Cervical spine and craniovertebral region function in elite Short Track Speed Skating athletes

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ABSTRACT

__Objective__: The aim of this study was (1) to describe the cervical spine (CS), and craniovertebral region (CVR) function of elite short track speed skating (STSS) athletes and the possible relationships between neck pain or headache and pain provocation and/or segmental stiffness with manual spine examination, (2) determine if athletes with or without a history of previous concussion differ in their function, and (3) to explore possible correlations between athletes' number of previous concussions and their CS and CVR function. *__Study Design__*: A descriptive cross-sectional study with members of the Canadian STSS senior national and regional development teams. *__Methods__*: CS and CVR-function measures of range of motion, strength and endurance, as well as manual spine examination assessments, were added to the usual pre-season testing. Other components of pre-season testing, including the vestibular and oculomotor screening (VOMS) and the modified balance error scoring system (m-BESS), were also gathered. *__Results__*: The entire sample displayed a range of motion within normal limits, very high general neck endurance measures, deep neck flexor activation comparable to that of other populations of athletes, but performance index scores on the craniocervical flexion test (CCFT) were only comparable to those of general population samples. Three distinct measures were significantly different between groups of athletes with or without a history of concussion: the group with a history of concussion displayed less fibrillation on the Cervical Flexor Endurance Test (CFET) (p=0.039), expressed more pain with postero-anterior pressure applied on the Left side of their CS (p=0.046), and higher total change on the VOMS (p=0.03) than those without. No correlations were found between athletes' total number of previous concussions and their CS and CVR function characteristics. *__Conclusion__*: Elite STSS athletes may present with deficits in deep neck

flexors endurance and their CS/CVR function. Although CS/CVR function does not appear to be related to the number of concussions previously reported, this function tends to differ according to their concussion history in three distinct measures. Future work should focus on developing a targeted neuromuscular program for elite STSS athletes to optimize deep flexor endurance and contribute to preventing injuries.

ABRÉGÉ

Objectif: Le but de cette étude était de (1) décrire la fonction de la colonne cervicale (CC) et de la région craniovertébrale (RCV) chez des athlètes d'élite en patinage de vitesse courte piste (PVCP) et les relations possibles entre la douleur au cou ou les maux de tête et la provocation de douleur et/ou la raideur segmentaire perçue lors de l'évaluation manuelle de la CC, (2) déterminer si la fonction de la CC diffère chez les athlètes en PVCP avec ou sans antécédent de commotion cérébrale, ainsi que (3) explorer l'association entre le nombre de commotions cérébrales antérieures et la fonction de la CC et de la RCV. *Design*: Étude descriptive transversale avec des membres de l'équipe canadienne sénior de PVCP et de l'équipe régionale de développement. *Méthodes*: La fonction de la CC et de la RCV fut évaluée avec des mesures d'amplitude articulaire, de force et d'endurance et lors de l'évaluation manuelle de la CC. Ces mesures furent ajoutées aux évaluations habituelles effectuées présaison qui incluent le *vestibular and oculomotor screening* (VOMS) ainsi que le *modified balance error scoring system* (m-BESS). *Résultats* : Le groupe complet a affiché des mesures d'amplitude articulaire dans les limites de la normale, des mesures d'endurance très élevées, une activation des fléchisseurs profonds du cou comparable à d'autres populations d'athlètes, mais un index de performance au *craniocervical flexion test* (CCFT) comparable à celle d'un sous-groupe de la population générale. Trois mesures distinctes se sont avérées significativement différentes entre les athlètes avec et sans antécédent de commotion cérébrale. Ainsi, le groupe d'athlètes ayant des antécédents de commotions cérébrales avait moins de fibrillations au *cervical flexor endurance test* (CFET) (p=0.039), plus de douleur lors de pressions postéro-antérieures appliquées sur le côté gauche de leur CC (p=0.046), et obtenu des valeurs plus élevées de *total change scores* au VOMS (p=0.03). Aucune corrélation n'a pu être établie entre le nombre de commotions cérébrales antérieures et les caractéristiques de la fonction de la CC et de la RCV. *Conclusion*: Les athlètes d'élite de PVCP pourraient présenter des déficits d'endurance au niveau des fléchisseurs profonds du cou et pour certaines caractéristiques de la fonction de la CC et de la RCV. Malgré trois mesures distinctes qui diffèrent selon l'historique de commotions cérébrales, ces déficits ne semblent pas être en lien avec le nombre de commotions cérébrales rapportées antérieurement. Ces résultats suggèrent que le développement de programmes d'exercices neuromusculaires ciblés pour les athlètes d'élites de PVCP pourrait optimiser l'endurance des fléchisseurs profonds du cou et contribuer à la prévention des blessures.

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Also, special thanks to the other members of my supervisory committee, Dr. Suzanne Leclerc and Dr. Kathryn Schneider, for offering me this research opportunity when life was on hold during this pandemic era. Thanks as well to the three physical therapists who collected data: Antoine Léger, Émilie Turner and Marie-Anne Léveillé. Thank you all for your time and devotion to this project that has a potential reach far beyond us.

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Finally, last but not least, my deepest gratitude to the love of my life. Geneviève, thank you for landing in my life at the most precious moment of all, supporting me through the highs and lows of the challenges entering graduate studies bring at age 35. Your kindness is unique just as much as your patience is unmatched. My sincerest hope is that little Henri is proud of what his parents achieved as a couple in life.

PREFACE

Contribution Of Authors

The idea for this research was developed by the members of the supervisory committee, Dr. Kathryn Schneider and Dr. Suzanne Leclerc. The thesis was written by Julien Bernier, under close supervision of Dr. Isabelle Gagnon, revised by Dr. Marie-Hélène Boudrias, and feedback was provided by the supervisory committee. Ethics approval was obtained from the Institutional Review Board of McGill Faculty of Medicine and Health Sciences.

Thesis Organization:

The objectives of this thesis were to 1) describe the cervical spine (CS) and craniovertebral region (CVR) function in elite short track speed skating (STSS) athletes, 2) explore relationships between pain provocation during CS assessments, recent neck pain and recent headaches, 3) determine if athletes with or without a history of previous concussion differ in their CS and CVR function, and finally 4) explore if associations exist between the number of previous concussions and CS and CVR function. This was achieved by answering the following questions: 1) What are elite STSS athletes' CS and craniovertebral function characteristics? 2) Is there a relationship between pain provocation during CS assessments, recent neck pain and recent headaches? 3) To what extent do elite STSS athletes with a history of concussion differ in their CS and craniovertebral function from athletes without a history of concussion? 4) Is there an association between the total number of previous concussions and CS and CVR function in elite STSS athletes? Those questions were addressed in one manuscript, and a preliminary version of the results was presented virtually at the 98^{th} American Congress of Rehabilitation Medicine in September 2021. Chapters are organized to follow McGill Graduate Postdoctoral Studies (GPS) regulations for manuscript-based theses.

Chapter 1 reviews the literature regarding 1) sport-related concussion, its incidence, risks and contributing factors, and targets for injury prevention; and 2) STSS and its relationship with CS and CVR function.

Chapter 2 presents the rationales and objectives of the thesis.

Chapter 3 consists of a manuscript entitled “Cervical spine and craniovertebral region function in elite STSS athletes” with the methodology and results of our work, as well as a discussion of our findings.

Chapter 4 finally provides an overall discussion and conclusion of the thesis work.

CHAPTER 1: REVIEW OF THE LITERATURE

1. Sport-related concussion

1.1 Definition

According to the consensus statement on concussion in sport emanating from the 5th International Conference on Concussion in Sport, a sport-related concussion (SRC) is defined as a "traumatic brain injury induced by biomechanical forces. (…) (It) may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head". The impairments that follow a SRC in neurological functions usually resolve spontaneously, and the functional disturbances the SRC creates are not actual structural injuries (McCrory, Meeuwisse, et al., 2017). This explains why no abnormality is usually seen in standard structural neuroimaging studies after a SRC, unlike a more severe traumatic brain injury.

1.2 Incidence

SRC reporting has increased in the last decade due to improved awareness and recognition of the injury. According to nationally representative samples from the Canadian Community Health Surveys from 2000 to 2018, at least 1 in 450 Canadians aged 12 or older has reported an SRC during the preceding year (Gordon & Kuhle, 2022). The annual number has more than doubled from 2005 to 2014. In the United States, American football is the sport with the highest concussion rates overall (10.4 per 10,000 athlete exposure) (Kerr et al., 2019). Concussion rates are higher in competition than during practice, especially for ice hockey. Unfortunately, even with increased knowledge on the subject leading to better recognition and treatments, SRCs are still underreported, and their true burden is likely underestimated.

1.3 Clinical symptoms

Concussions can lead to various symptoms that are usually short lasting and are not necessarily specific to concussions (Iverson et al., 2020). For instance, concussion-related symptoms can also be present with cervical or vestibular dysfunctions (Cheever et al., 2016; Leddy et al., 2015; Leslie & Craton, 2013; Wong et al., 2021). The four main domains of clinical symptoms described in the literature are *cognitive (e.g.* difficulty concentrating and disorientation), *emotional (e.g.* being more emotional, nervousness or sadness), *sleep disturbances (e.g.* trouble falling asleep or drowsiness)*, and physical (e.g.* headaches, dizziness, nausea, visual *disturbances)* (McCrory, Feddermann-Demont, et al., 2017). Neck pain is another potential physical symptom often reported after concussions, even if neck injury is only reported in 7.2% of SRC (Carmichael et al., 2019). Refer to Appendix 1 for a full list of post-concussion symptoms.

1.4 Risk factors

To better understand what could predispose an athlete to sustain a concussion, a model of the etiology of concussion (Schneider et al., 2019) proposes that multiple factors, some intrinsic and some extrinsic to the athlete, interact to explain the origin of a SRC.

Examples of extrinsic factors are the type and nature of the sport chosen by the athlete (contact versus non-contact), the session type (practice versus competition), the equipment used, and the game's rules. These factors cannot be modified through training by the athlete. Still, they are modifiable through policy changes to maximize the athlete's protection, like banning helmet-to-helmet hits in the National Football League in 1996.

Examples of intrinsic factors are neuromuscular or sensorimotor control, previous concussion history, sex, age, weight or pre-existing symptoms. Indeed, someone who has already sustained a concussion in the past is more at risk of sustaining another one than someone who has not (Abrahams et al., 2014). Females tend to be at greater risk of sustaining a concussion (Abrahams et al., 2014; Dick, 2009; Gessel et al., 2007). Advancing in age tends to increase the chances of sustaining a concussion, and lighter-weight players are predisposed to concussions (Hollis et al., 2011). Pre-existing symptoms of headaches, neck pain and dizziness might further increase the risk of sustaining a concussion (Schneider et al., 2013). Among the listed intrinsic factors, early evidence suggests that neuromuscular or sensorimotor control could be increased by improving body movement control through specifically targeted exercises, thus decreasing the chances of sustaining a concussion. Indeed, there is favourable evidence for a 15-minute whole body neuromuscular training program performed at least three times per week, translating into a reduction in game-related injuries, including concussions (Hislop et al., 2017). Interestingly, an 8-week neuromuscular training program following a concussion could also prevent subsequent injuries of all nature from occurring for up to one year (Howell et al., 2022).

2. Short Track Speed Skating, cervical spine and clinical relevance

2.1 Short Track Speed Skating origins

Skating on iron blades was reported in Holland over 600 years ago (Van Ingen Schenau, 1989). Back then, it was more of a Nordic mode of transportation than a sporting competition. The first official Speed Skating World Championship took place in Amsterdam in 1891. The lack of 400-meter-long tracks in North America led skaters to practice on indoor ice rinks. A new sport called STSS rose in popularity and became an official Olympic sport in 1932. This popularity came from the avant-garde "pack-style" skating format this new sport invoked and the challenges linked to tighter turns and shorter straightaways (International Olympic Committee). Unlike long track speed skating, short track speed skaters don't compete against a clock but each other. A common trait for all forms of speed skating is that to maximize speed, one needs to minimize the aerodynamic drag, defined as the force an object needs to overcome as it moves through the air at a certain velocity (NASA). It is undoubtedly the main force acting on a speed skating athlete's body. Aside from other factors such as the texture of the fabric a skater wears, the posture this skater adopts will influence their speed by minimizing the total drag (Oggiano & Saetran, 2010).

2.2 Unique body position

Speed skaters display a unique trunk and neck position to strongly influence the aerodynamic drag (Van Ingen Schenau, 1989). To reduce air friction or drag, the skater must hold their trunk as close as possible to the horizontal to become as parallel as possible to the ice surface because for every degree of upward deviation from the ideal position, a long track speed skater loses 0.13 seconds per 400-meter lap travelled. Although this might seem trivial, a 10 degree upwardly elevated trunk would translate into a loss of 12 seconds on a 3000-meter race, more than enough to make the difference on a podium performance.

2.3 Neck position

To maintain a forward gaze during skating in the preferred position, the athlete must keep their cervical spine (CS) and craniovertebral region (CVR) in extension to counterbalance the effect of the required horizontal trunk position. This cervical and craniovertebral position place the regional neck flexors in a disadvantageous position of excessive stretch away from their resting position where a muscle is at its strongest, considering the muscle length-tension relationship (Robbins, 2022). Active Tensile strength is at its strongest in a resting position and weakens as the muscle is either shortened or lengthened. To allow adapted movements and control of the head, the neck's superficial and deep flexor and extensor muscles need to work in a coordinated manner to control the forces acting on the CS and CVR.

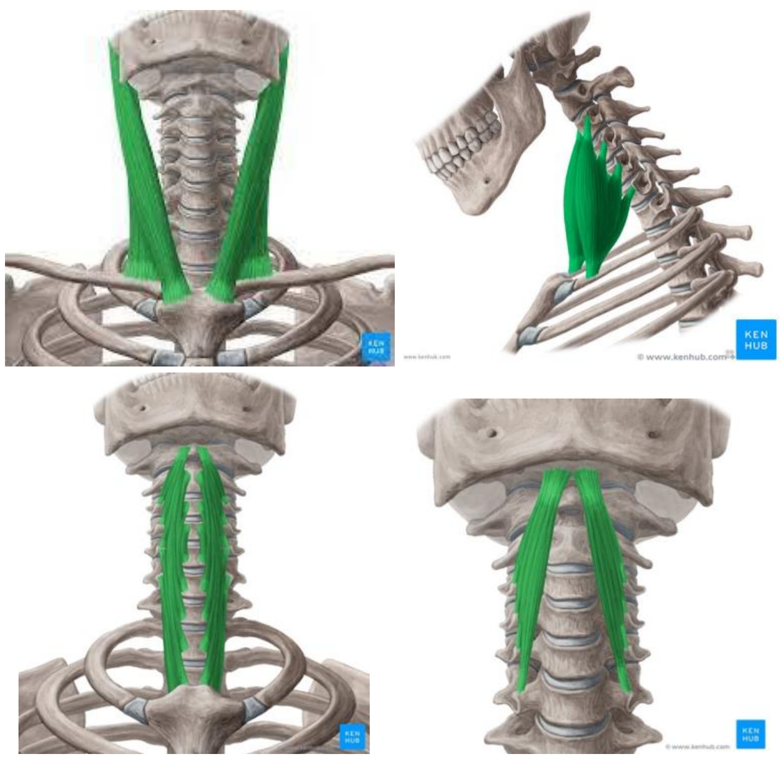
2.4 Superficial vs deep muscles

Skeletal muscles are divided into **global "movers"** and **local "stabilizers".** Global movers are more **superficial** and contribute principally to movement: they create torques using long levers and have a phasic on/off action. On the other hand, local stabilizers are **deeper**. Located closer to joints as opposed to superficial muscles, the main role of deep muscles is not one of strength (Akuthota et al., 2008). Though able of less force production than movers, stabilizers are tonic and rarely fatigue which is why their role in stabilization is so crucial. When function from stabilizers is impaired, an overload on movers can be expected (Jull & Falla, 2016).

2.4.1 Neck flexors

The sternocleidomastoid (SCM) and the anterior scalene (AS) are the main superficial cervical flexors (Drake et al., 2009). The two main **deep** cervical flexors are the longus colli and longus capitis, both playing an essential role in the segmental stabilization of the CS (Figure 1) (Palastanga & Soames, 2012). If impaired, like it has been shown in individuals with neck pain, increased activation during motor tasks (e.g. arm elevation) has been observed in "movers" such as the SCM and AS, as well as in upper fibers of the trapezius (Falla et al., 2004).

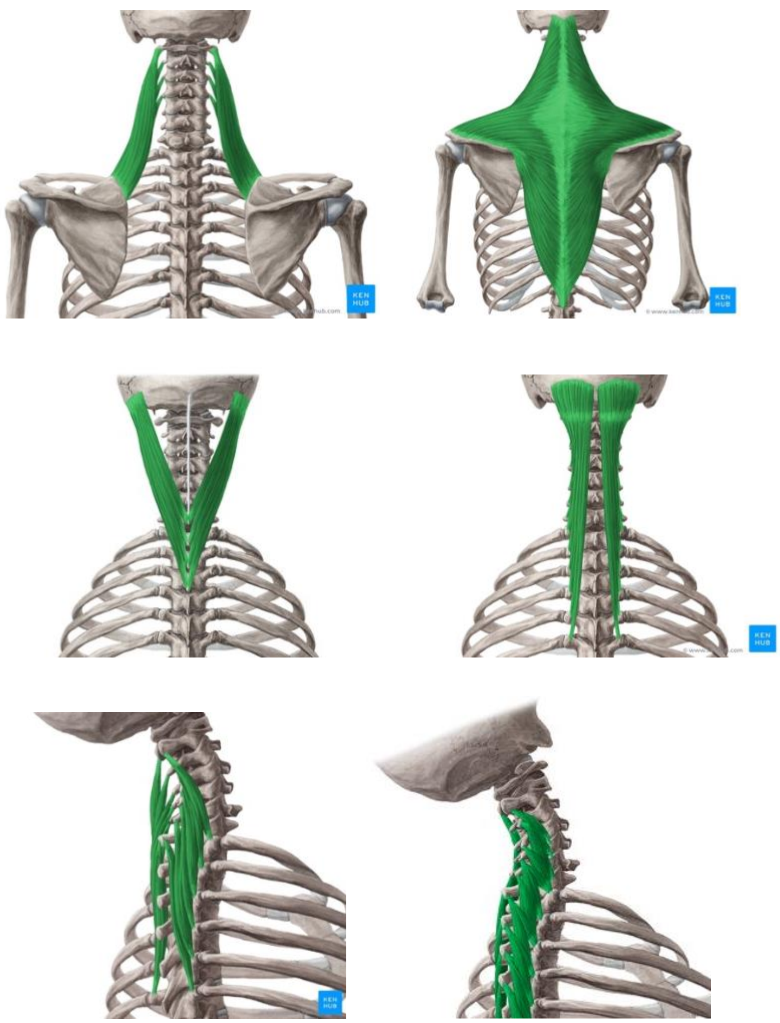
Figure 1. Superficial cervical flexors: sternocleidomastoid (top left) and anterior scalene (top right); Deep cervical flexors: longus colli (bottom left) and longus capitis (bottom right) © Kenhub (www.kenhub.com); illustrator: Yousun Koh (with permission).



2.4.2 Neck extensors

Neck extensors are divided into four layers (Stokes et al., 2007) (Figure 2). **Layer 1**, the most superficial, comprises muscles mostly involved in shoulder girdle motions: levator scapula and upper fibers of the trapezius. **Layer 2** & **Layer 3** are made up of the splenius capitis and the semispinalis capitis, respectively. Finally, the **fourth** and deepest layer, the deep neck extensors, consists of the semispinalis cervicis and multifidus. Overall, neck extensor strength is suggested to play a role in concussion prevention. Indeed, a recent study indicates that every 10% increase in neck extension strength is associated with a 13% decrease in concussion rate in male professional rugby players (Farley et al., 2022).

Figure 2. Neck extensors: layer 1 is made up of levator scapulae (top left) and upper fibers of the trapezius (top right); layers 2 and 3 are made up of splenius capitis (middle left) and semispinalis capitis (middle right); layer 4 is made up of semispinalis cervicis (bottom left) and cervical multifidus (bottom right) © Kenhub (www.kenhub.com); illustrator: Yousun Koh (with permission).



2.5 Neck pain and cervicogenic headaches

According to the International Classification of Headache Disorders (3rd edition), headaches can have multiple origins, one of which occurs after a trauma or injury to the head or neck (post-traumatic headache). It can also be of cervicogenic origin, meaning that dysfunction from the CS and its related myofascial connections can generate headaches (refer to Appendix 2 for full headaches classification). Noxious stimulation of cervical structures (posterior cervical muscles, zygapophyseal joints, intervertebral discs) from the occiput down to the C3-4 level can refer to pain in the head and neck (Bogduk & Govind, 2009). Muscle relaxants and non-steroidal anti-inflammatory drugs have shown efficacy in decreasing headaches in acute cases of neck pain. Still, the strongest evidence for alternative treatments as pain progresses favorizes exercises (Cohen & Hooten, 2017).

To date, little is known about the CS and CVR function and characteristics amongst populations of athletes. Even less is known about possible correlations between recent headaches or neck pain and cervical dysfunctions.

2.6 Clinical relevance and link with concussions

Both deep neck flexors and extensors play a crucial role in the segmental movement control (Farley et al., 2022; Schomacher & Falla, 2013). Spinal muscles maintain the spine within its neutral zone where minimal stress is placed on passive structures (Panjabi, 1992). Compared to controls, patients with neck pain disorders have decreased deep musculature activation and increased superficial compensatory strategies when considering both the cervical flexors (Jull et al., 2008) and extensors (Schomacher & Falla, 2013). Research currently suggests that the decreased segmental control does not resolve spontaneously but rather requires specific training (Jull et al., 2008; O'Leary et al., 2009). The emerging literature on concussion prevention suggests that a weaker neck could predispose an athlete to concussion upon impact (Collins et al., 2014). In addition, neck pain and impairments have been reported post-concussion in groups of athletes (Carmichael et al., 2019). The CS and CVR, therefore could be a target for both concussion prevention and treatment post-concussion, making it a region of interest for further research. Interestingly, little is known about the possible relationship between a concussion history and overall neck strength and endurance in the elite athlete community, let alone STSS athletes. To our knowledge, only one study has investigated STSS injuries (Quinn et al., 2003) and concussions were the second most common competitive injury after shoulder dislocation/separation.

CHAPTER 2: RATIONALES & MANUSCRIPT OBJECTIVES

RATIONALES

Short track speed skaters race at speeds exceeding 50 kilometers an hour. The *pack-style* format of STSS creates an environment of close passing at high speeds that often results in injurious collisions between skaters (Quinn et al., 2003). Unfortunately, sometimes these collisions lead to concussions, presenting with various symptoms. Though most often transient, the symptoms can linger in some athletes beyond the commonly accepted 10-14 days in adults (McCrory et al., 2017). Of the 22 possible symptoms related to concussion from the post-concussion symptom scale (PCSS) (Lovell et al., 2006), some, like neck pain and headaches, can also arise from the CS or the CVR, which is also at risk during injuries leading to a concussion.

From data collected directly at the *Institut National du Sport du Québec* (Montréal, Canada), between 15-30% of Canadian National STSS athletes sustain a concussion on a yearly basis. During the 2018 qualifications for the Pyeongchang Winter Olympics, the team suffered no less than 10 concussions, leaving the medical team looking for answers on possible future preventative measures. Recent work on neuromuscular control programs has arrived at promising results that could lead to effective concussion prevention programs (Hislop et al., 2017) and even protection against some of the consequences of concussions (Howell et al., 2022).

To date, little is known about the CS and CVR function in most elite sports. To our knowledge, no study has described these characteristics in a STSS elite population. Since these athletes not only push their body to the limit and do so in a posture favorable for drag but challenging for the head and neck with a trunk angle as close as possible to the horizontal, information on the CS and CVR function and its association with a history of previous concussion could be helpful to design prevention programs for this population.

MANUSCRIPT OBJECTIVES

The objectives of this study were:

1. To describe the CS and CVR function of elite STSS athletes, and the possible relationships between recent neck pain or headache and pain provocation and/or segmental stiffness with manual spine examination or segmental palpation
2. To determine whether differences exist in CS and CVR function between athletes with a history of previous concussion and those without.
3. To explore possible correlations between athletes' number of previous concussions and their CS and CVR function.

We hypothesized that:

1) a) Athletes would demonstrate a normal range of motion and above average strength and endurance compared to published general population norms since they compete at the highest level.

1) b) If athletes' neck pain and/or headaches have a cervical, myofascial or articular origin, differences in manual spine examination (segmental stiffness, pain provocation and

muscle tenderness) should be observed between the athletes with and without neck pain and/or headaches.

2) We should observe differences in CS and CVR function and previous history of concussion since residual loss of range of motion, decrease endurance in deep neck musculature can occur following a concussion.

3) An association between current CS and CVR function and the number of previous concussions should be observed since athletes with a history of concussion could have a residual loss of range of motion, decreased endurance in their neck flexor or extensor musculature after a concussion.

CHAPTER 3: MANUSCRIPT

Introduction

Short track speed skating (STSS) athletes skate at high speeds of over 50 km/hr and in proximity to other skaters during competition, which creates a favorable environment for collisions and potential injuries. It is reported that STSS athletes have a high incidence of injuries, including concussions (Quinn et al., 2003). Although usually short-lasting injuries, concussions can lead to a variety of deficits such as cognitive (Kerr et al., 2016), vestibulo-ocular (Kaae et al., 2022), autonomic (Dobson et al., 2017) as well as those involving the cervical spine (Carmichael et al., 2019). Finding ways to prevent concussions is important because short-lived or lingering symptoms following a concussion could harm an STSS athlete's chances to compete at the highest level.

The emerging literature on concussion prevention suggests that a weaker neck could predispose an athlete to a concussion upon impact (Collins et al., 2014) and that neuromuscular training could be the potential target for concussion prevention (Schneider et al., 2019). Indeed, there appears to be favorable evidence that a 15-minute whole body neuromuscular training program at least three times per week translated into a reduction in game-related injuries, including concussions, in a population of rugby players aged 14 to 18 (Hislop et al., 2017). Another preventative program showed that an 8-week neuromuscular training program following a concussion could prevent subsequent injuries of all nature from occurring for up to one year (Howell et al., 2022). These programs have yet to be adapted and tested on the STSS athlete population.

The cervical spine (CS) and craniovertebral region (CVR) are interesting targets for an STSS neuromuscular exercise program due to the unique trunk and neck position speed skaters adopt to positively influence the aerodynamic drag (Van Ingen Schenau, 1989). In fact, to reduce air friction, the skater must hold their trunk as close as possible to parallel in relationship with the ice surface because for every degree of upward deviation from the ideal position, a long track speed skater loses 0.13 seconds per 400m lap travelled. Although this might appear trivial, a skater with a 10 degree upwardly elevated trunk loses 12 seconds on a 3000-meter race, more than enough to make a difference in performance. To maintain a forward gaze during skating, the athlete must put the CS and CVR in extension to counterbalance the required horizontal trunk position. This cervical and craniovertebral position places the regional neck flexors in a disadvantageous position of excessive stretch away from the resting position, where a muscle is at its strongest when considering the muscle length-tension relationship (Robbins, 2022).

Despite being a possible target for intervention, little is known about the CS and craniovertebral function of STSS athletes. The position in which athletes train, combined with concussions sustained earlier in their career, could potentially leave them with deficits in neuromuscular control. Before developing a sport specific neuromuscular concussion prevention program for STSS athletes, it is essential to characterize their CS and CVR function to find potential areas to target in a sport-specific neuromuscular training program that would include elements involving neck function.

The purpose of this study was, therefore, to describe the CS and CVR function of elite STSS athletes, to explore whether athletes with neck pain or headaches have different CS and craniovertebral characteristics, to determine whether differences exist between athletes with a history of previous concussions and those without, and finally to explore possible relationships between athletes' total number of prior concussions and their CS and CVR function.

Methods

Design: A descriptive cross-sectional design was chosen to describe the CS and CVR function of elite STSS athletes and investigate the relationship between previous concussions and their CS and CVR characteristics.

Participants: All available members of the Canadian Senior National STSS team as well members of the Regional STSS Development Team were recruited to participate in this study at the time of their pre-season physical examination in the summer of 2020.

Procedure: As part of their pre-season evaluation, each athlete underwent a comprehensive evaluation documenting their general health, injury history, as well as post-concussion symptoms and other related functional outcomes. In 2020, for the purpose of this study, and after consultation with the medical and training staff, as well as the athletes themselves, cervical and craniovertebral range of motion, strength and manual examination assessments were added to the pre-existing Canadian National STSS team members pre-season testing already performed yearly.

All evaluations were performed by the Team's three Physical Therapists, who were trained before the evaluation of athletes by the Research Physical Therapist to ensure consistency in assessments and minimize evaluator bias.

Measures*:* The physical examination procedure specific to this study included measures of CS and CVR function, which are described in Table 1.

In addition, athletes were further assessed as part of their preseason evaluations in domains of vestibular/oculomotor function and static balance using the Vestibular and Oculomotor Screening (VOMS) (Mucha et al., 2014) and modified Balance Error Scoring System (m-BESS) (Hänninen et al., 2021) respectively. The m-BESS is a shorter, less time-consuming version of the original BESS in which static balance is only tested on a firm surface and not on the foam surface. Instead of having a total score out of 60, the m-BESS total score is 30.

Table 1. Description of different Cranio-Cervical tests by domain

Description of Measures of Cervical Spine and Craniovertebral Function	
Test	Description
Recent Neck Pain/ Headache	Both measures rated using an 11-point numeric scale were used to rate the athlete symptom levels in the last 24 hours for both neck pain and headache (MacDowall et al., 2018; Mongini et al., 2003).
Range of motion (**ROM**)	Estimations in percentage of complete ROM for Flexion, Extension, bilateral Rotations and Side Flexion motions were reported, all assessed in sitting. The result was additionally transformed into a dichotomic measure (full = Yes, partial =No).
Cervical flexor endurance test (**CFET**)	The CFET is a timed test (seconds), performed with the participant in a crook-lying position, holding their head against gravity until muscle fatigue and inability to maintain proper form. The testing was done with the chin "tucked" and head lifted 2 finger-widths as described in the literature (Edmondston et al., 2008; Olson et al., 2006).
Cervical spine extensor endurance test (**CSEE**)	The CSEE test is a timed test (seconds), performed with the patient in prone holding a 2 lbs weight against gravity, attached via a headband and a cord to just above the floor, until muscle fatigue and inability to maintain the position (Edmondston et al., 2008). A maximal time was pre-set at 180 seconds to complete the assessment in a realistic timeframe. Pain during the test was also recorded as a dichotomic measure (Pain Yes/No).
Cervical flexion-	The cervical flexion rotation test has been described as a measure to assess 1) the mobility of the C1-2 segment and 2) the presence of cervicogenic headache (Ogince et al., 2007). The participant's neck was placed into a position of maximal

rotation test (**FRT**)	flexion (to minimize movement at levels of the CS other than the C1-2 level), followed by rotation. The therapist reported a restriction in motion (a positive test defined as a firm end feel with a minimum perceived limitation of a 10° reduction in expected rotation and presence of pain (Yes/No).
Cervical rotation side-flexion test (**CRSF**)	The CRSF, also known as the anterolateral CS strength test has been reported to assess the strength (in Kg) of the anterolateral cervical flexor muscles (Metcalfe, 2006). The participant was supine, with their head maximally rotated in to one side. The neck was then laterally flexed off the plinth, and the subject was asked to hold their head still and to not let the therapist move them. A Medup Manual Muscle Tester (Model 103-034) was placed superior to the ear on the temporal region of the head. The direction of pressure was toward the floor until the subject could no longer maintain the testing position. The subject was then asked if the test was limited by weakness or pain. This test was performed 3 times on each side, and the mean of 3 trials on each side was calculated.
Head perturbation test (**HPT**)	The participant sat in an upright position, with arms crossed on the shoulders, and was given instructions to maintain their head as still as possible and keep their eyes closed. The examiner stood behind the subject and applied a gentle force in an unpredictable order and direction to the front, back, right side, left side, front right side, front left side, back right side, and back left side of the head. Initially, a practice session (2 times in each direction) was performed. Following this, the examiner applied a mild force (aimed at 2.27 kg or 5 lbs) randomly 3 times in each of the 8 directions. The examiner watched for a "bobble" in the head when the force was initially applied. This test as yet to be validated but proposed as one of many tests following a concussion by experts in the field. (Schneider et al., 2018)
Extension rotation test (**ER**)	Participant is seated and asked to extend their head and neck as far as possible. Rotation is then added and subjects report pain at the end of the motion. A positive test is defined as reproduction of familiar CS pain intensity (>=3/10) as a dichotomic value (Yes/No). Rotation is tested to both the left and right sides (Schneider et al., 2013).
Manual spine examination (**MSE**)	Subjects are positioned in prone with their CS in neutral. The examiner applied a posterior-anterior (PA) directed force over the articular pillars from C2-3 to C6-7 on each side. Perceived resistance and reported pain are noted for each segment and side (Schneider et al., 2013).
Palpation of segmental tenderness (**PST**)	Subjects are positioned in prone with their CS in neutral. The assessor palpates the segmental muscles overlying the facet joints from C2-3 to C6-7 bilaterally. The test is considered positive if the patient reports an increase in familiar pain (local or referred) at an intensity of >=3/10. The subject reported pain with this test with dichotomic measures (Yes/No) for each segment (Schneider et al., 2013).
Craniocervical flexion test (**CCFT**)	The patient is positioned in supine with the knees bent (crook lying) with neck in a neutral position. A pressure biofeedback unit (PBU) is placed behind the neck and abuts the occiput and is then inflated to 20mmHg. The patient is instructed that movement is performed gently and slowly as in a head nodding action. The patient progressively attempts to complete the test with five increments of 2mmHg to a maximum of 30mmHg through 2 stages.

	Stage 1: stage (22, 24, 26, 28, and 30 mmHg) at which the athlete could efficiently hold a 3-second contraction with correct craniocervical flexion without palpable activity of superficial flexors (Jull et al., 2008). *Stage* 2: for time constraints, and to get a continuous outcome score to compare to original preliminary results, the *performance index* score was used (Jull et al., 1999). The score was calculated by the number of times the athlete could hold 10 second contractions, multiplied by the maximal pressure achieved in stage 1. Since the maximal number of contractions is 10, and the maximal increment from 20 mmHg is 10 (30-20), the highest *performance index* (PI) score is 100. Stage 2 of the 2008 original article requires starting over at 22 mmHg and perform 3 contractions of 10 seconds to move to the next level. The final score is a categorical one of maximal pressure reached with 3 successful contractions of 10 seconds. For example, a participant who would achieve 26 mmHg in stage 1 and complete 8 repetitions of 10 seconds before stopping would get a PI score of 48 ((26-20)*8).

Data Analysis

Statistical analysis was conducted using SPSS version 27. Descriptive statistics were calculated for all variables. Demographic and pre-season examination data as well as data on CS and CVR function were summarized using medians and interquartile ranges (IQR) for continuous variables and frequencies and percentages for dichotomous or categorical variables. Continuous data were tested for normality using the Shapiro-Wilk test. A Mann-Whitney U test was used to compare athletes with and without concussions for continuous variables, while a Fisher's exact test was used to compare proportion of positive tests between groups. Finally, a Spearman product-moment correlation was run with the whole group to assess the relationship between participants' number of previous concussions and cervical/craniovertebral function at the time of assessment. Statistical significance was set a priori at alpha = 0.05, two-sided.

Results

Participants characteristics

Table 2 presents demographic and history data for the whole group, and for participants with and without a history of prior concussions separately. Continuous data is presented using medians and interquartile range (IQR) unless otherwise specified. Means are not presented due to abnormal distributions of data for all characteristics after Shapiro-Wilk test rejected the null hypothesis of normality.

Table 2. Summary of demographic and preseason testing on symptoms, static balance and vestibulo-ocular functions in athletes

	total group		Hx of concussion		no Hx of concussion		test statistic
	N		**N**		**N**		
age	41	19 (17-22)	23	19 (18-24)	15	18 (17-19)	$U = 220.0; z = 1.44; p = 0.149$
biological sex (% male)	41	21 (51.2)	23	13 (56.5)	15	8 (53.3)	$X^2 = 0.037$; p=0.847
Level of training (N, % senior team)	41	25 (61.0)	23	15 (65.2)	15	8 (53.3)	$X^2 = 0.537$; p=0.464
SCAT Post-Concussion Symptom Scale							
total # symptoms	38	2.00 (0-6)	23	2 (1-6)	15	2 (0-6)	$U = 194.5; z = 0.667; p = 0.505$
total score	38	3.00 (0-7.25)	23	3 (1-9)	15	3 (0-7)	$U = 193.0; z = 0.620; p = 0.535$
Balance Error Scoring System							
feet together	37	0 (0-0)	23	0 (0-0)	14	0 (0-0)	-
tandem	38	0 (0-1.25)	23	0 (0-1)	15	0 (0-3)	-
single leg	38	1 (0-3)	23	1 (1-3)	15	1 (0-3)	-
Total BESS score	37	2 (0.5-4.5)	23	2 (1-4)	14	1.5 (0-3)	$U = 166.5; z = 0.175; p = 0.861$
Vestibular Ocular Motor Screening (VOMS)							
total change score	38	0 (0-0.25)	22	0 (0-1.63)	15	0 (0-0)	$\mathbf{U = 217.0; z = 2.137; p = 0.033}$
Smooth pursuit change score	38	0 (0-0)	22	0 (0-0)	15	0 (0-0)	-
Horizontal saccades change score	38	0 (0-0)	22	0 (0-0)	15	0 (0-0)	-
vertical saccades change score	38	0 (0-0)	22	0 (0-0)	15	0 (0-0)	-
NPC change score	38	0 (0-0)	22	0 (0-0)	15	0 (0-0)	-
NPC average distance	38	3.00 (1-4.83)	22	2.83 (1-4)	15	3.00 (1-5.66)	$U = 158.0; z = -0.217; p = 0.828$
horizontal VOR change score	38	0 (0-0)	22	0 (0-0)	15	0 (0-0)	-
vertical VOR change score	38	0 (0-0)	22	0 (0-0)	15	0 (0-0)	-

1-Entire sample

The sample was composed of a total of 41 participants ranging from 17 to 21 years of age. Amongst them, 21 are males representing 51% of the sample. Twenty-six participants were part of the senior team and they trained separately from the junior development team (N=15). Information on previous concussions was available for 38 of the 41 participants as part of their pre-season questionnaires. It was nevertheless decided to retain as much information as possible for the whole group, explaining the difference between the total sample and the two subgroups. Looking at the entire sample, athletes reported a median of 2 [IQR 0-6] symptoms during their pre-season evaluation. Errors on the m-BESS (on a total possible 30) were quite low, with a median total of 2 [IQR 0.5-4.5]. Symptoms provoked during the administration of the VOMS were also very few, with change-scores median results and IQR almost all at 0 for the whole sample and a near point convergence measure of 3 centimeters, within the normal limit of 5 centimeters (Scheiman et al., 2003).

2- History of concussion vs no concussion

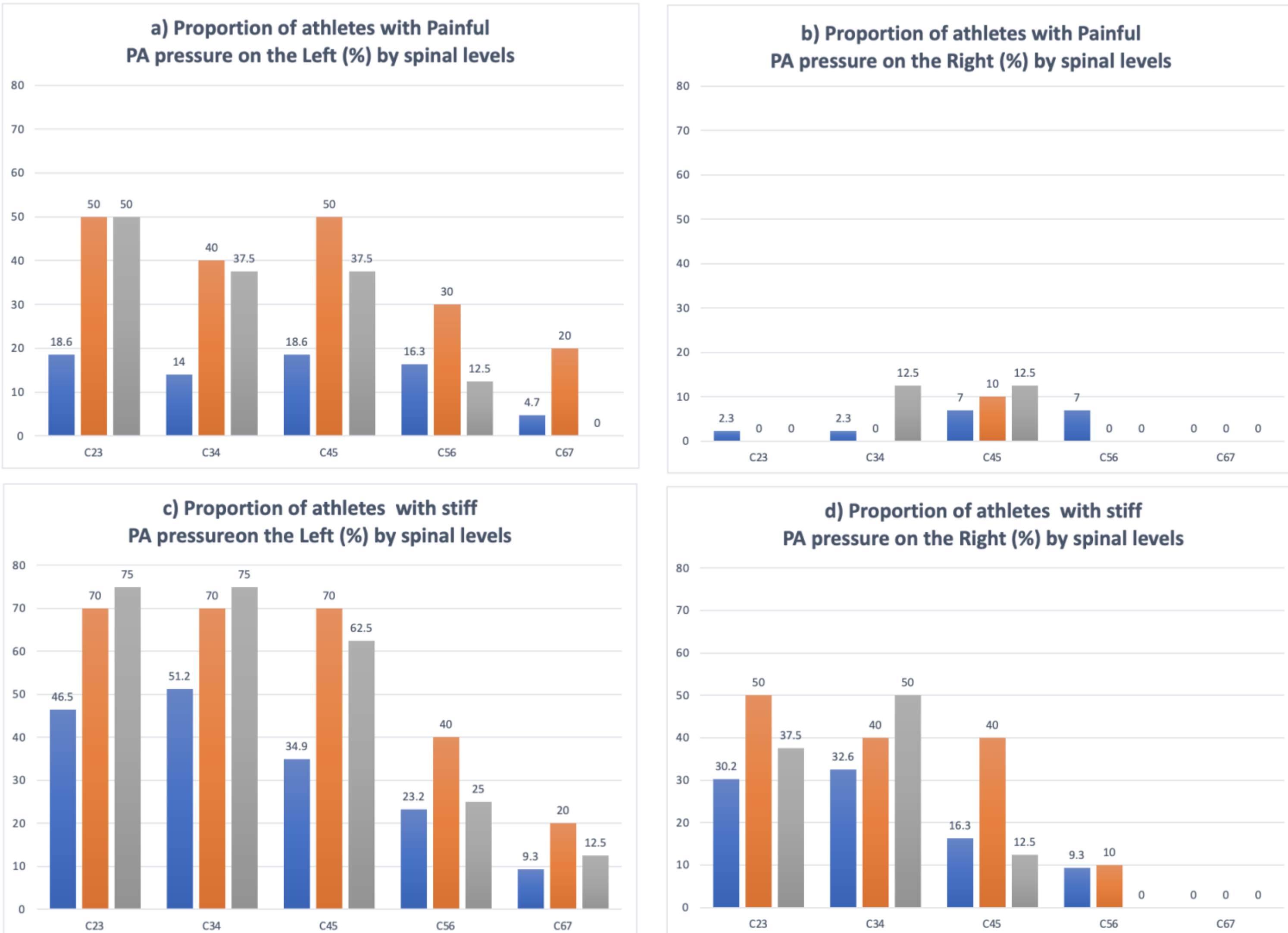
No significant differences between participants who had a history of concussion and those who did not were found for any of the demographic and history characteristics. A slightly higher percentage of participants from the senior team was present in the group with a history of concussion (65.2 %) compared to the no history of concussion group (53.3 %). Age and biological sex showed similar proportions. The number of symptoms reported on the SCAT5 post-concussion symptom scale (median = 2/22) and total symptom scores (median = 3/132) had identical median and similar IQR values.

Regarding balance, performance on the m-BESS revealed a floor effect with a median total score for the whole group of 2, whereas the history of concussion group had a median of 2 and the no history of concussion group had a median of 1.5. Likewise, median result on total change scores as well as individual change score on the VOMS was at a value of 0 for both groups, while near point convergence measures were similar and both under the normal limit of 5 centimeters. There was a marginal but significant difference in VOMS total change score (TCS). Even if both median scores were zero, only one athlete in the no history of concussion group has a total change score different from zero (TCS =1). In the history of concussion group, even if the third quartile has a value of 1.63, 8 athletes had TCS above zero, and five of them above 1. Clinically though, these total values are still too low to be significant.

Relationship between neck pain/ headache & pain provocation/stiffness on manual spine examination/segmental palpation

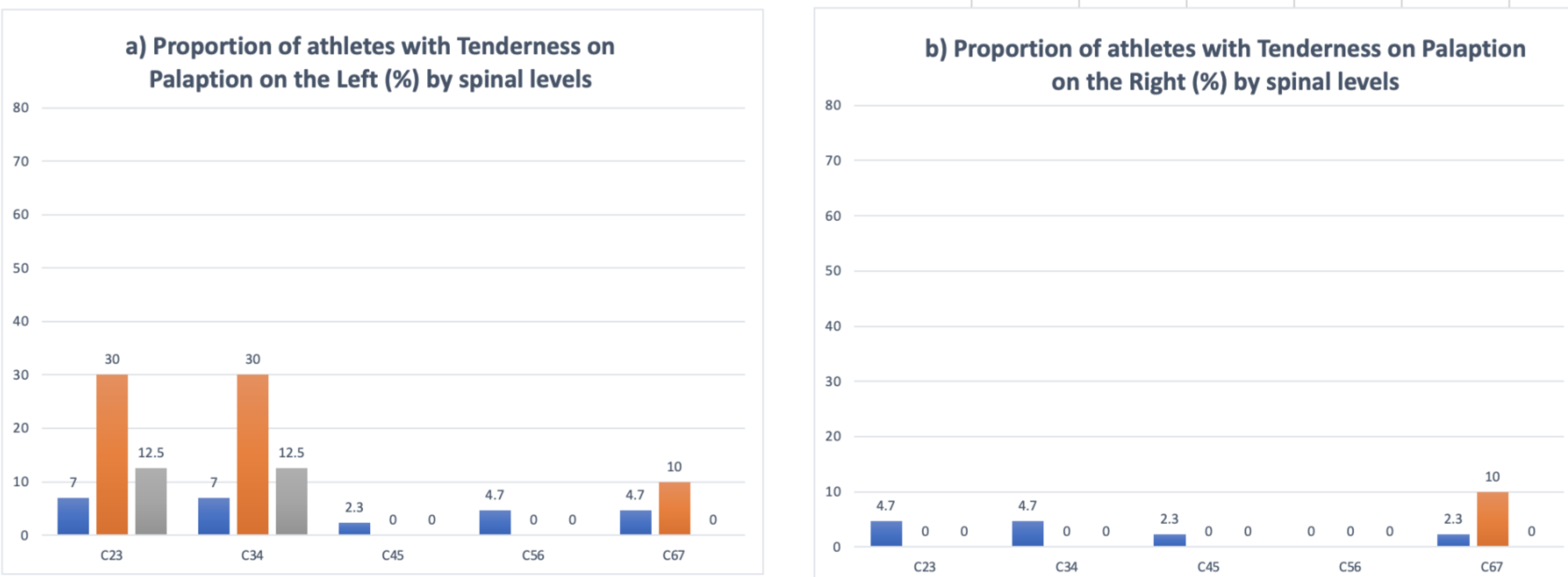
The hypothesis that postero-anterior pressure on spinal segments, both looking at pain reproduction or stiffness, could be higher in athletes that expressed neck pain or headache in the 24 hours prior to the CS and CVR assessment was explored for the whole group. As seen in Figure 3, the proportion of athletes expressing pain with pressure in the whole group (in blue; N = 43) appears lower at multiple cervical levels when compared to that of athletes reporting recent neck pain (in orange; N =10) or recent headache (in grey; N = 8). This is particularly apparent for the left side examination when putting the different column diagrams in contrast.

Figure 3. Summary of proportions (%) of segmental painful PA pressure a) on the left and b) right and stiffness found with PA pressure c) on the left and d) on the right by segmental levels related to the whole group (blue; N=43) versus the neck pain group (orange; N=10) and headache group (grey; N=8).



When comparing tenderness on palpation of paravertebral musculature between the whole group and the same subgroups, the difference in proportions again favors the left side, however only for the upper cervical segments, that is C23 and C34 only, as seen in Figure 4.

Figure 4. Summary of proportions (%) of segmental Tenderness on Palpation a) on the left and b) on the right by spinal levels related to the whole group (blue; N=43) versus the neck pain group (orange; N=10) and headache group (grey; N=8).



Cervical spine & craniovertebral region function

Table 3 presents the cervical and cranio-vertebral characteristics of subjects with or without history of concussion as well as of the whole group.

Table 3. Summary of cervical spine and craniovertebral region function characteristics in athletes

		N	total group	N	Hx of concussion	N	no Hx of concussion	test statistic
Neck Pain24	Neck Pain (last 24 hours) /10	41	0 (0-0)	23	0 (0-2)	15	0 (0-0)	*U* = 183.0; *z* = 0.421; *p* = 0.674
Headache 24	Headache (last 24 hours) /10	41	0 (0-0)	23	0 (0-0)	15	0 (0-0)	*U* = 200.0; *z* = 1.295; *p* = 0.195
ROM	Cervical Spine Range of Motion (% complete ROM)	41		23		15		
cspineROMF	Flexion		100 (90-100)		100 (90-100)		100 (100-100)	*U* = 150.0; *z* = -0.842; *p* = 0.400
cspineROMEx	Extension		100 (100-100)		100 (100-100)		100 (100-100)	*U* = 157.5; *z* = -1.157; *p* = 0.247
cspineROMrotl	Left Rotation		100 (100-100)		100 (100-100)		100 (100-100)	*U* = 147.0; *z* = -1.203; *p* = 0.229
cspineROMrotr	Right Rotation		100 (100-100)		100 (100-100)		100 (100-100)	*U* = 158.0; *z* = -0.645; *p* = 0.519
cspineROMsfl	Left Side Flexion		100 (100-100)		100 (100-100)		100 (100-100)	*U* = 146.5; *z* = -1.229; *p* = 0.219
cspineROMsfr	Right Side Flexion		100 (100-100)		100 (75-100)		100 (100-100)	*U* = 131.5; *z* = -1.733; *p* = 0.083
	Cervial Flexion Endurance Test	41		23		15		
CFET_pain	Pain (% yes)		2 (4.9)		1 (4.3)		0 (0)	X^2 = 0.670 ; p = 0.413
CFET_time	Time (seconds)		47.5 (35.9-72.5)		45.63 (33.37-78.48)		48.93 (38.38-71)	*U* = 157.0; *z* = -0.463; *p* = 0.643
CFET_fib	Fibrillation (% present)		23 (56.1)		9 (39.1)		11 (73.3)	**X^2 = 4.260 ; p = 0.039**
	Cervical Spine Extensors Endurance	40		22		15		
CSEE_pain	Pain (% yes)		0 (0)		0 (0)		0 (0)	-
CSEE_time	Time (% < max of 180 seconds)		2 (5)		1 (4.5)		0 (0)	X^2 = 0.701 ; p = 0.403
	Cervical Flexion-Rotation Test	40		23		15		
CFRTL	Left (% positive)		0 (0)		0 (0)		0 (0)	-
CFRTL_pain	Left Pain (% yes)		1 (2.4)		1 (4.3)		0 (0)	X^2 = 0.701 ; p = 0.403
CFRTR	right (% positive)		3 (7.3)		2 (8.7)		0 (0)	X^2 = 1.442 ; p = 0.230
CFRTR_pain	Right Pain (% yes)		0 (0)		0 (0)		0 (0)	-
	Cervical Rotation-Side Flexion Test (kg)	41		23		15		
CRSFTR	Right		22.1 (18.8-28.4)		22.05 (18.57-29.55)		22.91 (18.64-32.51)	*U* = 169.9; *z* = -0.105; *p* = 0.917
CRSFTL	Left		22.4 (17.2-26.8)		21.59 (17.22-28.22)		22.52 (15.95-28.04)	*U* = 177.0; *z* = 0.134; *p* = 0.893
HPT	Head Perturbation Test (/8)	41	8 (8-8)	23	8 (8-8)	15	8 (7-8)	*U* = 202.5; *z* = -1.413; *p* = 0.158
	Extension-Rotation Test	41		23		15		
ERTL	Left (% positive)		1 (2.4)		0 (0)		1 (6.7)	X^2 = 1.575; p = 0.210
ERTR	right (% positive)		1 (2.4)		0 (0)		1 (6.7)	X^2 = 1.575; p = 0.210
	Manual Spine Examination	41		23		15		
MSTLP	Left Pain (% at least one segment painful)		11 (26.8)		8 (34.8)		1 (6.7)	**X^2 = 3.971; p = 0.046**
MSTLStiff	Left Stiff (% at least one segment stiff)		28 (68.3)		16 (69.6)		9 (60)	X^2 = 0.369; p = 0.544
MSTRP	Right Pain (% at least one segment painful)		5 (12.2)		3 (13)		0 (0)	X^2 = 2.124; p = 0.145
MSTRStiff	Right Stiff (% at least one segment stiff)		20 (48.8)		12 (52.2)		5 (33.3)	X^2 = 1.304; p = 0.254
	Palpation of Segental Tenderness	41		23		15		
Palpation_num	tenderness in at least one segment (%)		7 (17.1)		5 (21.7)		2 (13.3)	X^2 = 0.427; p = 0.514
Palpation_#	Number of segments tender on palpation		0 (0-0)		0 (0-0)		0 (0-0)	*U* = 154.5; *z* = -0.796; *p* = 0.426
	Cranio-Cervical Flexion Test							
CCFT	Performance score index (/100)	41	64 (40-100)	23	60 (40-100)	15	64 (30-100)	*U* = 181.5; *z* = 0.278; *p* = 0.781
Press_ord	Pressure stage achieved (%)	36	30 (26-30)	22	29 (24-30)	11	30 (26-30)	X^2 = 1.815; p = 0.770
	22 mmHg		1 (2.8)		1 (4.5)		0 (0)	
	24 mmHg		7 (19.4)		5 (22.7)		1 (9.1)	
	26 mmHg		7 (19.4)		4 (18.2)		3 (27.3)	
	28 mmHg		2 (5.6)		1 (4.5)		1 (9.1)	
	30 mmHg		19 (52.8)		11 (50.0)		6 (54.5)	

1- Entire sample

As a whole, the participants in our sample demonstrated almost full range of motion in all related tests while not being symptomatic. Muscular strength and endurance values were more variable for the CFET, with and inter-quartile range extending over 35 seconds [35.9-72.5], with a median of 47.4 seconds. A ceiling effect was observed on the CSEE test, with only two participants performing under the maximal value set for the test administered at 180 seconds. A similar effect occurred with the Head Perturbation Test, where median scores and IQR were at 8/8 for the sample. For the CCFT, the majority of the athletes achieved stage 1 maximal value of 10 mmHg increase with a median value of 30 mmHg [IQR 26-30], while 77% achieved an increase of at least 6 mmHg (Refer to table 1 for CCFT description). The Manual Spine Examination revealed over two times more pain on at least one segment under postero-anterior (PA) pressure on the left side when compared to the right. Stiffness was also found more frequently on the left side.

2- History of concussion vs no concussion

Aside from two distinct outcomes, no other cervical and craniovertebral characteristics reached a significant level supporting a difference between short track speed skaters with or without a history of concussion. *Right side flexion* ROM did not reach significance, though a trend (p=0.083) with a lower interquartile range of 75% in the history of concussion group as opposed to 100% in the no history of concussion group. The average per group (not shown in the table) came down to 92.39% for the history of concussion group, and 98.33% for the other group.

The group without a history of concussion showed significantly more signs of fibrillations with the *CFET* (*p*=0.039). The group with a history of concussion appeared to express more pain when postero-anterior pressure were applied on the Left side of their CS. In fact, the percentage of subjects having at least one segment painful on palpation was 34.8% in the group with a history of concussion, as opposed to only 6.7% for the group without concussion (*p*=0.046). When ultimately looking at the CCFT results, even if the proportions appear to show that athletes with a history of concussions tend to be limited to lower levels of pressure contractions, this did not reach statistical significance (*p*=0.770). Median pressures were indeed very similar with values of 29 mmHg in the history of concussion group [IQR 24-30] as opposed to 30 mmHg in the history of concussion group [IQR 26-30].

Finally, table 4 illustrates the correlation coefficients and respective significance levels between athletes' total number of previous concussions and their CS and CVR function.

Table 4. Correlation between number of previous concussions and cervical and craniovertebral region function

Measures	**N**	**Correlation coefficient**	**Significance (bilat)**
Neck pain in the last 24 hours	38	0.124	0.459
Headache in the last 24 hours	38	0.247	0.135
Cervical Flexion	38	-0.089	0.597
Cervical Extension	38	-0.144	0.389
Cervical Left Rotation	38	-0.079	0.636
Cervical Right Rotation	38	0	1
Cervical Left Side Flexion	38	-0.159	0.34
Cervical Right Side Flexion	38	-0.266	0.106
Cervical Flexion Endurance Test (time)	38	-0.198	0.234
Cervical Spine Extensor Endurance (time)	37	-0.041	0.809
Right Cervical Rotation Side Flexion Test	38	-0.003	0.984
Left Cervical Rotation Side Flexion Test	37	0.026	0.878
Head Perturbation Test	38	0.285	0.083
CranioCervical Flexion Test	38	-0.027	0.871
Balance Error Scoring System Score	37	-0.078	0.644
Near Point Convergence in VOMS	37	0.073	0.667

Overall, no correlations were found between the number of previous concussions and CS and craniovertebral function assessed in this study. The only test that almost reached significance was the Head Perturbation Test (p=0.083).

Discussion

The objectives of this study were to describe the CS and CVR function of STSS elite athletes as well as to relate that to history of previous concussions in those athletes. We found that aside from the CCFT, STSS athletes displayed range of motion within normal limits and cervical endurance levels that were above published norms for the general population. We also found on visual inspection that these athletes tended to express more pain with PA pressure on the left side of their CS, as well as more stiffness felt by the therapist with those pressures on the left as well, leading to think that this may have a link with the fact that these athletes are always turning on the same side of the ice rink.

When comparing groups with and without a history of concussions, the group without a history of concussions unexpectedly showed more fibrillation with the CFET test, but a trend towards more right side flexion range of motion, and expressed less pain with PA pressure put on the left side of their CS than those with a history of concussion. All other comparative measures were not significant.

To our knowledge, this study was the first to describe CS and CVR function in STSS athletes. This study showed that these athletes have generally higher than average endurance on the *cervical flexor endurance test (CFET)* and the c*ervical spine extensors endurance (CSEE)* test when compared to athletic and general population samples respectively but appear to compare to results from a general population sample on the craniocervical flexion test (CCFT). The median time on the CFET observed in our sample of 47.5 seconds with IQR from 35.9 to 72.5 seconds is far above the normative values of 32 seconds for females and 36 seconds for males obtained previously on a sample of 81 high-school and collegiate athletes (Jarman et al., 2017). One hypothesis could be that training could explain our samples' higher results. Both groups demonstrated superior measure to the general population of females of 20 seconds and males of 25 seconds (Olson et al., 2006). For the general population, the mean CSEE test time holding the two-pound weight vary between 125 to 151 seconds (Edmondston et al., 2008). This places our sample above the general population since all but two participants achieved the time limit set at 180 seconds. A relationship has been established between neck isometric extensors strength and concussion: a 10% increase in isometric extensors strength was associated with a 13% decrease in concussion rate (Farley et al., 2022). Thus, the extensors endurance of our sample could have a protective effect against concussions, though neck extensors strength per se has not been tested in our study. The CFET and CSEE tests both assessed overall cervical muscle endurance, regardless of contribution from deep versus superficial musculature.

The CCFT on the other hand is a measure of deep cervical flexor activation, and the use of superficial muscles at least in the first three levels of stage one is a sign of failure (Jull et al., 2008). Preliminary measures on the CCFT on asymptomatic subjects aged 18 to 68 had determined a mean performance index score of 65.8 +/- 27.8 and activation score of 7.6 +/- 2.1 (Jull et al., 2008) which is similar to what our sample achieved. Compared to all the other strength-related tests, the CCFT is the only one where athletes perform at the same level as the general population, meaning that the deep neck flexors required for this test might not be at an optimal level for elite athletes. When looking at the literature on CCFT in other athletic sample populations, male elite rugby players without neck or shoulder pain were found to have CCFT scores of 28.4 mmHg (+/- 1.55) on average, though it was not specified if that result was on stage 1 (recruitment) or 2 (endurance) (Asker, 2014). Another study on high-school Football players found a median measure of 28 mmHg on stage 1 performance of CCFT(Smith et al., 2016). Finally, a study on collegiate soccer players had a median score of 26 mmHg on stage 1 of the CCFT which they refer to as CCFT3 (Reneker et al., 2019). Even if our study sample found stage 1 results similar, if not better than, other population of athletes, training the deep neck flexors endurance could potentially be a target for future exercise program implementation in a population of elite STSS that require optimal endurance and control from both neck flexors and extensors.

Since no differences were observed between groups with or without concussion, one could argue that if cervical and craniovertebral dysfunctions were present shortly after the concussion an athlete had sustained in our sample, these dysfunctions were no longer present at the time of testing. This is what the medical team expects as well if they clear these athletes to train with the rest of the pack and compete. This equity between groups should facilitate the implementation of a more uniform exercise program, since our findings suggest no precaution should be taken when facing STSS athletes with a history of concussion as they appear to perform as well as their colleagues exempt of such previous injury. In addition, no correlation could be made between our athletes' number of previous concussions and CS/CVR function. This tends to prove again that athletes have completely recovered from their previous concussion in order to compete at the highest level of their sport. Future studies should seek to support similar findings in other samples of elite STSS, or in other elite sports.

On visual inspection, there appears to be a larger proportion of athletes with headache and neck pain that either express pain with segmental postero-anterior pressures, or had the therapist find stiff levels with segmental postero-anterior pressures on one side of their CS. This was more often found on the left, leading to hypothesize that skaters whose sport focusses on left turns only could induce unilateral stiffness. Similar inferences on segmental tenderness on palpation visual inspection were not as obvious. Our data was underpowered to bring any level of significance here. Future studies seeking to replicate these findings should undoubtably consider a larger sample size, especially when employing tests using multiple categorical variables.

STSS athletes displayed excellent pre-season static balance as shown by the m-BESS score results. The results obtained on the BESS are aligned with results obtained in previous samples of young athletes (Ozinga et al., 2018) who demonstrated a mean of 2 with measures ranging from 0 to 22 on a sample 6762 student-athletes from 5 to 23 years of age.

STSS athletes also expressed almost no symptoms during pre-season Vestibular and Oculomotor screening. Finally, pre-season testing revealed significant differences in VOMS total change scores in the group with a history of concussions, leading to think that although suited to compete, these athletes might be more irritable with vestibular or oculomotor stimulations. Even if the history of concussion group has a significant total change score difference, the athlete in the history of concussion group with the most total change score had a TCS value of 5 on 8 tests, which is negligeable. Recovery of symptom provocation on VOMS have been demonstrated to take 8 days (Glendon et al., 2021) and the total change score to be a better indicator that the total score (Tomczyk et al., 2021).

These pre-season results obtained on static balance and symptom provocation with vestibular and oculomotor tests were not surprising. Our sample was a group of 41 elite short track speed skaters who should have proper static balance and optimal vestibular and oculomotor functions in order to compete at the highest level. One suggestion to avoid a floor effect on the m-BESS would be to employ tandem gait, as it seems to be a more effective way of testing dynamic stability and better pick up dysfunctions early on after a concussion (Oldham et al., 2018). Postural sway during BESS has also been shown to be a better indicator than the BESS alone (Parrington et al., 2019), but clinically unrealistic to practice due to time constraints.

Limitations

The population of interest for this study were elite STSS athletes that train at the *Institut National du Sport in Montreal*, Quebec, Canada as well as the development team training nearby. For the 2020-2021 season, the count of available skaters for the study was 41. The results were unfortunately underpowered for some of the proposed statistical analysis, especially when dividing the group in half for concussion comparative reasons. Increasing sample size and choosing tests for STSS athletes in which results do not reach a ceiling effect would be two possible ways helping to obtain more significance and normalization of data.

Though most of the measures taken were based on previously reported rigorous choices supported by literature, estimating ROM is probably the most widely used in clinics, being cost-effective. It remains not the most precise way to measure range of motion when compared to the CROM instrument that has been shown to have good construct validity, but at a high cost (de Koening, 2008).

Finally, the lack of blinding from history of concussion was inherent to the fact that the three physical therapists in charge of the STSS team divided the work of preseason evaluations amongst themselves. This pragmatical explanation potentially introduced an observer bias.

Conclusion

This was the first study describing CS and CVR function in elite STSS athletes. The results obtained revealed that these athletes have in general excellent range of motion, above average endurance, except for deep neck flexors activation. Aside from fibrillation on the CFET, right side flexion range of motion and VOMS total change score, no significant differences exist between elite STSS with or without a history of concussion, nor correlation between athletes' number of concussions and their respective CS and CVR function.

The next logical step would be to apply what has been learned from this research in a feasibility study looking at the possible positive impact of a neuromuscular exercise program involving not only the deep neck flexors, but also the extensors in order to reduce the risk of concussion in elite STSS

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CHAPTER 4: DISCUSSION

This thesis was the first of its kind to provide a description of the CS and CVR function in elite STSS athletes. The data gathered can serve as a benchmark upon which other elite groups of athletes will be able to compare themselves, whether related to speed skating or not.

Moreover, the results obtained from this research revealed that aside from a slightly significant difference in fibrillation on the CFET, right side flexion range of motion and VOMS total change scores, previous history of concussions does not seem to affect any CS and CVR function. This means that all elite STSS athletes can be considered on a level playing-field for the implementation of a neuromuscular exercise program.

Indeed, this research thesis was the first step towards implementing a targeted program to optimize neuromuscular control and strength of the CS and CVR function that could ultimately translate into decreasing the number of concussions elite STSS athletes suffer every year.

The next logical steps would be to gather a panel of experts in the subjects of concussions and neuromuscular control, then determine the proper exercises, dosage and progressions after reviewing available programs as well as analyzing STSS athletes' specific weaknesses during training. Subsequently, testing the feasibility of such a targeted program on the population sample under study should be tested, and measures of safety and adherence while exploring efficacy at some level should be gathered.

CHAPTER 5: SUMMARY & CONCLUSION

This research met the initially stated objectives. It described in detail the various CS and CVR function in a sample population of elite STSS athletes. Aside comparable results on CCFT measures of endurance, all other results obtained confirmed the initial hypothesis that STSS athletes have normal ROM and above average strength and endurance. Even with small subgroups not allowing results to reach any statistical significance, this research still gave a visual representation of possible relationships between these athletes' headache or neck pain and pain provocation or stiffness on manual spine examination. This research finally allowed to determine that aside from fibrillation on the CFET, right side flexion range of motion and VOMS total change score, no significant differences exist between elite STSS with or without a history of concussion, nor correlation between athletes' number of concussions and their respective CS and CVR function. While last sentence former statement partially confirmed our initial hypothesis, the latter contradicts what was initially hypothesised that associations should be observed between CS and CRV function and the athletes' number of previous concussions.

These findings suggest that a feasibility study on the possible implementation of a targeted neck neuromuscular exercise program with a focus on optimizing deep neck flexor endurance is the next logical step for elite STSS athletes. This could eventually lead to the actual implementation of a program on a larger scale (i.e., to sports other than STSS) and contribute to preventing injuries including concussions in sport.

APPENDIX 1

Post-Concussion Symptom Scale

Signs and Symptoms
Difficulty concentrating
Difficulty remembering
Feeling slowed down
Confusion
“Don’t feel right”
Fatigue or low energy
Trouble falling asleep
Drowsiness
Feeling “in a fog”
Balance problems
Dizziness
Irritability
More emotional
Nervous
Sadness
“Pressure in the head”
Headache
Neck pain
Sensitivity to light
Sensitivity to noise
Nausea or vomiting
Blurred vision

Reproduction of the Post Concussion Symptom Scale, which has showed a very strong internal consistency [0.92-0.93] in Collegiate athletes (Lovell et al., 2006).

APPENDIX 2

International Classification of Headache Disorders (3rd Edition) from the International Headache Society

Part I : The Primary Headaches
1. Migraine
2. Tension-Type Headache
3. Trigeminal autonomic cephalalgias
4. Other primary headache disorders
Part II : The Secondary Headaches
5. Headache attributed to trauma or injury to the head and/or neck
6. Headache attributed to cranial or cervical vascular intracranial disorder
7. Headache attributed to non-vascular intracranial disorder
8. Headache attributed to a substance or its withdrawal
9. Headache attributed to infection
10. Headache attributed to disorder of homeostasis
11. Headache of fascial pain attributed to disorder of the cranium, neck, eyes, ears, nose, sinuses, teeth, mouth or other fascial or cervical structure
12. Headache attributed to psychiatric disorder
Part III: Neuropathies & Fascial Pains and other headaches
13. Painful lesions of the cranial nerves and other facial pain
14. Other headache disorders

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