based parameters chosen for the neck assessment were done so for feasibility purposes and to allow for evaluation of a large sample of athletes. Future work should examine various strength loads to understand and potentially better capture the strength-endurance properties of the neck. Measures used to capture strength-endurance in this study may also have their own inherent errors. Sampling rates and algorithms used in motion capture were decided based on movement expectancy and subject markers were placed to best represent body segments, however, we cannot guarantee an exact representation of the body segment movement through this method of collection. Test-retest reliability was poor in the right and left lateral flexion conditions. This may in part be explained by small degrees of freedom in lateral flexion, where discrete changes in head posture may be deemed significant by the independent rater yet are recorded as a small change in total head motion using motion capture. Ranked statistical methods may hold error as there is no magnitude of difference between ranks, therefore discrete movements of the head scored similarly in the observational analysis would be ranked differently in the statistical method. Lastly, independent rater classification of pass and fail of the trials may hold bias and human error, however this method was chosen as it best represents the methods used in future utility of this assessment within the strength and conditioning and clinical environments.
2.5.7 Conclusion

Neck strength-endurance of interuniversity collision and contact sport athletes is strongest in the extension direction compared to that of flexion and left and right lateral flexion. The results of this study highlight discrepancies between previously reported maximal neck strength and current strength-endurance values which should be addressed in future work. Neck assessments may benefit from the inclusion of strength-endurance in addition to maximal isometric strength to account for these discrepancies observed. Strength and conditioning and sport medicine practitioners may include neck strength-endurance in evaluations and when prescribing neck training for contact and collision sport athletes.
Chapter 3
Discussion

3 Discussion

The present study evaluated neck strength-endurance in collision and contact sport athletes. The main finding of the thesis was that a high percentage of contact and collision-sport athletes failed the neck strength-endurance assessment. Contradictory to our hypotheses, performance was not significantly influenced by sex or history of concussion. Yet, the gaps in flexion and bilateral flexion observed may be of concern. Discrepancies in direction-specific neck strength-endurance measured in this study may be modified by strengthening and conditioning (S&C) the muscular properties of the neck(148,149). In theory, strength-endurance may be a protective factor against sport-related concussion (SRC), yet it remains unclear whether this factor directly relates to reduced SRC incidence in sport. Overall, our study identified neck strength-endurance as a property to be considered by S&C and sport medicine practitioners when evaluating and prescribing neck training for contact and collision sport athletes.

The primary purpose of this study was to characterize neck strength-endurance in male and female interuniversity athletes. The largest differences observed in this study were between the four directions of the neck strength-endurance. In the observational analysis, participants failed most often in the flexion condition (n=37) closely followed by left (n=32) and right (n=32) lateral flexion. In the motion capture analysis, participants exhibited the largest AD and reached PD the earliest in the flexion condition compared to the other three directions. These direction-specific strength patterns are similar to that of previous maximal neck strength evaluations, which report flexion and bi-lateral flexion to be significantly weaker than
extension(10,12,20,117,164,166). However, the magnitude of these discrepancies in the present study may be larger. In the current study, external force was applied to the head under scaled resistances of 10%, 12% and 15% BM in flexion, bi-lateral flexion and extension, respectively. This scaling, based off of previous maximal strength reports(149,164,165), was designed to normalize difficulty across the four directions. Despite this normalization, the differences indicate that external loading to the posterior aspect of the head, requiring extension strength, was the least difficult of the four directions. This may be explained in multiple ways. Participants in this study regularly took part in general resistance training involving the shoulders and upper back. These exercises may predominantly increase trapezius and erector strength and cross-sectional area, contributing to neck extension but not flexion or bi-lateral strength or passive resistance(73,127). Furthermore, the anterior and posterior portions of the cervical spine perform different functions for the neck(184). The vertebrae and musculature of the anterior neck are designed for mobility and head control whereas the posterior neck vertebrae and musculature are designed for loading and supporting the head(184). Muscle girth has previously been associated with neck strength and head stability(11,12,73). The posterior neck consists of approximately 75% of the total physiological cross-sectional area(133,152), whereas the anterior aspect of the neck consists of only 25%. This may have implications for moment generating capacity in the flexion and lateral directions due to lower passive neck stiffness, viscosity and isometric force(30,86), and thus give the posterior neck an advantage on this assessment. In a practical sense, the anterior cervical spine may not be adequately designed to withstand impulsive loading from collisions in sports, inherently increasing the risk of instability and injury in flexion and bi-lateral flexion directions. Furthermore, it is reported that impacts in collision and contact sports happen most frequently from the front and lateral sides of the head(35,189) and as a result,
concussions happen most frequently in these directions(15,35,53,100). In agreement with previous work, the present study identifies flexion and bi-lateral flexion to be the most vulnerable of the four directions.

To further highlight the direction-specific trends, participants in this study had a large performance discrepancy between flexion and extension. This muscular imbalance may pose some concern, as a large maximal strength ratio between flexion and extension has previously been identified as a risk factor for increased head acceleration after impact(13). Muscular imbalance may result in biased joint loading when co-contraction of muscle about a joint is performed(13), augmenting motion and instability. Specific to the neck, absorbing a “hit” or heading a soccer ball, involve co-contraction and coordination of cervical musculature(10,167) and may increase head acceleration and injury risk if there is a discrepancy in strength. For instance, Dezman and colleagues(13) report that a flexion-extension strength ratio closer to one reduced head accelerations after heading a soccer ball whereas possessing stronger maximal strength did not.

The results from this study highlight the need for S&C coaches and/or medical practitioners to consider direction-specific strength in addition to absolute strength and strength-endurance of the neck. Testing multi-directional neck strength-endurance is an effective way to identify direction-specific neck strength properties as demonstrated in this study. Since specific neck training is effective at increasing neck strength and endurance(125,148,149), subsequent training can be used to target specific neck directions in attempt to mitigate head accelerations leading to concussion in sport.

Head motion in flexion and extension both aligned with observational failure rates, showing the highest and the lowest average head displacement, respectively. On the other hand, left and right
lateral flexion showed average head displacements similar to extension, despite the different failure rates. This may be explained by the features used to determine failures and physiological range of motion of the head. First, the physiological degrees of freedom of the cervical spine in flexion and extension are quite large with averages between 68-78 degrees(190). In contrast, lateral flexion has only 45 degrees of physiological motion(190), resulting in less room for displacement from neutral position. Because of this small range of motion, observational decision making about position of the head may rely more on subtle head posture changes rather than total head motion. If this is the case, it would account for some of the inconsistency observed between flexion and bilateral flexion motion capture results despite similar failure rates. In contrast to absolute head displacement, head absement was statistically greater in those who failed the assessment compared to passed trials in each direction. This suggests that the “coach’s eye” was effective at detecting changes in head posture over time, and in turn, making decisions about performance on the assessment.

The second hypothesis of this study predicted that participants with a history of concussion would fail the neck assessment more often than those with no history of concussion. This was primarily based off of the epidemiology findings of Collins and colleagues(20), who reported that high school students with weaker maximal isometric neck strength were more likely to sustain a SRC in the subsequent sport season. This group went on to state that with every 1lb increase in neck strength, the risk of sustaining a SRC was reduced by 5%. Although this is attractive evidence for promoting neck training as protection against concussion successive work investigating this relationship is unsupportive.

The findings in the present study are in line with other recent literature, which do not support a relationship between neck strength and/or endurance and history/risk of SRC. Specifically,
Engleman et al. (186) reported no relationship between peak neck strength and history of SRC in asymptomatic pediatric athletes, and Smith et al. (178) reported no relationship between deep cervical flexor endurance and history of SRC in youth football players. Furthermore, Mihalik and colleagues (26) did not find an association between maximal isometric neck strength and head accelerations experienced in male youth hockey. Other biomechanical analyses show that neck strength is only influential when the individual is both expecting and braced for impact (11, 16, 191). The protective quality of neck strength is thought to reduce head accelerations by dampening forces transmitted to the head (85) and also by coupling the head and torso to increase overall segment mass and reduce acceleration after a head blow (10, 11, 26). However, although head accelerations are influential in concussion incidence, there is a wide range of impact severities that can lead to concussion (7, 192), and further exploring the neck and concussion relationship is warranted. It may be that higher-powered studies with less-explored neck properties in addition to maximal neck strength are needed to match the work of Collins et al. and further investigate the protective role of neck strength in high risk sport.

Neck pain is related to compromised neck musculature (142, 160, 193) and is a predictor of concussion in youth athletes when assessed at baseline (194). The present study excluded individuals currently experiencing head, neck and/or shoulder pain which eliminated our ability to evaluate the relationship between neck pain and neck strength-endurance. In the acute stages post-concussion there are changes in cervical flexor endurance (178) and cervical spine dysfunction (175) that accompany neck pain and other concussive symptoms, yet these symptoms often resolve by return to play (175, 178). Despite the high frequency of cervical spine dysfunction in acute stages post-concussion, there appears to be no long-term deficits in neck strength after this injury.
Another factor that potentially limited observed differences between history of concussion groups were the high failure rates (68%) among participants. It is possible that using lower percentage of body mass applied to each direction would sway the failure rates and study outcomes. Also, a larger sample size would have permitted the examination of potential differences in athletes with multiple concussions compared to athletes with one or no prior concussion. A larger sample size may also allow for evaluation across sports, as different neck requirements and head impacts may exist across collision and contact sports. Future studies should consider using both lower percentages of body mass and a sample size sufficient to examine the relationship between multiple concussions and neck strength-endurance.

Additionally, the cross-sectional design did not allow for prospective evaluation of concussion incidence that the work by Collins et al. (20) did. This may be one reason for inconsistent findings between studies, eluding to the importance of prospective evaluations of neck properties and incidence of concussion.

It is also important to consider the different biomechanical consequences of body verses head impacts in sport, and the role the neck plays in each. Specifically, forces applied to the head from direct head impacts may be mitigated by a coupled head and torso from a stiff neck, as there is an increased segment mass. In contrast, forces transmitted to the head during a body hit may theoretically be greater with a stiff neck. If this is the case, greater neck-strength endurance which may reflect greater neck stiffness capacity may not truly be a protective factor for concussion. These are important features that need to be addressed in future biomechanical analyses of SRC. There was no significant difference in neck strength-endurance between males and females in the current study. This is contradictory to previous work, as the overwhelming majority of maximal neck strength in the literature demonstrate that female have far weaker (40-
60% less) absolute and relative neck strength than males(11,164,167). This may be explained by the strength property that was assessed in this study. Typically, females possess similar, if not superior, relative endurance properties than males(187), which may explain this discrepancy. There may also be some influence from the scaling of body mass, as females were resisting less external load than males, partially contributing to the similarities in performance.

The initial purpose of this study was to examine strength-endurance properties of neck in interuniversity athletes. However, during the data collection period, qualitatively it became apparent that participants were failing in the trails in two distinct patterns. These initial observations were verified during the quantitative analysis. Specifically, if an individual moved past neutral, failing the assessment at 2 seconds, it is probable that they did not possess the absolute strength properties to withstand that load. In contrast, an individual who was unable to maintain position at 13 seconds may have the strength but lack the endurance properties to sustain force generation against the external load. This information can be very useful for designing and implementing strength and conditioning programs for the neck; the coach or practitioner can design training to target both direction-specific strength and/or endurance as needed.

The study must be interpreted in the context of its limitations. The neck assessment used in this study was limited to the standardized resistance and time domains based off of best-practice recommendations in the literature. Because of the novel nature of this study, steps had to be taken to establish a “starting” point to inform future investigations into neck strength-endurance. The parameters chosen for the neck assessment were done so for feasibility purposes and to allow for evaluation of a large sample of athletes. Future work should examine various strength loads to understand and potentially better capture the strength-endurance properties of the neck.
Furthermore, for practicality and safety purposes, the study was centered around isometric, strength-endurance capacity which is limited to static and anticipated conditions. The collection methods used in this study may hold some inherent error. Sampling rates and algorithms used in motion capture were decided based on movement expectancy and the subject markers were placed to best represent body segments. This being said, it is not guaranteed that these markers are an exact representation of the body segment movement through this method of collection. The re-test reliability was poor in right and left lateral flexion conditions. This may be explained by the combination of small degrees of freedom in lateral flexion which also effected the agreeability between motion capture and independent rater decisions. Ranked statistical methods may hold error as there is no magnitude of difference between ranks, therefore small, discrete movement of the head that would be scored similarly in observation will be ranked differently in the statistical methods. It has become clear in the analysis that lateral flexion is more difficult to accurately judge. This tool may be used in future studies to better objectify lateral head movement to determine a cut off for pathological and physiological movement past neutral position.

Future studies should focus on how a variety of neck properties can modify concussion risk using high-powered studies. Specific to strength-endurance, neck properties should be tested under a range of body weight percentages to better understand values of a given population and to further explore the relationship to risk of SRC. Future work should establish baseline values of neck strength-endurance and prospectively observe how they may change over an athlete’s season and after injury. Direction-specific neck strength-endurance and concussion risk should also be further explored as this may be related to vulnerable impacts in sport. Lastly, identifying
an optimal value of neck strength and/or endurance for protection against SRC may be a goal for future studies.

The present study introduced an alternative neck assessment strategy to be used by S&C and clinical practitioners involved with contact and collision sport athletes. Neck strength-endurance was assessed in ninety-seven interuniversity athletes, revealing extension as considerably more robust than both flexion and left and right lateral flexion in this cohort. These direction-specific trends are potentially concerning considering the high frequency of frontal and lateral impacts experienced in sport-specific scenarios. These findings lend support for the continual exploration of the neck’s role in SRC, while also offering an alternative variable to consider in addition to maximal neck strength. Neck strength-endurance may be of value in neck muscular assessments and in training strategies in attempt to mitigate an internal modifiable risk factor of SRC.
Chapter 4

4 References


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Physical Activity Readiness Questionnaire (PAR-Q)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions below. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
2. Do you feel pain in your chest when you do physical activity?
3. In the past month, have you had chest pain when you were not doing physical activity?
4. Do you lose your balance because of dizziness or do you ever lose consciousness?
5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
7. Do you know of any other reason why you should not do physical activity?

If you answered NO honestly to any of the above questions, tell your fitness or health professional.

YES to one or more questions

- Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.
- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:
- Start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 140/90, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:
- If you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better.
- If you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should alter your physical activity plan.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

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Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.
5.2 Consent Form

ETHICS REVIEW INFORMATION SHEET/CONSENT FORM

Title of research project: “Neck screening protocol: potential utility in sport-related concussion.”

Investigators:
Mary Claire Geneau (Principal Investigator)
Faculty of Kinesiology and Physical Health Education
University of Toronto
e-mail: mary.geneau@utoronto.ca
phone: (416) 949-5719
Michael Hutchison, PhD., University of Toronto
Doug Richards, M.D., University of Toronto
Tyson Beach, PhD., University of Toronto

Background & Purpose of Research:
Identification of modifiable risk factors for sport concussion has increased in recent years. Of particular interest, neck strength may play a role in stabilization of the head during impact, thereby assisting with prevention of concussion. The purpose of this study is to examine neck strength-endurance capacity in male and female university athletes.

Eligibility:
To participate in this study, you must be a Varsity Blues athlete participating in one of the following sports: football, field hockey, basketball, ice hockey, soccer, rugby or volleyball. Both male and female athletes are invited to participate in this study. Additionally, you must be deemed fit to participate based on a satisfactory score on the Physical Activity Readiness Questionnaire (PAR-Q), as well as be medically cleared from any previous neck, shoulder or head injury.

Procedures:
Your strength-endurance capacity test will occur prior to or during a regularly scheduled team strength and conditioning session. The strength-endurance capacity test will be scaled to a percentage of your body weight. With a member of the research team, you will sit in four different positions on a bench and resistance will applied to your head by a custom-built pulley system with weighted disks. You will have to hold resistance in each of the positions for 15-seconds. During this test, your performance will be recorded using motion capture and generic digital video.

Voluntary Participation & Early Withdrawal:
Your participation in this study is voluntary and you may withdraw from this study at any time by notifying the investigator. Your withdrawal from this study or refusal to participate in no way affects your care or access to strength and conditioning or medical services, and will in no way affect your academic or athletic status.

Risks/Benefits:
Benefits:
There are no known specific benefits to you participating in the study. However, participation in this study will likely result in a greater understanding of individual and population neck strength, informing future training and better care as a result of better knowledge of this research.

*Risks:*

Risks to participating in the study are minimal. Minor physical risk exists in the submaximal strength testing procedure. The test will be terminated immediately with any pain, discomfort or if you feel unable to continue. The resistance will be adjusted to a percentage of body weight, to a maximum of 25kg, to ensure resistance is safe and effective for each individual. The test will be monitored by strength and conditioning professionals who will ensure the device is safely applied to the head and will remove the resistance immediately when necessary.

*Privacy & Confidentiality:*

Your performance will not be released to anyone other than the principal investigator for purposes of the study. Acquired data will be de-identified and electronic record which will be stored in a password-protected folder on a secure server operated by the Faculty of Kinesiology and Physical Education. The research study you are participating in may be reviewed for quality assurance to make sure that the required laws and guidelines are followed. If chosen, (a) representative(s) of the Human Research Ethics Program (HREP) may access study-related data and/or consent materials as part of the review. All information accessed by the HREP will be upheld to the same level of confidentiality that has been stated by the research team.

*What are the costs of participating in this study?*

Participating in this study will not require any additional time or financial burden as data collection will occur during or surrounding a scheduled training session with your team. As such, there will be no compensation for participation in this study.

*Publication of Research Findings:*

Following the conclusion of this study, the results may be published. No information that could reveal you as a participant will be disclosed in any publication.

*New Findings:*

If anything comes to light during the course of this research which may influence your decision to continue, you will be notified.

*Rights of Subjects:*

You wave no legal rights by participating in this trial. If you have any questions regarding your rights as a participant, you may contact:

- Office of Research Ethics, Health Sciences
- Email: ethics.review@utoronto.ca
- Tel: (416) 946-3273

*Dissemination of Findings:*

The results of this study will be presented or published in collective form. Your personal information will not be used and as such, any published results cannot identify you as an individual. As a research participant, you have the right to request a copy of the final report of the findings if this research study.
Title of research project: “Neck screening protocol: potential utility in detecting risk of concussion.”

By signing this form, I agree that:

- The study has been explained to me.
- All of my questions were answered.
- The possible harms and discomforts and the possible benefits of this study have been explained to me.
- I understand that I may refuse to participate without any problems.
- I am free now, and in the future, to ask any questions about this study.
- I understand that there is a slight risk while I partake in the neck strength test, and that ending the test at any point is safe and permitted.
- I understand that I can stop at any point during the screen if I experience any discomfort or concern.
- I understand that the submaximal efforts during this screen are temporary.
- I have been told that my personal records will be kept confidential.
- I understand that I will receive a signed copy of this consent form.
- I agree that my data may be used for future testing in similar research projects.

Name (PRINT NAME): ____________________________________________

A) I hereby consent to participate in the study.

Signature: ____________________________ Date: ____________

B) I do not consent to participate in the study at this time.

Signature: ____________________________ Date: ____________

I, the undersigned, have fully explained the study to the above participant.

Investigator/Designate Name: __________________________________

Investigator/Designate Signature: ________________________________

Study Contact:
If you have any questions about the study now or in the future, please contact Dr. Michael Hutchison at (416) 946-4050 or michael.hutchison@utoronto.ca
History of Resistance Training
How long have you participated in deliberate resistance training? (i.e. using free-weights, or machines for the purpose of improving muscle size/strength).

Have you completed neck strengthening exercises before? 
Yes  No
If so, have you in the past 6 months? 
Yes  No
How often do you do neck strengthening exercises? (times/week)  

History of Concussion
Have you sustained a concussion this year? 
Yes  No
### 5.3 Operational Definitions

<table>
<thead>
<tr>
<th><strong>Aggregate Head Distance</strong></th>
<th>An accumulation of the scalar quantity, distance, which is the total “ground covered”. This is used to quantify head motion under the conditions of the neck assessment.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Head Displacement</strong></td>
<td>The maximal displacement in the positive or negative direction reached by the head during each trial.</td>
</tr>
<tr>
<td><strong>Flexion</strong></td>
<td>A direction of the neck assessment that an external load was applied in the forced-extension direction (anterior to posterior) which the participant was required to resist by producing flexion moment and translational force.</td>
</tr>
<tr>
<td><strong>Extension</strong></td>
<td>A direction of the neck assessment that an external load was applied in the forced-flexion direction (posterior to anterior) which the participant was required to resist by producing extension moment and translational force.</td>
</tr>
<tr>
<td><strong>Bi-lateral flexion</strong></td>
<td>A direction of the neck assessment that an external load was applied in the forced-right or -left directions which the participant was required to resist by producing left or right moment and translational force, respectively.</td>
</tr>
<tr>
<td><strong>Independent Rater</strong></td>
<td>A single investigator conducted a video analysis of each trial of the neck assessment. Using a “coach’s eye”, this individual determined if a participant moved beyond a neutral posture to fail the test, or if they were able to maintain posture within the parameters. They were to record the time from a visual cue of hand release by the assistant who gradually released the resistance on the participant’s head.</td>
</tr>
<tr>
<td><strong>Pass</strong></td>
<td>The participant was able to maintain neutral posture and remain in contact with the restraining device and pressure sensors for the duration of the assessment. A score of 15/15 would be given.</td>
</tr>
<tr>
<td><strong>Fail</strong></td>
<td>The participant was unable to maintain neutral posture or contact with the restraining device and pressure sensors for the duration of the assessment. Time of which this occurred was the score given (i.e. a failure at 3 seconds would be 3/15).</td>
</tr>
<tr>
<td><strong>Strength-Endurance</strong></td>
<td>As a resistance to loading, this property consists of both moment generating capacity of the neck (muscular moment arms and isometric strength of the muscle) and the passive tissues of the cervical spine that provide resistance to motion. The ability to sustain resistance of a submaximal load differentiates this property from peak strength.</td>
</tr>
<tr>
<td><strong>Maximal Strength</strong></td>
<td>The maximal force output that a muscle group can produce. Interchangeable with maximal voluntary contraction (MVC) or maximal isometric contraction for the purposes of this paper.</td>
</tr>
</tbody>
</table>
5.4 Tables and Figures

Table 1. Participant characteristics (mean ± SD) stratified by sex

<table>
<thead>
<tr>
<th></th>
<th>Males (n = 47)</th>
<th>Females (n = 50)</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22.4 ± 1.7</td>
<td>21.7 ± 1.2</td>
<td>0.520</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>184.1 ± 6.5</td>
<td>170.2 ± 8.7</td>
<td>0.00</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>92.0 ± 14.4</td>
<td>69.4 ± 9.0</td>
<td>0.00</td>
</tr>
<tr>
<td>History of concussion</td>
<td>42%</td>
<td>38%</td>
<td>0.590</td>
</tr>
</tbody>
</table>

Table 2. Absence between directions. * indicates \( p = 0.05 \) significance, ** indicates \( p = 0.001 \) significance

<table>
<thead>
<tr>
<th>Direction</th>
<th>Extension</th>
<th>Flexion</th>
<th>Left Flexion</th>
<th>Right Flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension</td>
<td></td>
<td>W = 80403, ( p = 0.006^* )</td>
<td>W = 7098, ( p = 0.7961 )</td>
<td>W = 6259.5, ( p = 0.1807 )</td>
</tr>
<tr>
<td>Flexion</td>
<td>W = 80403, ( p = 0.006^* )</td>
<td></td>
<td>W = 8640, ( p = 0.001^{**} )</td>
<td>W = 7728, ( p = 0.144 )</td>
</tr>
<tr>
<td>Left Flexion</td>
<td>W = 7098, ( p = 0.7961 )</td>
<td>W = 8640, ( p = 0.001^{**} )</td>
<td></td>
<td>W = 7850.5, ( p = 0.094 )</td>
</tr>
<tr>
<td>Right Flexion</td>
<td>W = 6259.5, ( p = 0.1807 )</td>
<td>W = 7728, ( p = 0.144 )</td>
<td>W = 7850.5, ( p = 0.094 )</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Mean differences in aggregate displacement (cm) between passed (n = 31) and failed (n = 66) conditions

<table>
<thead>
<tr>
<th>Direction</th>
<th>Mean Differences</th>
<th>Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension</td>
<td>0.765</td>
<td>( t = 2.443, df = 9, p = 0.037 )</td>
</tr>
<tr>
<td>Flexion</td>
<td>1.039</td>
<td>( V = 449, p &lt; 0.001 )</td>
</tr>
<tr>
<td>Left Flexion</td>
<td>0.958</td>
<td>( t = 4.103, df = 27, p &lt; 0.001 )</td>
</tr>
<tr>
<td>Right Flexion</td>
<td>0.615</td>
<td>( V = 373, p = 0.003 )</td>
</tr>
</tbody>
</table>

Table 4. Average peak displacement of the head relative to torso (cm) between males and females and those with and without a history of concussion.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Male (n = 47)</th>
<th>Female (n = 50)</th>
<th>Statistic</th>
<th>Hx (n = 39)</th>
<th>No (n = 58)</th>
<th>Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension</td>
<td>1.79</td>
<td>2.28</td>
<td>W = 1316, ( p = 0.1226 )</td>
<td>1.94</td>
<td>2.11</td>
<td>W = 1200.5, ( p = 0.5091 )</td>
</tr>
<tr>
<td>Flexion</td>
<td>2.20</td>
<td>2.00</td>
<td>W = 1167, ( p = 0.9037 )</td>
<td>1.81</td>
<td>2.29</td>
<td>W = 1258, ( p = 0.2761 )</td>
</tr>
<tr>
<td>Left Flexion</td>
<td>2.09</td>
<td>1.80</td>
<td>W = 1349, ( p = 0.1454 )</td>
<td>1.71</td>
<td>1.09</td>
<td>W = 1238.5, ( p = 0.3453 )</td>
</tr>
<tr>
<td>Right Flexion</td>
<td>2.13</td>
<td>1.99</td>
<td>W = 1222, ( p = 0.600 )</td>
<td>1.82</td>
<td>2.21</td>
<td>W = 1182, ( p = 0.6015 )</td>
</tr>
</tbody>
</table>
Figure 1. Flow chart of recruitment procedures and athlete participation
Figure 2. Neck assessment experimental equipment and set up.
Figure 3. Aerial view of neck assessment experimental motion capture hardware arrangement.
Figure 4. Marker placement used for segment creation and tracking in motion capture.
Figure 5. Illustration of head absement relative to torso in passed trails of each direction.
Figure 6. Peak head displacement during each trial of separated by dichotomized subpopulations.
Figure 7. Participant in each of the four testing directions. A: Flexion, B: Extension, C: Left Lateral Flexion, D: Right Lateral Flexion. The red arrow identifies force application by the pulley.
Figure 8. Visual observation of a clinical failures in flexion (A, B) and left lateral flexion during an actual trial.