Neck Strength and Cervical Range of Motion in Male and Female University Rugby Union Athletes

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Abstract

This study investigated whether androcentric research is appropriate for female rugby players. The direct relationship between neck strength and cervical range of motion (CROM) was assessed in male and female players. The efficacy of a neck strength training intervention was explored. New methods of measuring neck length and CROM were developed and validated.

Three university rugby cohorts of male union (*n*=27), female union (*n*=24) and male league controls (*n*=10) were recruited. Isometric neck strength (pre-season, mid-season and post-season) and endurance (pre-season and post-season) were assessed in union cohorts. The union cohorts underwent a neck strength intervention. A novel CROM measurement system, employing a harness board apparatus, was validated. Union and league cohorts were assessed for CROM at mid-season.

Males had significantly greater neck strength (*Mdn* = 219 N, *IQR* = 64 N) than females (*Mdn* = 129 N, *IQR* = 23 N, p <.001), and significantly lower neck strength endurance (*M* = 25 s, *SD* = 7 s) than females (*M* = 40 s, *SD* = 12 s, p <.001). Unlike the female cohort, males exhibited positional differences in neck strength. Female union (*M* = 56º, *SD* = 4º, p <.007) and male league (*M* = 57º, *SD* = 8º, p <.010) had significantly greater CROM than male union (*M* = 49º, *SD* = 7º), with no cohorts exhibiting positional differences. There were no significant associations between neck strength and CROM in male players, whereas directional associations were observed in females.

The sex differences in anthropometry, neck strength and CROM suggest that women should not undergo training and injury prevention strategies based on androcentric research. The efficacy of dynamic neck strength training and the implications on post-season CROM could not be assessed due to COVID-19. The harness board apparatus with ImageJ procedure demonstrated excellent reliability as a measure of CROM.

Declaration and Statements

DECLARATION This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

STATEMENT 1 This thesis is the result of my own investigations, except where otherwise stated. Where correction services have been used, the extent and nature of the correction is clearly marked in a footnote(s).

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

STATEMENT 2 I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed [redacted]

Date 08.08.2021

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List of Abbreviations

BUCS	British university college sport
CBS	Crouch-bind-set
CISG	Concussion in Sport Group
CROM	Cervical range of motion
CRT	Concussion recognition tool
CTPE	Crouch-touch-pause-engage
DAI	Diffuse axonal injury
EMG	Electromyography
Ext	Neck strength extension
Ext	CROM extension
Flx	Neck strength flexion
Flx	CROM flexion
HIA	Head Impact Assessment
INSTA	Isometric neck strength testing apparatus
ISAK	International Society for the Advancement of Kinanthropometry
L-Lflx	CROM left lateral flexion
LNL	Lateral neck length
L-Rot	CROM left rotation
LtFlx	Neck strength left lateral flexion
MNL	Midline neck length
mTBI	Mild traumatic brain injury
MVC	Maximal voluntary contraction
NIH	National Institutes of Health
PRISP	Professional Rugby Injury Surveillance Project
RAE	Relative age effect
R-Lflx	CROM right lateral flexion
R-Rot	CROM right rotation
RtFlx	Neck strength right lateral flexion
RTP	Return to play
SCAT	Sport concussion assessment tool

SCM	Sternocleidomastoid
SRC	Sports-related concussion
TBI	Traumatic brain injury
UG	Universal goniometer
UT	Upper trapezius
VE	Visual estimation
WISP	Women's Rugby Injury Surveillance Project

CHAPTER 1: Introduction

1.1 Gender Data Gap

Rugby union is traditionally a male dominated sport. The women's game is the fastest growing area of rugby union with an estimated 2.8 million active female players, increasing by 28% per year, reported by World Rugby in 2018 (World Rugby, 2019). Blanket definitions such as 'rugby union players' are used in existing studies that do not include females in their cohorts. Study findings are then generalised to all rugby playing populations (Hendricks et al., 2020). Women are chronically understudied in medical and sports science research. Male-focused research can have far-reaching consequences in medical misdiagnoses and treatment recommendations (Berger et al., 2006). There is growing evidence that sex-specific research is required in many domains (Costello, Bieuzen, & Bleakley, 2014). Women are 2.6 times more likely to sustain a concussion in sport (Zuckerman et al., 2015) and experience symptoms of a greater severity and duration (McGroarty, Brown, & Mulcahey, 2020). A combination of factors account for sex disparities in concussion epidemiology, such as anthropometry (Yoganandan et al., 2006), neuronal physiology (Dolle et al., 2018), cervical spine geometry and neck strength (Antona-Makoshi, Mikami, Lindkvist, Davidsson, & Schick, 2018). The evolution of women's rugby is far behind men's rugby. The elevated vulnerability of women to cervical injuries and concussion indicates the need for sex-specific training and equal playing opportunities. An objective, female-specific evidence base regarding training patterns and injuries is required to develop training and injury protocols that allow safer play for women.

1.2 Concussion Incidence in Rugby Union

Participating in competitive contact sport poses risk of injury from the inherent features of play, such as high acceleration and deceleration, rapid change of direction and collisions (Harper, Carling & Kiely, 2019). Over 8.5 million people participate in rugby worldwide and since becoming a professional game for men in 1995, the incidence of injury has risen (Methenitis, 2020). The Professional Rugby Injury Surveillance Project (PRISP) began in 2002, making it the longest-running and most comprehensive report, assessing trends in injury risk of Premiership rugby players in training and competition (England PRISP Steering Group, 2018). For professional men's rugby, the 2017-18 season recorded the highest average severity and incidence of match injuries since 2002 (England PRISP Steering Group, 2018). This increase was the second consecutive season that injury severity rose above the upper limit of season-to-season variation. The most prevalent match injury across the last seven seasons in professional men's rugby was concussion. Concussion represented 18% of all injuries to the ball carrier and 37% of all injuries to the tackler in the 2017-18 season (England PRISP Steering Group, 2018). This highlights the importance of training strategies to improve tackle technique and injury prevention strategies to identify characteristics within the tackle that may predispose players to concussion. Much like men's rugby, concussion was the most common injury within women's Premiership rugby, accounting for 19% of all injuries (Kemp et al., 2018).

1.3 Neck Strength and Cervical Range of Motion

Sufficient neck strength is required to sustain cervical spine biomechanical alignment during contact events in rugby (Geary, Green, & Delahunt, 2014). Greater neck strength has been found to reduce inertial loading of the head during impact (Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014). Neck pain has been related to poor neck musculature strength and cervical spine mobility (Kauther, Piotrowski, Hussmann, Lendemans, & Wedemeyer, 2012). Greater playing experience is also associated with decrements in cervical range of motion (CROM). This is likely due to a gradual degeneration of cervical structures from the physical demands of rugby (Lark & McCarthy, 2007). Isometric neck strength training has been found to reduce match-related cervical spine injuries in professional rugby union players (Hrysomallis, 2016). There is no available research on the direct relationship between neck strength and cervical range of motion (CROM) in rugby populations. There is also a significant gender data gap with scarce research in female rugby union CROM. Thus, the effect of neck strength on CROM in male and female rugby union will be explored in this thesis.

1.4 Research Objectives and Hypotheses

The primary aim of this thesis is to determine whether current injury prevention protocols and training recommendations, based on male-derived data, are appropriate for female rugby players. Neck strength and CROM were measured and sex differences were assessed. Positional differences in neck strength and CROM were also assessed for males in females. It was hypothesised that forwards have greater neck strength and a lower CROM due to their positional characteristics of play. The second aim was to investigate the relationship between neck strength and CROM and the changes that occur over a rugby playing season. Male and female rugby players undertook a neck strength training programme during the season, which was implemented for a related master's research project. It was hypothesised that neck strength training would reduce decrements in CROM that occur over the season, relative to rugby league controls. Validation studies were conducted for new methods of measuring CROM and neck length.

1.5 Thesis Chapter Structure

Chapter 2: Literature Review

A review of literature concerning these issues are presented in Chapter 2. The gender data gap in sports science research is outlined in Chapter 2.1. An overview of rugby union, brain injury symptomology and safety management measures are evaluated in Chapter 2.2. Other contact sports with similar impact mechanics to rugby union have received much scientific attention, such as American football. Chapter 2.3 explores the influence of repeated concussion on the development of long-term neurological disorders in rugby union and American football. Key concepts of the mechanisms involved during head impacts and the pathophysiology of brain injury in rugby union is reviewed in Chapter 2.4. Chapter 2.5 summarizes the key components of the neck for the understanding of head-neck stability. Sex differences in concussion incidence may be due to anthropometric variables such as head-neck segment mass. The influence of anthropometric factors on head accelerations are analysed in Chapter 2.6. There is no anthropometric standard for measuring neck length provided by the International Society for the Advancement of Kinanthropometry (ISAK) body (Norton, 2019). This warranted the design of a new repeatable, accurate and reliable method for this project. Chapter 2.7 critically analyses the literature relating to the effect of neck strength and neck strength imbalances on head accelerations. Additionally, sex disparities in anthropometrics and neck strength are critically analysed, including their influence on head impact kinematics. The events associated with cervical spine injury are highlighted in Chapter 2.8, including the evolution of scrum laws over the decades. Lastly, Chapter 2.9 provides a critical analysis of existing literature related to the effect of rugby on the cervical spine. A review of

CROM research methods warranted the design of an inexpensive and reliable alternative for this project.

Chapter 3: Methodology

Participant and ethical approval details are presented in Chapter 3.2 and anthropometric measurement methods in Chapter 3.3. Neck strength testing equipment (Chapter 3.4) and testing protocols (Chapter 3.5) are followed by details of a neck strengthening intervention undertaken by rugby union participants (Chapter 3.6). The development and validation of the proposed novel CROM measurement methods are presented in Chapter 3.7 and the CROM testing procedures used in this thesis in Chapter 3.8. The rationale and development for the neck novel neck length method are presented in Chapter 3.9 with corresponding validation testing. As data collection was ended prematurely due to COVID-19 restrictions, all post-season data collection was cancelled. This resulted in limited neck strength and CROM data analysis. Neck length validation testing was also compromised. An overview of the statistical methods used in this thesis is provided in Chapter 3.10.

Chapter 4: Results

The results of this research project with statistical analysis are outlined in Chapter 4. Chapter 4.1 describes player anthropometrics. Chapter 4.2 and 4.3 assesses neck strength and isometric neck strength endurance. Chapter 4.4 and 4.5 assesses CROM and neck strength interactions. Chapter 4.6 outlines the results from the ImageJ CROM validation study.

Chapter 5: Discussion

The results from this research project are interpreted and discussed with existing literature in Chapter 5. Modifiable risk factors are highlighted for injury prevention strategies to make rugby safer for players. The design of sex-specific and cohort specific training programmes are recommended for future directions and methodological limitations are outlined.

CHAPTER 2: Literature Review

2.1 Gender Data Gap in Research

2.1.1 Gender Data Gap in Clinical Research

Women are the most chronically understudied population in medical and sports science research, yet they make up 49.6% of the population (World Bank, 2019). The implications of androcentric research can have extensive, far-reaching consequences, resulting in medical misdiagnoses and poor treatment recommendations for females (Berger et al., 2006). Females metabolize some drugs differently to males, for example, often requiring lower dosages resulting in adverse health effects if incorrectly prescribed (Berger et al., 2006). The United States General Accounting Office removed ten prescription drugs from the U.S market from 1997-2000, eight of which were omitted due to adverse health risks to females (U.S. Government Accountability Office, 2001).

In the 1990's, the National Institutes of Health (NIH) established guidelines for the inclusion of women and minorities in clinical research. Despite this policy, females remain underrepresented in clinical research. Between 2011 and 2012, sex bias was assessed in 2,347 articles of surgical biomedical research (Yoon et al., 2014). For publications in animal research that specified sex, 80% were male only, 17% were female only and 3% included both sexes (Yoon et al., 2014). For publications in cell research that specified sex, 71% were male only, 21% were female only and 7% included both sexes (Yoon et al., 2014). A large proportion of animal and cell publications did not specify sex at all (22% and 76%, respectively) (Yoon et al., 2014). Similar sex bias findings in different biological disciplines revealed 80% of animal research to be conducted on male rodents only in 2009 (Beery & Zucker, 2011).

2.1.2 Sex Disparities in Brain Injury Research

Females are 17% more likely to die in a car accident than males (Kahane, 2013). Females may be more susceptible to injury, as per adverse outcomes to various pharmaceuticals, due to the androcentric nature of research and testing protocols. For example, anatomical testing devices used in vehicle safety testing are designed based on the 50^{th} percentile male (Xu, Sheng, Zhang, Lui, Liang and Ding, 2018). Globally, the mean height of females is approximately 12 cm shorter than males

(Roser, Appel & Ritchie, 2013). The difference in physical size may prompt females to position themselves closer to the steering wheel than males, resulting in differing seat belt positionings. These positional differences have implications on how females respond in car crashes (Bose, Segui-Gomez, & Crandall, 2011). Sex disparities between seat and belt positioning may explain why belted females are up to 71% more susceptible to car crash injuries than belted males (Bose et al., 2011). Similarly, belted females are up to 67% more likely to sustain chest and spine injuries than belted males (Bose et al., 2011).

Females are up to three times more likely to experience whiplash associated disorders than males in vehicle collisions (Kullgren & Krafft, 2010). The greater risk among female occupants is attributed to sex disparities in cervical spine geometry, neck strength and the relative positioning of the head restraint (Berglund, Alfredsson, Jensen, Bodin, & Nygren, 2003; Bose et al., 2011). Females are 1.5 times more likely to sustain a concussion compared to male belted occupants (Antona-Makoshi et al., 2018). Alongside neck strength and anthropometry, a combination of biomechanical factors affects how occupants respond in car crashes. Such factors include the reaction time of the occupant, composition of cervical musculature and seated spinal alignment (Antona-Makoshi et al., 2018). Therefore, females are not simply scaled down versions of males as they are physiologically and geometrically different, heightening their vulnerability when exposed to impacts.

Women are 2.6 times more likely to sustain a concussion in sport (Zuckerman et al., 2015) and experience symptoms of a greater severity and duration (McGroarty et al., 2020). A combination of factors account for sex disparities in concussion epidemiology, much like car collision research (Antona-Makoshi et al., 2018; Berglund et al., 2003; Kullgren & Krafft, 2010). Females have smaller axons with fewer microtubules than males, heightening the risk of axonal failure during trauma (Dollé et al., 2018). Research identified sex differences in white matter diffusivity following repetitive sub-concussive head impacts, suggesting females are more vulnerable under the same applied loads (Sollmann et al., 2018). The gender gap in medical research is further highlighted as these major physiological differences among females were only identified in 2018 (Sollmann et al., 2018). This highlights the importance of including females in study designs and sex-disaggregated study results.

2.1.3 Gender Gap in Rugby Union Research

In current rugby studies, blanket definitions of 'rugby union players' do not always include female participants, but the findings are often generalised to whole populations (Hendricks et al., 2020). Hendricks et al., (2020) published a consensus paper and devised a framework for video analysis in rugby union. All 17 reviewed articles were of male populations only (Hendricks et al., 2020). Sex was not stated but was presumed given the nature of the games analysed, such as Super Rugby and U18 Craven Week tournament. Descriptors and definitions were based on key actions and events in male rugby union. The authors recommend the framework to be integrated with injury surveillance data for medical personnel to understand and identify injury mechanisms and risk factors. Women are more susceptible to injury in comparable loading conditions (Dollé et al., 2018), and exhibit different biomechanical responses to comparable exposures and recover differently to men (Antona-Makoshi et al., 2018). Therefore, females would benefit from a sex-specific framework with the incorporation of sex-specific injury surveillance strategies. Authors should clearly state the sex of participants and apply the findings to sex-specific populations (Hendricks et al., 2020).

2.2 Collisions in Rugby, Background and Context

2.2.1 Rugby Union Rule Overview

Rugby union (rugby) is a physically demanding, full contact sport. The following rules are outlined by World Rugby Laws (Methenitis, 2020). Each team fields 15 players consisting of eight forwards and seven backs. The forwards aim to gain and retain possession of the ball. They are typically powerful players that take part in lineouts and make up the scrum formation (Methenitis, 2020). The backs aim to create opportunities in scoring points through tries and conversions. They are typically faster with greater agility and ball-handling skills (Duthie, Pyne, & Hooper, 2003). Players can run with the ball, kick it forwards or pass backwards (Methenitis, 2020). The opposing team aims to retain possession of the ball and prevent point scoring opportunities by tackling the ball carrier, form mauls or rucks (Methenitis, 2020). The scrum is implemented to restart play when a forward pass or knock on infringement occurs (Methenitis, 2020). The scrum formation consists of the forwards from each team in set positions driving possession of the ball whilst gaining territory (Methenitis, 2020).

2.2.2 Brain Injury Nomenclature

Participating in competitive contact sport poses risk of brain injury from the inherent features of play. Severe brain injuries are referred to as traumatic brain injuries (TBI) which can involve a long period of unconsciousness lasting longer than 30 minutes following a severe trauma (McCrory, Feddermann-Demont, et al., 2017). More common in sports are mild traumatic brain injuries (mTBI), which can cause changes in mental status and in rare cases, a loss of consciousness for less than 30 minutes (McCrory, Feddermann-Demont, et al., 2017). Concussion is referred to as a subset of mTBI, however, numerous varying definitions of concussion exist in the literature (McCrory, Feddermann-Demont, et al., 2017). Concussions sustained during sporting activities are often referred to as sports-related concussion (SRC). The current international consensus statement on concussion in sport (McCrory, Meeuwisse, et al., 2017) has defined SRC as "a traumatic brain injury induced by biomechanical forces", with the following common features:

- Caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive fore transmitted to the head
- Typically results in the rapid onset of short-lived neurological impairment, with symptoms evolving over minutes to hours
- May result in neuropathological changes, with the presentation of functional disturbances rather than structural changes, thus no abnormality is usually seen using neuroimaging
- Results in a range of clinical signs and symptoms, may not involve the loss of consciousness, often resolve spontaneously but some symptoms may be prolonged

Given the fast-paced, high impact nature of rugby, concussions are common, but are frequently undiagnosed, underreported and untreated (Gardner et al., 2014). Multiple SRCs over a rugby playing career and exposure to repetitive head impact events have been linked to long-term neurocognitive deficits and mental health implications (Hume et al., 2016; Zetterberg et al., 2019).

2.2.3 Concussion Epidemiology in Rugby Union

Concussion is a high profile and common injury in rugby. The 2017-18 Professional Rugby Injury Surveillance Project (PRISP) reported concussion to be the most prevalent match injury across the last seven seasons in men's professional rugby (England PRISP Steering Group, 2018). The 2017-18 season exhibited a small incidence reduction of 19.9/1000 hours of play compared with the previous season, which amounted to one less concussion per eight games. In professional men's rugby, concussion contributed to 20% of all match injuries in 2017-18, a decline from the previous two seasons in 2016-17 and 2015-16 (22% and 25%, respectively) (England PRISP Steering Group, 2016, 2017). The retirement of ten players in 2017-18 from injury appears to be low in comparison to previous reports; however, 40% of the retirements were due to head or neck injuries (England PRISP Steering Group, 2018). In professional men's rugby, concussion represented 18% of all injuries to the ball carrier and 37% of all injuries to the tackler (England PRISP Steering Group, 2018). Similarly, concussion was the most common injury within women's Premiership rugby, accounting for 19% of all injuries (Kemp et al., 2018). The gender data gap is further highlighted here as this was the first Women's Rugby Injury Surveillance Project (WRISP) report (Kemp et al., 2018). Situational factors should be considered when comparing reports of concussion incidence. King, Hume and Clark (2012) observed the ball carrier to be most frequently concussed, particularly when tackled at shoulder height, in their blind vision, when two of more tacklers were involved or in the final quarter of the match (King, Hume & Clark, 2012).

2.2.4 Symptomology of Brain Injury in Sport

Concussion can result in somatic, cognitive and emotional symptoms, cognitive impairment, behavioural issues and sleep disturbance (McCrory et al., 2017). Research compared 94 collegiate American football players with SRC and 56 non-injured controls to assess symptom recovery time, cognitive functioning and postural stability recovery time (McCrea, Guskiewiez, & Marshall, 2004). Post-concussion, symptoms resolved by day seven, cognitive functioning resolved within 5-7 days and postural stability resolved within 3-5 days (McCrea et al., 2004). Symptomology and recovery may be affected by age and gender (Covassin et al., 2012). These authors assessed 296 concussed athletes and found females to report more symptoms following a concussion, with worse mean visual memory scores than males (65.1% and 70.1%, respectively). Verbal and visual mean scores were worse in high school athletes (78.8% and 65.8%, respectively) than college athletes (82.7% and 69.4%, respectively), with the high school athletes experiencing verbal memory impairment seven days post-concussion (Covassin et al., 2012). The differences in symptomology across age and gender may prompt clinicians to interpret symptoms and recovery differently per target population or perform more sex-specific research in females.

2.2.5 Management of Concussive Injury in Sport

Upon the onset of concussion, athletes should be removed from the activity immediately as the brain is vulnerable to further impairment of neuropathophysiological processes (Asken et al., 2016). A study showed athletes who were not immediately removed from activity after concussion were in recovery for approximately eight more days than athletes who were immediately removed (Asken et al., 2016). The Concussion in Sport Group (CISG) have developed an expert consensus-based approach for physicians and healthcare providers to identify and improve understanding of SRC and return to play (RTP) processes (McCrory, Meeuwisse, et al., 2017). The Concussion Recognition Tool 5 (CRT5) serves as an educational tool for non-medically trained persons to assist medical providers in identifying and managing a potential SRC (Echemendia et al., 2017). Presently, World Rugby instils the Sport Concussion Assessment Tool (SCAT5) used by healthcare professionals and the CRT5 for Head impact assessment (HIA) processes (Methenitis, 2020). Other assessment tools, such as wearable head impact telemetry systems, have been developed to quantify the magnitude of head impact events. These include the use of instrumented helmets (Duma & Rowson, 2012), mouthguards and ear patches (Bartsch et al., 2019). However, authors have previously found limitations in the reliability of such devices (Siegmund et al., 2016).

Ample research reports lack of adequate knowledge and compliance of concussion management guidelines by athletes, parents, coaches and medical personnel (Niederer et al., 2018 (a); Niederer et al., 2018 (b); Wing et al., 2019). Connell and Molloy (2016) found 75% of male and female players would continue to play with a concussion during an important match and 39.1% would manipulate medical assessments, with 78.2% claiming it was easy to do so. These findings corroborate previous research that premature RTP is often due to attitudes that embody pressures to succeed and not letting the team down (Cusimano et al., 2009). Even athletes in an elite, sub-elite and high school population may feel embarrassed reporting a concussion (Register-Mihalik et al., 2013). It is important to note the absence of female athletes in these studies. Where they have been included, such as the Connell & Molloy study (2016), the results were not sex-disaggregated to show differences between sex.

2.3 Longitudinal Studies in Brain Injury

2.3.1 Rugby Union

The influence of repeated concussion on the development of long-term neurological disorders in rugby players has been investigated (Decq et al., 2016; Hume et al., 2017). Decq et al., (2016) compared 239 retired male rugby players with 138 retired male non-contact sport athletes for the prevalence of depressive disorders, cognitive disorders and headaches. The retired male athletes were aged 45-65 years and competed for at least 10 years, reaching national or international level. Questionnaires releveled higher rates of major depressive disorders and mild cognitive disorders in the rugby players, with more reported concussions per player than the non-contact sports group (Decq et al., 2016). Headache severity was significantly associated with the frequency of reported concussions; however, there was no observed association between cognitive disorders and reported concussions (Decq et al., 2016). This study comes with limitations as the findings cannot be generalised to females or athletes at lower playing levels. Secondly, there is potential memorization bias when reporting concussion retrospectively as such events can be accompanied by amnesia symptoms. Therefore, the frequency of reported concussions may be significantly underreported.

Similar research assessed cognitive function in 366 male retirees of elite rugby, community rugby and non-contact equivalents using the online CNS Vital Signs neuropsychological test battery (Hume et al., 2017). Retirees recalling one or more concussions (elite 85 %, community 77 % and non-contact 23 %) performed worse than players who had not recalled concussions for cognitive flexibility, executive functioning and complex attention tests (Hume et al., 2017). Overall, the elite rugby group performed worse on all neurocognitive tests compared to the non-contact group (Hume et al., 2017), supporting previous research indicating neurocognitive deficits (Shuttleworth-Rdwards & Radloff, 2008). The limitations of the previous study include the cross-sectional design as it cannot assume causality of rugby participation with impaired cognitive functioning. Neurocognitive tests were not administered before sports participation to identify baseline individual differences. Secondly, the elite players stopped competing in 1990-2000 and community players in 2000-2010. The nature of the game has changed over the years since professionalism in 1995 (Methenitis, 2020), with faster, heavier and stronger players (Quarrie & Hopkins, 2007). Self-report concussions may not align with medically diagnosed concussions or reports of concussions experienced in a later decade (Kerr et al., 2015). Awareness in concussion and side-line medical management has improved over the years (McCrory et al., 2017), which may have an influential effect on long-term health in players.

2.3.2 Other Contact Sports

Other contact sports with similar impact mechanics to rugby have received much scientific attention. Studies in American football have shown interest in the long-term effects of SRC on brain morphometry. Relative to age-matched controls, retired athletes with a history of concussion exhibited abnormal enlargement of the lateral ventricles, cerebral cortical thinning and decline in episodic memory and verbal fluency (Tremblay et al., 2012). These neuroimaging profiles were correlated with long-term cognitive deficits associated with SRC (Tremblay et al., 2012). Supporting research identified cognitive impairments and depression in retired NFL athletes (Hart et al., 2013). These cognitive impairments were correlated with white matter abnormalities. In the cognitively impaired group, differences in regional blood flow (left temporal pole, inferior parietal lobule, and superior temporal gyrus) corresponded to impairments in memory, language and word-finding (Hart et al., 2013).

Strain et al., (2015) assessed the relationship between hippocampal volume, cognition and history of concussion in 28 male retired professional American football athletes, with and without mild cognitive impairment. Athletes with mild cognitive impairment had worse verbal learning scores with a history of concussion than those without (Strain et al., 2015). Athletes with grade-3 concussion history (losing consciousness) had significantly smaller hippocampal volumes than healthy controls (Strain et al., 2015). Athletes older than 63 years with grade-3 concussion history were all diagnosed with mild cognitive impairment, whereas only one-fifth were diagnosed without grade-3 concussion history (Strain et al., 2015). The study showed accentuated age-related decline anatomically and cognitively. Measures of hippocampal volumes and neuropsychological tests before head trauma may have identified the influence of age on the development of degenerative diseases. Individuals with small hippocampi may be predisposed to cognitive impairment before athletic participation, so concussion should not be generalised as a sole causal factor. Similar research in nine former NFL players found significant right hippocampus and amygdala atrophy with poor verbal learning and memory scores (Coughlin et al., 2015). Greater sample sizes would strengthen these research findings of pathological contribution to cognitive decline (Coughlin et al., 2015; Strain et al., 2015).

2.4 Brain Injury in Rugby Union

2.4.1 Biomechanics of Head Impact Events

Rapid movement of the head induced by biomechanical forces can impair brain tissue, altering the chemical and metabolic function of brain cells (McCrory et al., 2017). Direct head impacts cause focal injuries from linear accelerations and decelerations of the head (Kleiven, 2013). Indirect impacts, usually to the torso, cause impulsive head motions of linear and rotational accelerations and decelerations, known as inertial loading (Tierney & Simms, 2017b). Inertial loading causes shearing forces throughout the brain (Kleiven, 2013). The brain has a high resistance in changing volume, but a poor resistance in changing shape when shear forces are applied (Kleiven, 2013). Rotational loading has a high potential of causing brain strain (Takhounts, Craig, Moorhouse, McFadden, & Hasija, 2013) and is suggested to be the major mechanism of injury in concussion (Fanton, Kuo, Sganga, Hernandez, & Camarillo, 2019; Hoshizaki et al., 2016; Takhounts et al., 2013).

Research using primates found isolating the rotational component of accelerative trauma from linear significantly reduced the likelihood of causing unconsciousness (Ommaya & Gennarelli, 1974). When including the rotational component of accelerative trauma, the likelihood of causing unconsciousness increased (Ommaya & Gennarelli, 1974). Research observed the difference between radial and oblique head impacts into a polypropylene foam at initial velocity of 6.7 m/s (Kleiven, 2007). Significantly greater strain levels in the brain were caused by oblique impacts at a 45° angle compared with perpendicular impacts. The radial impacts caused significantly greater stresses in the skull which is associated with an increased risk of skull fractures. Later research reinforced that rotational head kinematics increases intracranial strain and linear kinematics increases intracranial pressure (Kleiven, 2013). Biomechanical data on head kinematics have been studied using multibody simulations (McIntosh et al., 2014), computer modelling (Tierney et al., 2015) and wearable sensors (King et al., 2015). To date, research has not universally quantified the threshold severity of a concussive impact.

2.4.2 Pathophysiology

A factor contributing to the clinical symptomology of TBI is diffuse axonal injury (DAI). DAI is the widespread axonal shearing and tearing in the cerebral hemispheres of the subcortical white matter (Goriely et al., 2015). DAI occurs when the brain rapidly accelerates and decelerates within the skull from impacts experienced in car accidents or contact sports (Post, Blaine Hoshizaki, Gilchrist, & Cusimano, 2017). Primary and secondary axotomy are mechanisms of DAI (Smith, Hicks, & Povlishock, 2013). Primary axotomy occurs upon the onset of injury, where axonal fibres are sheared from direct mechanical force (Smith et al., 2013). Secondary axotomy develops after the onset of injury where inflammatory responses disrupt axoplasmic transport, leading to axonal swelling and disconnection from its downstream counterpart (Douglas Smith et al., 2013). Secondary axotomy degeneration may develop over hours, days or even years following a TBI (Faden et al., 2015). Persistent axonal degeneration is a major risk factor in the development of neurodegenerative disease, such as Alzheimer's (Fleminger et al., 2003). DAI can occur in all severities of TBI with neurological deficits ranging from minor neurocognitive impairment to a state of coma, depending on the severity of injury (Johnson, Stewart, & Smith, 2013).

SRCs are associated with damaging magnitudes of strain in the corpus callosum from impacts (Ting et al., 2016). Authors agree that longer durations of acceleration require a lesser magnitude to sustain strains associated with brain injury (Hoshizaki et al., 2016; Post et al., 2017). Hitosugi et al., (2014) found rotational accelerations of 3300 rad/s^2 with durations longer than 20m/s to cause subdural hematomas, whereas Post et al., (2017) found rotational accelerations of 5000 rad/s^2 with durations longer than 10m/s to cause strain values associated with SRCs. Comparing head impact research comes with limitations as authors use different methods of accelerometers (Hitosugi et al., 2014) and finite element models (Post et al., 2017) to measure head accelerations. This may explain why the magnitude and durational threshold of acceleration required to cause concussion is unknown, differing between and within individuals (Hoshizaki et al., 2016).

2.5 Key Components of the Neck

One function of the cervical vertebrae is to protect the blood vessels and spinal cord (Tortora & Derrickson, 2018). The cervical spine is more vulnerable to severe injuries in comparison to the thoracic and lumbar spine as it supports the weight of the head whilst maintaining a large range of motion (Tortora & Derrickson, 2018). The mobility of the cervical spine increases the neck's vulnerability in attempt to maintain stability (Inoue & Orias, 2011). Maintaining stability with the weight of the head can place strain on the cervical spine with the effects exacerbated during sudden high force movements (Inoue & Orias, 2011). With limited bony protection and musculature support, damage to these structures are critical and can cause morbidity and mortality in trauma patients (Khanpara, Ruiz-Pardo, Spence, West, & Riascos, 2020).

The cervical spine must be statically and dynamically stable through support of the surrounding cervical musculature. Static stabilizers within the neck include cervical intervertebral discs, articular capsules and ligaments (Tortora & Derrickson, 2018). Collectively, they mechanically restrain the neck from abnormal movements and control the skeletal segments for stability (Koivikko, 2005). The nucleus pulposus sustains loads from impacts and distributes the compressive forces to the anulus fibrosis through hydrostatic pressure (Inoue & Orias, 2011). The anulus fibrosis fibre arrangement functions to resist stresses produced from the hydrostatic pressure (Inoue & Orias, 2011). The evenly distributed forces across the vertebral body dampens the stresses placed on the cervical structures. Repetitive compressive axial loading, often adopted during a tackle position, has been associated with structural damage of the cervical spine, neck injury and cervical spine buckling (Swartz, Floyd, & Cendoma, 2005).

The primary dynamic stabilizers of the head-neck segment are the sternocleidomastoid (SCM) and upper trapezius (UT) which absorb energy from direct and indirect impacts (Dezman, Ledet, & Kerr, 2013; Mansell, Tierney, Sitler, Swanik, & Stearne, 2005). Oi, Pandy, Myers, Nightingale, & Chancey (2004) found the SCM to produce the greatest cervical flexor moment and the UT to produce the greatest cervical extensor moment. Authors refer to the UT and SCM as prominent contributors in head-neck stability (Morimoto, Sakamoto, Fukuhara, & Kato, 2013). Morimoto et al., (2013) assessed 28 male rugby players in tackle positions with their head up and with their heads down. Greater activity of the SCM and right UT occurred when the head was positioned upward as opposed to downward. These findings suggest adopting an upward facing head position during tackles optimal for head-neck stability and muscle activation (Morimoto et al., 2013).

Dynamic stability depends on feed-forward and feedback motor control mechanisms when anticipating and reacting to cervical loads and movements (Sangwan, Green, & Taylor, 2014). The feed-forward mechanism uses previous experience to produce a motor response and has been suggested to control muscle pre-activation (Sangwan et al., 2014). The feedback mechanism is associated with reactive muscle activity and utilizes reflex pathways to regulate motor control (Smith, Haug, & Walsh, 2019). Vestibular, visual and proprioceptive signals elicit reflex responses for head and neck stabilization (Smith, Haug, & Walsh, 2019). Receptors send afferent impulses to the central nervous system involving proprioception, kinesthesis and muscle tension to coordinate an efferent response (Tortora & Derrickson, 2018). Sensory information from mechanoreceptors help regulate dynamic joint stabilization by coordinating muscle activity during movement (Tortora & Derrickson, 2018). Mechanoreceptors are situated in the skin, muscles, tendons and articular structures surrounding joints (Tortora & Derrickson, 2018).

2.6 Anthropometric Factors in Head Impact Severity

2.6.1 Head Mass

Head mass is an important variable when quantifying head impacts and neck injury thresholds (Roush, 2010). Head mass, centre of gravity and principle moments of inertia are important elements in defining the human response to head impacts (Roush, 2010). Following Newton's Law of Acceleration, a lower head mass results in higher head accelerations under the same applied loads. There is difficulty in measuring head mass of a living human accurately without segmentation. There is no standard measure of head mass. Measures of head mass have been defined using 3D modelling (Roush, 2010) and regression calculations (Zhang et al., 2018). Percentages of total body mass have been used in research to estimate the head-neck segment mass of men (8.26%) and women (8.20%) (Caccese et al., 2018; Mansell et al., 2005; R. Tierney et al., 2008). The accuracy of calculated estimations are poor, as research found a wide range of possible head mass for a given body mass (Plaga, Funke, Galster, & Nelson, 2005).

Females have a greater risk of sustaining concussion than males (McGroarty et al., 2020). Sex differences in concussion incidence may be due to anthropometric variables such as head-neck segment mass. A study investigated sex differences in head impact kinematics and dynamic stabilization in collegiate soccer heading (Tierney et al., 2008). Participants performed four headers for three headgear conditions while wearing a custom mouthpiece accelerometer to assess head acceleration. Males had 15% greater head-neck segment mass, 5% greater head-neck segment length and 12% greater neck girth than females (Tierney et al., 2008). Females exhibited greater linear head accelerations than males by 10-44% across headgear conditions (Tierney et al., 2008). The findings revealed head mass and neck girth to be inversely correlated with linear head acceleration in both sexes (Tierney et al., 2008). The study supports the theory that individuals with less head mass are more likely to experience greater head accelerations in response to a standardized external force than those with a greater head mass. The findings are limited to collegiate players with five years of heading experience, so may not be generalisable to players with underdeveloped heading skills as technique may be an influential factor. Small head-neck segment mass predisposes players to greater head accelerations (Tierney et al., 2008). Alignment of the torso with the head-neck segment during and after ball contact can decrease head accelerations (Caccese & Kaminski, 2016). Additionally, the sample sizes were small and uneven of 29 females and 15 males, which would not be generalisable to whole populations within sex. Lastly, this study's findings are limited to linear acceleration only as rotational acceleration was not measured.

Caccese et al., (2018) investigated factors contributing to linear and rotational head acceleration in 42 male and 58 female soccer players. Linear and rotational head accelerations were measured during soccer heading trials using a triaxial accelerometer and gyroscope (Caccese et al., 2018). Regression analysis revealed head mass and neck girth to contribute to 22.1% variance in peak linear acceleration and 23.3% variance in peak rotational acceleration (Caccese et al., 2018).

Interestingly technique was not a significant factor in predicting head accelerations (Caccese et al., 2018). Technique did not vary considerably across participants to identify influential factors and predominantly entailed trunk extension pre-contact, flexion upon contact and follow through for most participants (Caccese et al., 2018). Greater variance may have been observed if novices were included in the study with less than a year of soccer heading experience. Strength of SCM and UT contributed to 13.3% variance in peak linear acceleration and 17.2% variance in peak rotational acceleration (Caccese et al., 2018). The results show that head mass, neck girth and neck strength are influential factors in predicting linear and rotational head accelerations (Caccese et al., 2018). Unlike the previous study, the age span was greater (12-24 years) for representing different population groups. Comparatively, the results are only valid for anticipated impacts and may not reflect what might be observed for unanticipated impacts. The nature of a laboratory experiment lacks ecological validity as controlled headers may differ from in-play headers. Even so, the study shows the influence of anthropometric variables on head accelerations across various ages in both sexes.

2.6.2 Neck Length

Measuring neck length is important for the calculation of head and neck moments when quantifying head impacts. The relationship between neck length, neck strength and their effects on head accelerations are key variables to consider. A longer neck could mean greater difficulty in stabilizing the head-neck segment during impacts resulting in greater accelerations. Moment arm is an essential component in cervical spine musculoskeletal models as it transforms muscle force into joint motion (Suderman & Vasavada, 2017). Tendon excursion is a method of calculating moment arm by the principle of work where muscle length displacement is assumed to be a function of joint displacement, $\frac{dl}{d\theta}$ (An, Takahashi, Harrigan, & Chao, 1984). Tendon excursion is often used in cadaver experiments (Arnold, Salinas, Hakawa, & Delp, 2000), which is not appropriate for all research. Moment arm can also be calculated using a geometric method by the perpendicular distance of the centre of rotation to the muscle line of action (An et al., 1984). However, this geometric method using MRI is not an efficient and accessible method for all researchers.

There is no ISAK anthropometric standard of measuring neck length (Norton, 2019). This has resulted in varying methods of measuring neck length in existing literature. Head impact research has predominantly measured head-neck as a segment and not neck length singularly. This is plausible given the subsequent variables used for head acceleration research, such as head-neck segment mass when quantifying head impacts. Han et al., (2015) defined neck length as a ratio of midline neck length (MNL) and lateral neck length (LNL). MNL was the distance between the upper margin of the hyoid bone to the jugular notch (Han et al., 2015). LNL was the distance from the mandibular angle to the mid-portion of the ipsilateral clavicle (Han et al., 2015). Difficulty in locating the mid-portion of the ipsilateral clavicle may produce inaccurate and unreliable results as it is not a standard anatomical landmark (Norton, 2019). Harty, Quinlan, Kennedy, Walsh, and O'Byrne (2004) defined neck length as the distance between the occiput to the C7 spinous process and the mandibular angle to the sternal notch. These authors did not specify whether C7 was measured from its midpoint, superior or inferior point, producing unreliable results (Harty et al., 2004). Tabaee et al., (2005) defined neck length as the cricosternal distance, from the cricoid cartilage to the sternal notch. Studies have used x-ray to demonstrate radiological parameters for measuring neck length (Ahmed, Qamar, Imram, & Fahim, 2020; Taha et al., 2014). Although accurate and reliable, radiology can be impractical for research studies as it is expensive, requires specialist training and is not necessarily available. Thus, the design of a new repeatable, accurate and reliable method of digitally measuring neck length is wanted.

2.6.3 Maturation

Adolescents experience a series of developmental processes upon puberty which are often beneficial in sports (Tyler, Foweather, Mackintosh, & Stratton, 2018). Such changes include increases in body mass, improvements in neurological functioning, improvements in cognitive functioning and changes in growth hormones, increasing bone and muscular maturation (Ford et al., 2012; Grobler, Shaw, & Coopoo, 2017). These changes are identifiable in adolescents within a 12-month age gap and is referred to as the Relative Age Effect (RAE) (del Campo, Vicedo, Villora, & Jordan, 2010). RAE athletes exhibit advantageous rugby characteristics, such as strength, power, body mass, stature and skill level (Hancock, Ste-Marie, & Young, 2013).

Collins et al., (2014) found small head-neck circumference ratio and low neck strength to be significantly associated with concussion incidence in schoolboys. Females exhibited weak correlations between concussion and neck strength and no significant associations with head-neck circumference ratio (Collins et al., 2014). These authors calculated that for every pound increase in neck strength, the concussion risk reduced by 5% (Collins et al., 2014). Therefore, the effect of RAE and physiological characteristics of neck strength and anthropometric ratios are influential in the risk of concussion in rugby. Since the game's professionalisation, the mass of rugby players have increased and subsequently, so too have the engagement forces, which are predominantly absorbed by front row players (Preatoni et al., 2013).

Theoretically, sex differences should not be emerging pre-puberty as individuals have not fully developed in terms of bone structure, muscle mass and hormone level (Siervogel et al., 2003). For example, upon the onset of puberty, females experience significant joint laxity increases, whereas males do not, suggesting why females are more susceptible to injury (Quatman, Ford, Myer, Paterno, & Hewett, 2008). Research devised the Dragon Challenge assessment which measured factors of physical competence including balance, poise, rhythmic movement patterns, complex movement patterns and refined movement patterns (Tyler et al., 2018). The results found prepubescent schoolboys to exhibit greater Dragon Challenge scores than prepubescent female counterparts (Tyler et al., 2018). These differences emerging before puberty in movement and skill capability may transpire into greater sex disparities between male and female university rugby players.

2.7 The Importance of Neck Strength in Head Impact Mitigation

2.7.1 Head-Neck Stability

Cervical strength training has been suggested to reduce the severity of concussion from cervical musculature attenuating head accelerations from impacts (Toninato et al., 2018). Neck strength and anticipatory cervical muscle activation were investigated in a cohort of 46 male and female contact sport athletes, aged between eight and 30 years (Eckner et al., 2014). Head kinematics were recorded during external force application per plane of motion for anticipated and unanticipated impacts. The results showed isometric neck strength and anticipatory cervical muscle activation to be inversely associated with linear and angular head acceleration

(Eckner et al., 2014). Contrasting literature investigated the effect of neck strength training on dynamic head-neck stabilization (Mansell et al., 2005). A cohort of 36 male and female collegiate soccer players underwent an eight-week isotonic cervical resistance training program (Mansell et al., 2005). The training programme increased isometric neck flexor strength by 15% in both males and females. Only females increased their isometric extensor strength by 22.5% (Mansell et al., 2005). No effect was seen in reducing head-neck dynamic stabilization during external force application, even with greater neck strength (Mansell et al., 2005). The results suggest other factors may have a greater impact on enhancing dynamic restraint, such as feedforward and feedback motor control mechanisms.

Cervical muscle strength and stiffness are essential in dampening external forces placed on the head (Dezman, Ledet, & Kerr, 2013). Stiffening the neck musculature forms a head-neck segment whereby kinetic energy from impacts are absorbed and dissipated through to the torso (Dezman et al., 2013). The effect of pre-impact anticipatory cervical muscle contraction has been investigated. A study examined the head-neck kinematic and dynamic stabilization response to anticipated and unanticipated impacts in 40 male and female participants (Tierney et al., 2004). Electromyography (EMG) recordings of the trapezius and SCM measured maximum voluntary contraction (MVC), MVC activity area and muscle onset latency. In male participants, the head-neck segment peak angular acceleration decreased by 25% when the force application was known, compared to unknown (Tierney et al., 2004). No significant differences between conditions were observed in females. Females exhibited 50% greater head-neck segment acceleration than males (Tierney et al., 2004). This difference could be due to their lower levels of isometric strength (49% difference), neck girth (30% difference) and neck stiffness (29% difference) (Tierney et al., 2004). The participants were physically active volunteers, so there may be limits where these findings can be generalised to professional athletes. During rugby collisions, the neck musculature will mimic a viscoelastic shock absorber to stabilize the head-neck segment and dampen impact head oscillations (Tierney et al., 2008). Not all collisions in rugby are anticipated, so players are still at risk of experiencing concussive injuries.

2.7.2 Neck Strength Symmetry

Imbalances in neck muscle coordination have been suggested to account for higher head accelerations during heading actions in novice football players (Riches, 2006). A study measured neck strength imbalances in 16 collegiate male and female football players (Dezman et al., 2013). Head accelerations were recorded of the athletes returning the football with heading action (Dezman et al., 2013). Footballs were thrown and returned at mean velocities of 4.29 m/s and 5.48 m/s, respectively (Dezman et al., 2013). In contrast to the majority of published studies, there were no significant differences between sex in flexion neck strength, extension neck strength or flexion-extension imbalances (Dezman et al., 2013). The results showed a positive correlation between flexion-extension imbalances and angular head acceleration (Dezman et al., 2013). There were no correlations between directional neck strength and head acceleration, indicating the importance of neck strength symmetry for head-neck stabilization, as opposed to flexion and extension independently (Dezman et al., 2013). The small cohort limits the extent the findings can be generalised to greater populations at different playing levels. Additionally, the flexion-extension strength testing was not randomized, which may have predisposed flexion scores to be greater when tested first. Lastly, the findings can only be generalised to low velocity impacts (4.29 m/s), unlike those seen in other contact sports such as ice hockey (Rousseau, 2014).

2.7.3 Sex Differences

The physiological differences in anthropometrics and muscle strength between males and females may explain the differences observed in head kinematics (Debison-Larabie, 2016). A study found males to have greater neck girth than females, which presented a significant negative relationship with linear and rotational accelerations during soccer heading (Bretzin, Mansell, Tierney, & McDevitt, 2017). Linear acceleration was negatively correlated with neck flexor, left lateral flexor and left rotator strength (Bretzin et al., 2017). Females exhibited significantly less flexor and left lateral flexor strength than males, resulting in greater head impact kinematics (Bretzin et al., 2017). Unlike most research in this field, the study's strength was the disaggregation of data identifying sex differences. However, the small sample size of 13 collegiate athletes limits the extent to which the results can be generalized to greater populations or differing playing levels. Secondly, a hand-held dynamometer was used to measure isometric neck strength, whereas heading actions require isotonic contractions. Lastly, the nature of soccer heading means all impacts were anticipated, unlike impacts experienced in rugby or ice hockey. Greater head kinematics may have been observed if head impact oscillations were not dampened to such an extent from the stiffening effect (Dezman et al., 2013).

Geometric differences were assessed in 14 gender-matched pairs in height and neck length (Vasavada, Danaraj, & Siegmund, 2008). Females were more slender in the neck by 18% and had 33% greater head mass per unit neck muscle area than size-matched males (Vasavada et al., 2008). In the anterior-posterior dimension, females had significantly smaller vertebrae between C3 and C7 than males (Vasavada et al., 2008). This was not significant in the medial-lateral dimension. Females were significantly weaker in flexion and extension neck strength (32% and 20%, respectively), which corresponded to their geometric differences (Vasavada et al., 2008). The small sample was not representative of a normal population as only the tallest women were matched with the shortest men to meet the criteria. Additionally, the women were significantly lighter by 7.8 kg, which may have caused variability in the results. Nonetheless, the study demonstrated geometric sex differences and that females do not exhibit a scaled-down form of the male neck.

2.8 Scrummaging

2.8.1 Injury Risk

The forceful engagement of the scrum exposes front row players to cervical spine injury (Brown et al., 2014). Upon scrum engagement, the front rows absorb the initial horizontal forces applied by the opposing forwards then maintain form throughout the scrummage push (Preatoni, Stokes, England, & Trewartha, 2014). The forward’s formational coordinated push places vertical, horizontal and lateral loads on the musculoskeletal structures (Preatoni, Cazzola, Stokes, England, & Trewartha, 2016). Prior to 2014, the scrum was associated with 40% of catastrophic injuries, primarily to the spinal cord (Preatoni et al., 2014). Fewer scrums occur in play compared to tackles, but the detrimental effects of these can be more severe. The small proportion of front players affected in the scrum has masked the incidence rates of injury in epidemiology studies (Brown et al., 2014). Of all scrum injuries reported in professional men’s rugby, 91% were sustained by front row players (Trewartha, Preatoni, England, & Stokes, 2014). The scrum is a high injury risk event and comparatively controllable than other parts of the game. Scrum laws have changed over the years to improve safety.

2.8.2 Crouch-Touch-Pause-Engage (2007)

The 2007 scrum law (International Rugby Board, 2006) of crouch-touch-pause-engage (CTPE) aimed to reduce initial impact forces placed on the front rows by controlling the distance prior to engagement. Preatoni, Stokes, England, and Trewartha, (2013) investigated compression forces during engagement on an instrumented scrum machine from six playing levels adopting the CTPE call. Peak compression force occurred during impact engagement for a short duration, followed by a minimum pressure dip then rising to a sustained push. Peak compression force ranged from 16.5 kN in international and elite players, to 8.7 kN in female players (Preatoni et al., 2013). Sustained compression force ranged from 8.3 kN in international players to 4.8 kN in female players (Preatoni et al., 2013). Peak compression forces were approximately twice the magnitude of sustained compression forces for all levels, showing the physical demands placed on the front row upon impact (Preatoni et al., 2013).

2.8.3 Crouch-Bind-Set (2013)

The 2013 scrum law (University of Bath, 2014) of crouch-bind-set (CBS) removed “pause” from the sequence to speed the process and minimise scrummage collapse. The “bind-set” call allows the front row to make formation into a pre-load position with their heads resting on the opposing players shoulders without the driving force of the forward packs (University of Bath, 2014). The “bind-set” action minimises errors in engagement timing and pack positioning (Preatoni et al., 2014). Cazzola, Stone, Holsgrove, Trewartha, and Preatoni (2016) found greater UP and SCM activity pre and during the engagement phase of CBS than CTPE in machine scrummaging. The findings suggest that pre-binding braces the cervical spine for impact by the stiffening of muscles. Live scrummaging produced greater erector spinae activity during the sustained push phase than machine scrummaging (Cazzola et al., 2016). The lack of ecological validity in a lab setting and decreased erector spinae activity suggests that machine scrummaging does not represent live scrummaging conditions. Moreover, the small sample size of nine university standard male participants lacks confidence in the data to generalise to greater populations at different playing levels or sex.

Cazzola, Preatoni, Stokes, England, and Trewartha (2014) compared the biomechanical loading of CTPE and CBS engagement techniques on 22 male professional forward packs in a live outdoor scrum. Pressure sensors were placed on each shoulder of the front row players to estimate the contact forces and inertial measurement units on C7 to measure accelerations. The CBS technique exhibited the least biomechanical stress on front row players during scrum engagement. The pressure sensors recorded 35% less force and 16% less average peak acceleration on C7 compared to the CTPE technique (Cazzola et al., 2014). There were no significant differences in average exerted force during the sustained push phase, suggesting that CBS has no decreased ability in generating force and offers safer scrummaging. The findings cannot be generalized to reduce cervical spine injury as the study did not measure how the external forces dissipate into local injuries and stresses on the cervical spine. Similarly, the findings cannot be generalised to female rugby players as they have geometrically different cervical spines to males (Stemper et al., 2008). No studies have included the effects of cervical spine loading in female forward-pack rugby cohorts. Similar research (Preatoni et al., 2016) studied forward players in live scrums at different playing levels. The findings showed CBS to exhibit 14-25% less peak biomechanical stress acting on the front row players for all playing levels than CTPE, without reducing the force production during the sustained push phase (Preatoni et al., 2016). The pressure sensors used in the two previous studies were placed on the shoulders and neglected any force contributions exerted on the head, underestimating the contact area between the front rows. Additionally, the forces could have been greatly underestimated as only perpendicular components were measured, disregarding the shear forces produced between the players' shoulders.

2.8.4 Outlaw of Pre-Binding (2019)

The 2019 scrum law (World Rugby, 2019) removed the practice of “de-loading” the mass of the forwards onto the opposing shoulders in the scrum between the “bind-set” call to reduce axial loading on front row players. Axial loading concentrates the scrum force on the opposing hooker as opposed to the force being diffused along the shoulders of the front row (Cazzola et al., 2014). Axial loading of high magnitude and eccentricity can cause bending moments in the cervical spine, resulting in ligament damage and facet dislocations (Dennison, Macri, & Cripton, 2012; Kuster, Gibson, Abboud, & Drew, 2012). The compressive axial loads on a constrained head can cause a buckling mechanism to occur (Kuster et al., 2012), characterised by superior to inferior motion of the head while the cervical spine adopts a C-shape (Dennison et al., 2012). Injury mechanisms from axial loading within the scrum have been attributed to hyperflexion and buckling (Dennison et al., 2012; Kuster et al., 2012; Trewartha et al., 2014).

2.9 Cervical Spine Range of Motion

2.9.1 Importance of Cervical Spine Range of Motion

The cervical spine is the attachment point and axis of rotation to the head (Swartz et al., 2005). The severity of cervical spine injury depends on head impact location and cervical spine alignment upon impact (Nightingale, Camacho, Armstrong, Robinette, & Myers, 2000). The onset of injury can occur at once between two and 30 milliseconds after impact before observable motion of the head (Nightingale et al., 2000). Axial loading is a common mechanism of injury in rugby and often occurs in a tackle or scrum position when the cervical spine is compressed between the head and torso with the neck flexed at approximately 30º (Nightingale et al., 2000). Failure and injury of vertebral components occur when compressive loads exceed the cervical spine's absorption capabilities (Swartz et al., 2005). Clinical trials have used CROM as an outcome for the assessment of cervical disorders and whiplash injuries (Strimpakos, 2011a). Therefore, measuring CROM is important for the diagnosis and treatment of cervical spine pathology and rehabilitative practices.

2.9.2 The Effect of Rugby on the Cervical Spine

A systematic review was conducted to determine the primary mechanism of cervical spine injury in rugby (Kuster et al., 2012). The most common injuries were bilateral facet dislocations occurring between C4 and C6 (Kuster et al., 2012). A "buckling" effect of the vertebrae was suggested to occur from compressive loading during impact, causing injury to the cervical spine (Kuster et al., 2012). Another mechanism suggested to cause cervical injury is hyperflexion of the neck, occurring most often in the scrum (Dennison et al., 2012). In French rugby union, the scrum accounted for 51.3% of cervical spine injuries (Bohu et al., 2009). This cause of injury suggests why forwards accounted for 89.2% of cervical spine injuries, of which 56.8% were front row players and 37.8% were hookers (Bohu et al., 2009). This retrospective epidemiological study analysed spinal injuries between 1996-2006 with scrum laws having since developed and become safer (Bohu et al., 2009). The increase in player size over the past 30 years has been correlated with increasing compressive forces acting on front row players during scrum engagement (Preatoni et al., 2013). Front row players absorb greater loads of the scum engagement force than second and back row forwards, which is positively associated with the body mass of the opposing forward pack (Cazzola et al., 2014).

The repeated microtrauma experienced in rugby plays a role in cervical spine degeneration as radiographic evidence showed greater degenerative changes in players involved in higher rates of repetitive loading (Triantafillou, Lauerman & Kalantar 2012). High rates of repetitive loading are most prevalent in front row players, specifically when exposed to compressive and shear forces within the scrum and during tackles (Preatoni et al., 2013). Watson, Hodge and Gekis (2014) found neck pain to be more prevalent amongst forwards than backs, attributed to tackling as the cause of pain. Watson, Hodge and Gekis (2014) relied on retrospective self-reports of neck pain which is subject to recall bias. Secondly, neck pain does not identify or determine the cause of cervical abnormalities.

Static MRI was used to identify cervical spine abnormalities in 127 professional male rugby players, aged between 18 and 38 years (Castinel et al., 2008). Almost half of the players exhibited cervical spine abnormalities, with degenerative lesions being the most prevalent abnormality regardless of age (Castinel et al., 2008). Players older than 21 years exhibited a greater proportion of degenerative discopathy, often associated with disc hernia (Castinel et al., 2008). Players younger than 21 years had a high incidence of cervical spine stenosis (Castinel et al., 2008). Although young, these players had been playing rugby for at least seven years prior, suggesting that these progressive impairments may be attributed to biomechanical factors experienced in rugby.

Degenerative changes observed in rugby forwards were found to exhibit similar CROM profiles to patients with acute whiplash injuries (Dall'Alba, Sterling, Treleaven, Edwards, & Jull, 2001). A functioning CROM is crucial in rugby when passing the ball and scanning the field. With possession of the ball, the upper body and head are typically inclined towards the dominant hand-carrying side (Sayers & Ballon, 2017). Studies suggest that decreased CROM direction may be attributed to handedness, with right rotation to be most affected (Lark & McCarthy, 2009). Yet, previous findings by the same authors found a lesser decline in right rotation than other directions (Lark & McCarthy, 2007). The effect of handedness could not be assessed as so few players were left-hand dominant for comparisons to be made (Lark & McCarthy, 2009).

The effect of a single rugby game on CROM was assessed in 21 male Premiership rugby players (Lark & McCarthy, 2009). The results showed a reduction in all players for all directions, concluding a single game of rugby reduces the neck's functional capacity (Lark & McCarthy, 2009). It could be argued that reductions in CROM were due to muscle stiffness (Vibert et al., 2001), structural damage (Swartz et al., 2005) or game fatigue (Pinsault & Vuillerme, 2010). Therefore, the findings cannot be applied to all games, specifically as the number of impacts and severity were not recorded. A follow-up study assessed changes in CROM over a season in 22 male Premiership rugby players (Lark & McCarthy, 2010). CROM declined for both forwards and backs, with the backs displaying a greater CROM throughout the season (Lark & McCarthy, 2010). The backs exhibited the greatest decrease in left lateral flexion, flexion and extension (-15.4%, -6.6%, and -14.6%, respectively). The forwards exhibited the greatest decrease in flexion, extension and right lateral flexion (-15.4, -8.5% and -13%, respectively). A limiting variable to this study is the small sample size aged between 23 and 25 years (Lark & McCarthy, 2010). Additionally, the findings cannot be generalised to females as they have geometrically and anatomically different necks (Vasavada et al., 2008).

2.9.3 Sex Differences

Researchers studying CROM have reported age and sex as the main influential factors (Pan et al., 2018). It has been accepted that there is a tendency for CROM to decrease with age (Kuhlman, 1993) and conflicting research on the influence of sex (Pan et al., 2018). Studies report females to have greater CROM than males (Kuhlman, 1993), whereas opposing studies report no sex differences (Hole, Cook, & Bolton, 1995). Unlike most research in this field, the strengths of the study by Hole et al., (1995) were the use of similar sex-specific sample sizes, disaggregating the reported results and bridging the gender data gap in CROM research. Although Kuhlman (1993) obtained CROM values of both sexes, the data was not disaggregated when reported. Sex-specific findings should be disaggregated and not generalised into age categories, specifically as women have geometrically different vertebral structures (Vasavada et al., 2008). A recent systematic review reported inconsistent sex differences for directional CROM between age categories (Pan et al., 2018). Pan et al., (2018) reported no sex differences in the 20s age category, whereas males exhibited smaller frontal and transverse CROM in the 30s and 40s age category. Conversely, these authors found males in the 50s age category exhibited greater CROM in all planes and smaller sagittal CROM than females in the 60s age category (Pan et al., 2018).

2.9.4 Cervical Range of Motion Research Methods

Several methods of measuring CROM range in practicality (inclinometers and goniometers) and accuracy (radiographic and 3D electromagnetic technologies). Despite various limitations, one choice of method may be deemed more appropriate than another for certain studies. Nonetheless, all methods must be reliable and valid. Youdas, Carey, & Garrett (1991) compared the CROM device, universal goniometer (UG) and visual estimation (VE) on 60 patients. The CROM device exhibited the greatest intertester ($0.84 < ICC < 0.93$) and intratester reliability ($0.73 < ICC < 0.92$) for all measurements of active range of motion. The application of the CROM device is easy to mount on the head without the variance of anatomical landmark location. The UG predominantly exhibited high intertester ($0.78 < ICC < 0.90$) and good intratester reliability ($0.54 < ICC < 0.79$). VE predominantly exhibited poor intratester reliability ($0.42 < ICC < 0.70$). The UG and VE techniques rely on anatomical landmark location which may explain the lower ICC scores.

A systematic review investigated the reliability and validity of CROM methods (Williams, McCarthy, Chorti, Cooke, & Gates, 2010). The CROM device was the most prevalent method across research and the most reliable (Williams et al., 2010). Other devices evaluated with “good” reliability and validity were the Spin-T goniometer and single inclinometer (Williams et al., 2010). VE was shown to have the least reliability and validity across the studies reviewed (Williams et al., 2010). Another method of measuring CROM is the calculation of head-neck kinematics using 3D motion capture. Computer graphic biomechanical models demonstrate the kinematic analysis of the musculoskeletal joints and theoretical join motions (Richards, 1999). The accuracy of 3D motion capture is high, with a location error of less than 1mm (Richards, 1999). However, it requires the anatomical positioning of landmark markers, which increases the chance of palpation error. Although reliable, the CROM device, electromagnetic motion analysis and radiographic estimation may be impractical in research settings as they can be cumbersome, time-consuming, expensive, require specialist raining or involve radiation exposure. Thus, the design of a new CROM measure that is inexpensive, readily available and reliable is warranted.

2.10 Summary

Rugby union is traditionally a male dominated sport. The women's game is the fastest growing area of rugby union worldwide, with an estimated 2.8 million active participants (World Rugby, 2019). Despite the growing participation, women are chronically understudied in rugby union research (Costello et al., 2014). Existing research predominantly investigates male participants (Hendricks et al., 2020), which are extrapolated to female populations. This is despite a lack of empirical evidence to support the efficacy and generalisability, given the anthropometrical, physiological and geometric differences. This begs the question whether safety protocols based on androcentric research, such as current World Rugby recommendations, are appropriate for female rugby players.

There is sparse data exploring the changes in CROM over a season and how it correlates with neck strength for male and female university athletes. Exploring neck strength and its preventative function against injuries and concussion will accentuate the importance of strengthening the neck as part rugby training programmes. As neck injury has potential catastrophic effects, preventative actions to limit the associated risks will be a major health benefit to players participating in rugby and other contact sports.

Measuring neck length is important in head impact research for the calculation of forces and moments on the neck. There is no ISAK anthropometric standard of measuring neck length (Norton, 2019). This has resulted in varying methods of measuring neck length in literature and warrants the design of a reliable, repeatable and valid technique.

Previous methods of measuring CROM may be impractical in a clinical setting as they can be cumbersome, time consuming, expensive, require specialist raining or involve radiation exposure. The limitations and barriers of choosing various CROM measurement techniques warrants the design of a new methodology for this research project.

CHAPTER 3: Methodology

3.1 Methodology Overview

This thesis involved an observational, longitudinal study, comparing anthropometrics and the functional properties of the head and neck between male and female university rugby players. Anthropometric, neck strength and cervical range of motion (CROM) data were collected for study participants. In addition, as the current ISAK measurement guidelines do not include neck length (Norton, 2019), a novel neck length measurement method was designed. A second novel methodology was also developed to enhance the reliability of existing CROM measurement procedures.

3.2 Participant Recruitment and Ethical Approval

Three cohorts of healthy volunteers were recruited from the Swansea University Rugby Football Club. Participants were either members of the men's 1st rugby union team (*n*=27), the women's 1st rugby union team (*n*=24) and the men's 1st rugby league team (*n*=10). The participants were aged between 18 and 24 years; male union (20.5±1.3 yrs), female union (20.4±2.0 yrs) and male league (20.6±1.5 yrs). The three cohorts were further grouped into forwards (male union *n*=12, female union *n*=10, male league *n*=3) and backs (male union *n*=15, female union *n*=14, male league *n*=7). Healthy male (*n*=2) volunteers (23.5±2.5 yrs), who did not partake in contact sports, were recruited through Swansea University for the CROM validation study.

Ethical approval was obtained through Swansea University College of Engineering, reference 2016-059, Amendment 6.0.

Prior to participation, participants were briefed about the research background and aims via a PowerPoint presentation, followed by a question-and-answer session. All participants read an additional information sheet and signed a corresponding consent form, agreeing that their confidentiality was maintained. Each participant completed pre-exercise questionnaires (PARQs) which included sporting and injury history, including concussion. Participants were excluded if they had a current neck injury, neck pain and/or if they were receiving medical treatment for their cervical spine, shoulder or head-neck region. Only rugby union players were included in the anthropometric measurement and neck strength testing. CROM testing included both rugby league and rugby union participants.

3.3 Anthropometric Measurements

Pre-season measurements of neck circumference, head circumference, shoulder breadth, body height and body mass were recorded using methods recommended in the current ISAK guidelines, summarised in Table 1 (Norton, 2019). One replicate was recorded for height and body mass. Three replicates were performed for the other variables, recorded to the nearest millimetre.

Table 1 ISAK measurement methods (Norton, 2019) for anthropometric variables used in this thesis, excluding neck length.

Anthropometric Variable	Measurement Method
Neck circumference (cm)	Anthropometric tape, participant seated upright, with tape encircling the neck just below the larynx.
Head circumference (cm)	Anthropometric tape, participant seated upright, holding tape between the eyebrows, above eyebrow line.
Shoulder breadth (cm)	Sliding callipers, participant seated upright, measured at end-tidal expiration, between the most lateral points of the acromion processes. Firm pressure compressing overlying tissue.
Height (cm)	Stadiometer (Seca 225), participant standing erect with eyes facing forward.
Body mass (kg)	Electric weight scales, participant standing erect with eyes facing forward.

3.4 Neck Strength Testing Equipment

A bespoke isometric neck strength testing apparatus (INSTA) was developed for this and parallel studies. The INSTA was based on the design by Salmon et al., (2014) with a number of modifications. A description of the specifications of the INSTA is provided in Appendix-A. The INSTA was used to test all rugby union participants in a simulated prone contact position. The prone testing position was designed to mimic the posture exhibited when approaching a tackle position or during a scrum. The neck in a neutral posture with horizontal torso was deemed functionally relevant for game-play postures in rugby. Additionally, a neutral cervical spine posture facilitates the force-generating capacity of the neck musculature and reduces the risk of injury (Strimpakos, 2011b).

The INSTA consisted of a padded bench, a headpiece rig structure with four inward-facing load cells, knee platform, and harnesses. The four calibrated load cells (Tedea-Huntleigh 1022, 50 to 150 kg capacity) were cushioned with thin neoprene pads to prevent injury and facilitate force application. The headpiece was adjustable to ensure the load cells aligned inferiorly on the supraorbital ridge, superiorly above the occipital protuberances and above the external auditory canal of the ear (Figure 1). Measurement settings were recorded for each participant to ensure repeatability of position for subsequent testing sessions. The INSTA was designed to achieve repeatable, reliable and valid isometric flexion (Flx), extension (Ext), left lateral flexion (LtFlx) and right lateral flexion (RtFlx) neck strength data collection. Key components of the neck strength testing rig are illustrated in Figure 1.

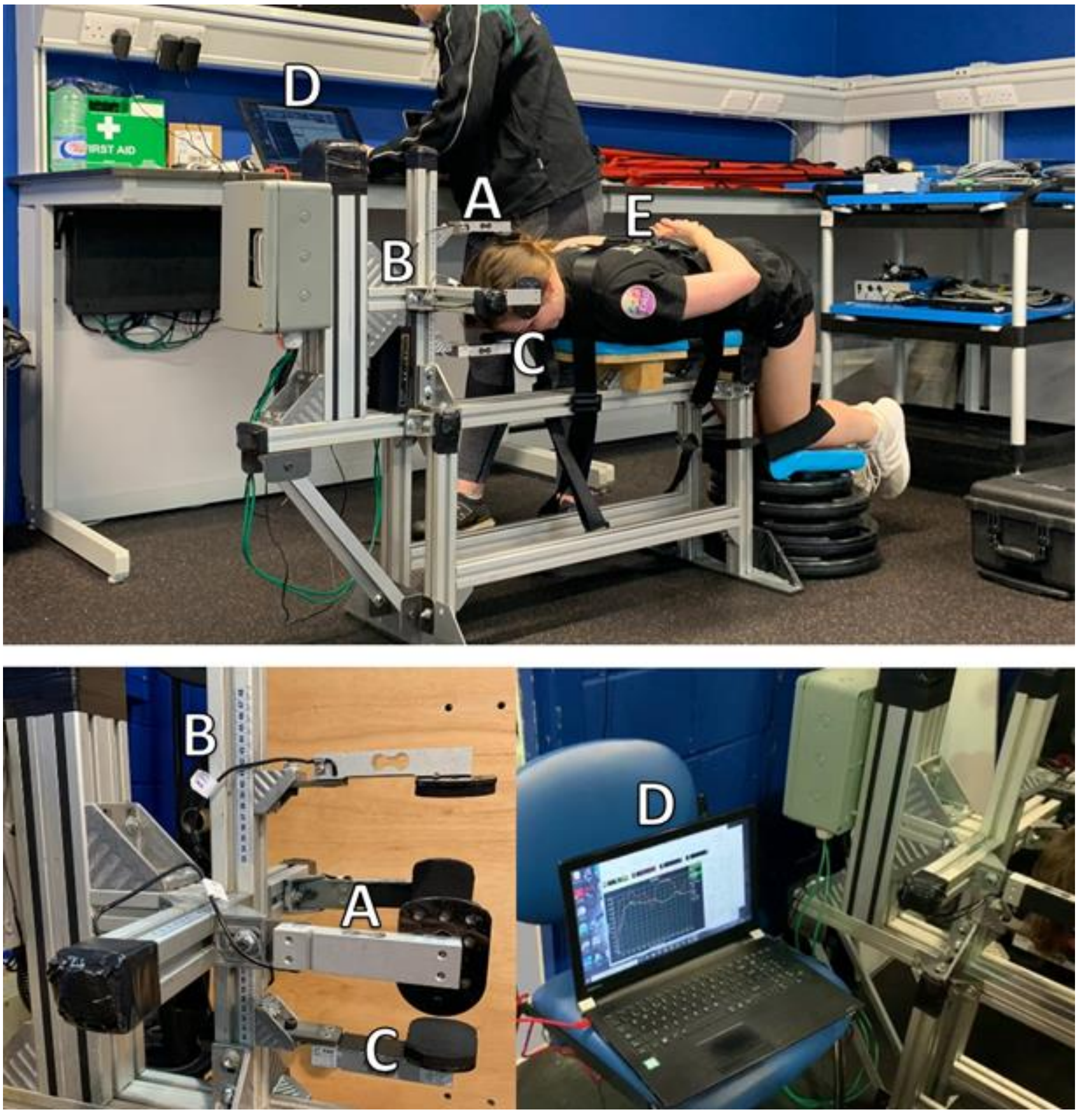

Figure 1 Key components of the isometric neck strength testing apparatus showing: the four inward-facing load cells (A), adjustability settings of load cells (B), neoprene pads (C), the connected laptop computer (D) and four-point car racing harness (E), restricting accessory muscle involvement.

3.5 Neck Strength Testing Procedures and Protocols

3.5.1 Neck Strength Familiarisation Sessions

Lim, Benbasat, & Todd (1996) suggested that test results may differ considerably between initial and subsequent testing sessions due to the learning effect associated with task familiarisation. To minimise the influence of the learning effect on any improvements between baseline and mid-season values, neck strength testing familiarisation sessions were conducted prior to baseline measurement sessions. These familiarisations sessions also served to acquaint participants with the testing requirements and help researchers to further refine procedures.

Testing procedures should be efficient, consistent, and succinct to limit variance in the results. During familiarisation sessions, the timing and length of rest breaks between sets and repetitions were refined and standardised for all participants. The optimal duration for maximum MVC measurement was also established as three-seconds. The efficacy of two motivational strategies was also assessed during these trials. Positive reinforcement and motivational techniques were successful in obtaining greater MVC scores through positive feedback and verbal encouragement (Duda, 2007). Competitive motivational strategies were also successful in achieving greater MVC scores (Duda, 2007). This was achieved by informing participants that an unnamed teammate obtained a greater MVC score by 100 N after their first replicate in each direction. Researchers also practiced adjusting the INSTA during the familiarisation trials to ensure proficiency ahead of the baseline measurement sessions. A fan was also added to the apparatus to cool the participants down as perspiring was observed.

Neck strength testing procedures were systematically controlled where possible to reduce data variability. Pre, mid and post season testing per participant was instructed by the same researcher during similar times of the day. All researchers followed the neck strength testing protocol detailed in Appendix-B.

3.5.2 Neck Strength Testing Session Protocols

When participants arrived at the laboratory for baseline and mid-season neck strength sessions, the following procedures were conducted:

i. Researchers asked for participant's current neck pain and injury status. No testing was conducted on any participant reporting pain or injury.
ii. A standardized, supervised warm-up of the upper back and neck musculature was undertaken by all participants. This included an aerobic component on a rowing ergometer and sequential shoulder and neck activation exercises consistent with Salmon, Sullivan, Handcock, Rehrer, & Niven, (2018). Participants then performed prone chin-tuck isometric protractions and retractions for three repetitions of ten seconds before being set up on the INSTA.
iii. The INSTA was adjusted specifically for each participant, as described in Chapter 3.4 and Appendix-A. Each participant's torso was then securely strapped to the bench with a four-point racing harness and their upper legs strapped to the

INSTA above the knee with a seatbelt. INSTA settings were recorded for each participant to maintain standardized procedures for pre, mid and post season testing.

iv. To re-familiarise with the INSTA, participants were instructed to perform 50% of their MVC in each direction twice for three seconds with 20 seconds rest between directions. Rapid and forceful jerking into the load cells can cause injury (Salmon et al., 2015), so participants were informed to avoid jerking and instead to gradually reach their MVC within the three second timeframe. The maximal strength testing then commenced.

3.5.3 Maximal Strength Testing

The direction of contraction was randomly ordered per participant (Flx, Ext, LtFlx and RtFlx). Isometric MVCs were held for three repetitions of three seconds in each direction. A 30 second rest interval was timed between trials and a 60-second interval between each direction for participants to recover. The competitive and positive reinforcement motivational strategies were implemented during each effort. Previous research has also reported verbal encouragement to have a positive effect on scores (Salmon et al., 2015). The peak force was measured in Newtons (N).

3.5.4 Endurance Strength Testing

Neck strength endurance testing was carried out 20-minutes after the MVC testing. The direction of contraction was randomly ordered per participant. Participants were instructed to sustain one isometric contraction for as long as possible at 70± 5% of their MVC. A rest interval of two minutes was timed between each trial for participants to recover. Participants had the option of having visual and verbal aids for maintaining the required force. Verbal aids involved the researchers informing the participants to push harder or softer. Visual aids involved bringing the computer screen in view of the participant, so they could see their force production on the real-time graph. The maximum amount of time held at 70±5% of their MVC was recorded. Competitive motivational strategies were implemented throughout testing.

Participants were debriefed and informed to stretch as per the same procedure in the standardized warm-up. During a three day follow up period, participants were instructed to inform a member of the research team or medical staff if they experienced any neck pain or discomfort.

3.6 Neck Strength Training

3.6.1 Neck Strength Training Overview

All rugby union players underwent neck strengthening over the university rugby season as part of their gym-based strength and conditioning program. Neck strengthening was consistently scheduled for three days a week throughout the season. The neck strength programme consisted of two phases: isometric resistance training (Appendix-G) and dynamic weight training (Appendix-H). Within each phase, players would progress through stages increasing in difficulty, with expert supervision.

Figure 2 Dynamic neck strength pulley system with a player performing extension.

Player compliance regarding strength and conditioning session attendance varied, affecting the progression rates within the team. All players completed Phase 1 between pre-season and mid-season. Phase 2 of the neck strengthening program included dynamic neck strength using a pulley based on previous research (Naish, Burnett, Burrows, Andrews, & Appleby, 2013). Dynamic weight training consisted of an adjustable head harness attached to a cable holding weights through a pulley system (Figure 2). Availability of the pulley apparatus delayed the commencement of

Phase 2 between mid-season and post-season. Few players progressed to Stage 2 of Phase 2 due to COVID-19 restrictions terminating training prematurely.

3.7 Design of a Cervical Range of Motion Testing Method

3.7.1 Cervical Range of Motion Method Design Aims

Previous methods of measuring CROM may be impractical in a clinical setting as they can be cumbersome, time consuming, expensive, require specialist raining or involve radiation exposure. The limitations and initial inaccessibility of various CROM measurement techniques prompted the design of a new methodology for this research project. In brief, the development of a new CROM measurement method involved the measurement of CROM using ImageJ software (ImageJ, US National Institutes of Health, Bethesda, Maryland, United States) and the design of a fixed harness apparatus to restrict upper body movement. The purpose of this sub-study was to validate a new repeatable method of measuring CROM using the CROM device as a reference standard (Williams et al., 2010). Range of motion was assessed in the frontal (lateral flexion), sagittal (flexion and extension) and transverse (rotation) plane. Directional CROM entailed flexion (Flx), extension (Ext), left lateral flexion (L-Lflx), right lateral flexion (R-Lflx), left rotation (L-Rot) and right rotation (R-Rot). Additionally, important criteria to fulfil were easy application, efficient application, available to users and inexpensive.

3.7.2 ImageJ Cervical Range of Motion Measurement Method Design

CROM was measured using three video cameras in each plane (frontal, sagittal and transverse) to avoid parallax error. The cameras were situated at controlled distances on tripods in each measurement plane. An adjustable scrum cap was worn by participants throughout testing. The scrum cap had vertical and horizontal reference lines used for ImageJ processing purposes. A fixed calibration reference scale was placed on the scrum cap for pixels per millimetre to be calculated on ImageJ. Videos were processed using ImageJ software for the calculation of angular distances by triangulation.

Table 2 Apparatus components and justification for the ImageJ method of measuring cervical range of motion labelled in Figure 3

Apparatus Component	Justification
Camera (Panasonic Lumix TZ70)	• Each plane limits parallax error • Easy application • Available device • Repeatable application
Tripod	• Fixed placement - repeatable protocol set-up
Scrum cap	• One scrum cap - repeatable protocol set-up
Measurement tape	• Reference line (A) • Calibration measurement reference (25mm) (B)
ImageJ	• Calculate triangulation • Limits measurement error • Free, open source software • Repeatable calculations • Precise measurements

Figure 3 ImageJ methodology set-up representation of right lateral flexion harnessed within the cervical range of motion board apparatus, justified in Table 2.

3.7.3 Harness Board Apparatus

The purpose of the harness and board apparatus was to restrict movement of the body during testing. Movement of the shoulders and torso can contribute to greater measured cervical range of motion, so limiting this is required. The four-point car racing harness increases the repeatability and accuracy of the method design by controlling for extraneous variables.

With participants stood upright, the harness board was adjusted to their shoulder height, ensuring full CROM in the frontal plane. Clamps secured the board to the squat rack bars. Participants were instructed to stand with their back against the wooden board with harnesses fastened. Adjustments to the four-point harness were made to secure the upper body in place and restrict movement. The four-point harness could be unbolted to wider or smaller span widths, adjusting for all body sizes.

Table 3 Apparatus design and justification for a new method of measuring cervical range of motion illustrated in Figure 4

ID	Apparatus component	Justification
A	Wooden board clamped to a standard squat rack	• Ensures vertical positioning of the participant with upper body movement restricted
B	Clamps	• Adjusted to the participants height • Easy application
C	4-point car racing harness	• Upper body movement restricted • Easy application
D	Nuts and bolts	• Position of harness adjusted to each participant
E	Squat rack	• Ensures vertical positioning of wooden board and participant • Availability

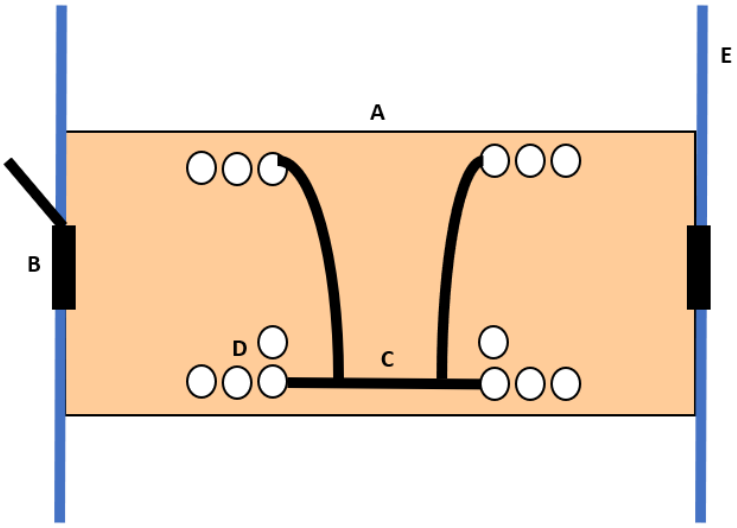

Figure 4 Diagram of the harness board apparatus with justification of components described in Table 3.

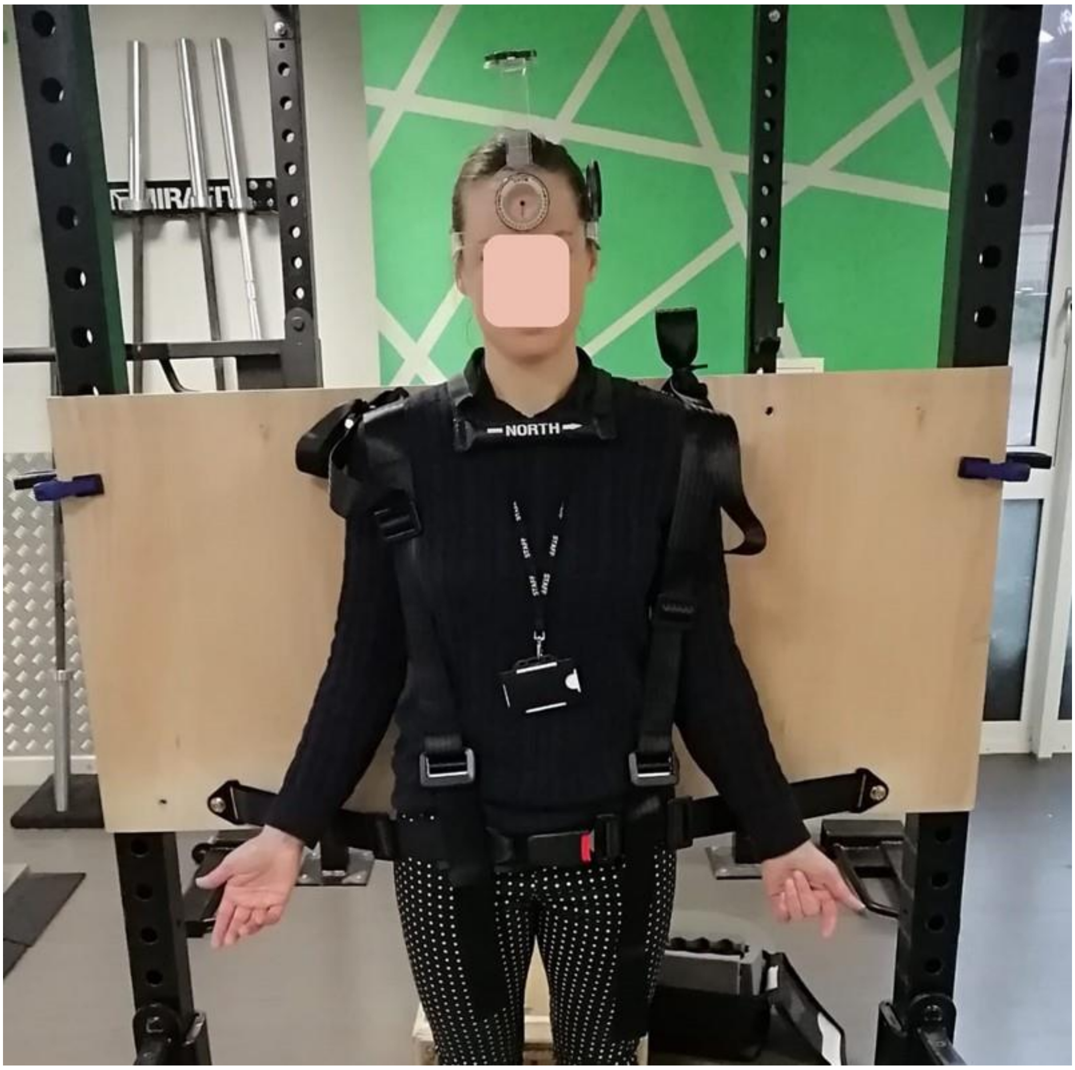

Figure 5 Photo showing a participant strapped to the harness board apparatus using the CROM device to measure cervical range of motion.

3.7.4 Cervical Range of Motion Validation Testing

The CROM device has been found to be a valid, reliable and accepted method of measuring CROM (Williams et al., 2010). The CROM device was compared with measurements performed using ImageJ to test for concurrent criterion validity. Prior to testing, pilot studies were conducted to become familiar with testing procedures and apparatus. The protocol set-up was consistent throughout testing sessions and adjustments to the harness apparatus were noted. CROM was measured using both the CROM device and ImageJ on the same participants at two different time points (Testing 1 and Testing 2). Three repetitions of CROM were measured per movement direction (Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot). Researchers followed the experimental procedure ensuring systematic and controlled testing for each method, detailed in Appendices C and D.

3.7.5 Cervical Range of Motion Validation Testing Statistical Analysis

All data was normally distributed and analysed using the ICC. A two-way mixed-effects model based on single measures and absolute agreement assessed the intratester repeatability for the CROM device and ImageJ method. Mean estimations along with 95% confidence intervals were reported for each ICC. Interpretation was as follows: "poor" (ICC < 0.5), "moderate" (0.5–0.75), "good" (0.75–0.9) and "excellent" (ICC > 0.9). Bland-Altman analysis determined the systematic bias and 95% limits of agreement (LOA) in CROM test (trials 1–3) and re-test trials (trials 4–6) per measurement method. One-sample t-tests were conducted to assess the level of agreement within each CROM method between test and re-test trials. Statistical results from Bland-Altman plots and Pearson correlation coefficients (R^2) are presented in Chapter 4.6.

The coefficient of variation for CROM methods was calculated to identify agreement between methods across testing sessions. Individual CROM Device and ImageJ coefficient variation for directional CROM per participant is presented in Table . Combined method coefficient variation for directional CROM per participant is presented in Table .

A two-way mixed-effects model based on single measures and absolute agreement assessed the intratester reliability between the CROM Device and ImageJ method. Bland-Altman analysis determined the systematic bias and 95% limits of agreement in average CROM between the CROM device and ImageJ. One-sample t-tests were conducted to assess the level of agreement between the CROM device and ImageJ method. Statistical results from Bland-Altman plots and Pearson correlation coefficients (R^2) are presented in Chapter 4.6.5.

Both methods using the CROM device and ImageJ technique had good intratester and intertester reliability with the use of the harness apparatus. Since the development of this research project, the CROM device became accessible for data collection. Despite validating a new method of measuring CROM using ImageJ, the CROM device was chosen for this research project. This method was modified with the addition of the harness board to eliminate extraneous variables caused by upper body movement.

3.8 Cervical Range of Motion Testing

3.8.1 Testing Session Protocols

CROM testing procedures were systematically controlled where possible to reduce data variability. All researchers followed the CROM testing protocol outlined below and detailed in Appendix-C. The ImageJ method followed the same protocol without the use of the CROM Device. Instead, video recordings were taken in each movement plane, as described in Appendix-D.

3.8.2 Cervical Range of Motion Tests

Participants were instructed to stand vertically upright, straight back, feet shoulder width apart and hands hanging beside their body (Figure 5). CROM was tested in the following directions: Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot. For each test, participants were instructed to move their head in the relevant direction, until they reached the end of their active range. Researchers ensured participant’s shoulders remained in a fixed position and no torso movement occurred throughout the movement. Three replicates were measured in each direction and participants were instructed to return to the neutral position after each. Participants were debriefed following testing and informed to stretch as per the same procedure in the standardized warm-up.

The pre-testing protocols described in Chapter 3.5.2: discussion of pain and injury, warm up, equipment adjustment and familiarisation, were also used for CROM testing. The harness board was adjusted for the participant’s height (Chapter 3.7).

Participants were instructed to place the CROM device on themselves as if it were a pair of glasses, which was then secured in place with a Velcro strap by the researcher. Magnetic yokes were placed around the participants neck with Velcro straps for cervical rotation only. Participants were instructed to practice the CROM movements to become familiar with the CROM device on their head whilst fastened into the harness.

3.9 The Development of a Neck Length Measurement Method

3.9.1 Novel Neck Length Measurement Method Rationale

There is no ISAK anthropometric standard of measuring neck length (Norton, 2019), resulting in varying methods being reported in the literature. Some of these may be impractical in a clinical setting, too expensive, require specialist training or involve radiation exposure (Ahmed et al., 2020; Han et al., 2015; Harty et al., 2004; Tabaee et al., 2005). The purpose of this exercise was to design a new repeatable, accurate and reliable method of measuring neck length. Intertester and intratester reliability was assessed with qualified anthropometrists to determine the most repeatable and reliable method of measuring neck length to be proposed as a standard measure.

The four neck lengths chosen to be assessed were deemed appropriate for a rugby playing population (Figure 6). For example, neck lengths requiring the location of C7 were excluded due to difficulty in digitally identifying the bony landmark on a front-row player with a large body mass. L1 was the distance between the sternal notch and the temporomandibular joint. L2 was the distance between sternal notch and the upper margin of the hyoid bone. L3 was the distance between sternal notch and the external acoustic meatus. L4 was the distance between the mid-point portion of the ipsilateral clavicle and the mandibular angle. The harness board apparatus controlled for extraneous variables ensuring players exhibited straight backs throughout testing. The board apparatus and camera set-up ensured consistent protocol procedures, increasing method reliability and repeatability. ImageJ is an inexpensive technique, providing repeatable calculations and precise measures. This technique is readily available for researchers in comparison to expensive MRI techniques which require specialist training.

3.9.2 Neck Length Validation Testing

Researchers were instructed to follow the experimental procedure, ensuring systematic and controlled testing for neck length measurements (Appendix-E). Regrettably, the neck length validation testing was inconclusive due to COVID-19 restrictions. The most repeatable and reliable anatomical locations defining neck length (L1, L2, L3 or L4) could not be determined.

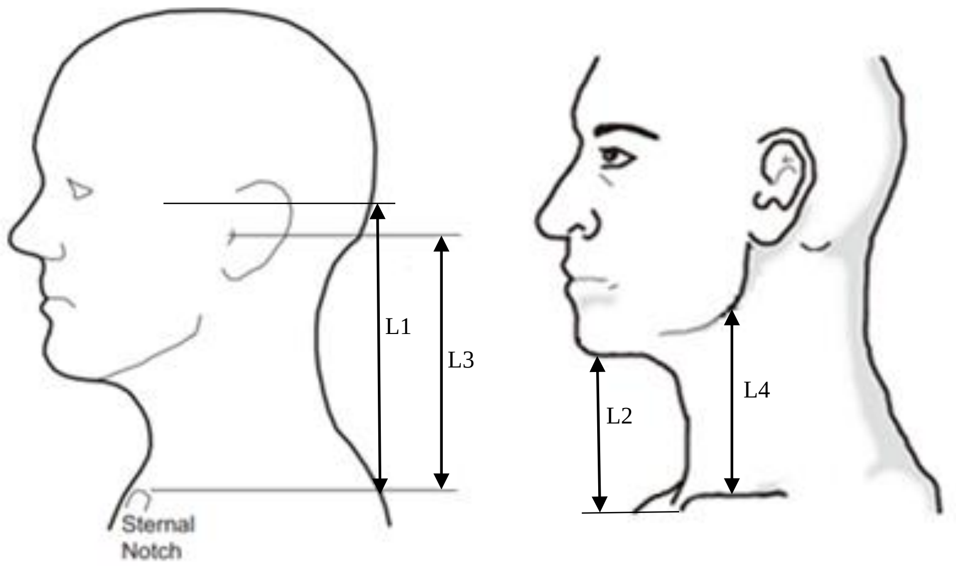

Figure 6 Anatomical landmark locations of four neck lengths, adapted from Han et al., (2015) and Vasavada et al., (2008).

Table 4 Apparatus components and justification for the ImageJ method of measuring neck length

Apparatus Component	Justification
Camera (Panasonic Lumix TZ70) and tripod	• Sagittal plane • Efficient application • Available method • Repeatable measurements • Repeatable protocol set-up
Measurement tape	• Calibration measurement reference (25mm)
ImageJ	• Limits measurement error • Free and available software • Repeatable measurements • Precise measurements • Accurate measurements
Harness board apparatus	• Ensures straight back • Consistent protocol setup in line with camera

3.10 Statistical Analyses

All data were screened for normality and appropriate parametric or non-parametric tests were used accordingly. Male and female rugby union cohorts were compared for this analysis. Positional groups refer to forwards and backs and were compared within each cohort.

3.10.1 Descriptive Statistics

Body mass and height of participants were compared between male and female cohorts, and positional differences within each cohort. Independent t-tests were conducted to compare head circumference, neck circumference and shoulder girth between the male and female cohorts. Independent t-tests were conducted to compare forwards and backs within each cohort for head circumference, neck circumference and shoulder girth. A Spearman's correlation was conducted to assess the relationship between neck strength and neck circumference for all participants, presented separately for the male and female cohorts (Chapter 4.1)

3.10.2 Baseline Neck Strength Testing

Absolute and relative neck strength were compared between cohorts assessing sex and within cohorts assessing positional differences. Mann-Whitney U tests were conducted to compare absolute average neck strength between cohorts and independent t-tests to compare relative average neck strength between cohorts (Chapter 4.2.1). Univariate MANOVA tests were conducted to compare positional differences in absolute and relative directional neck strength within each cohort (Chapter 4.2.2).

Absolute values of sagittal and frontal neck strength were assessed for within-plane symmetry per cohort (Chapter 4.2.3). Dependent t-tests were conducted to compare differences between LtFlx and RtFlx neck strength for frontal plane symmetry. Equally, dependent t-tests assessed differences between Flx and Ext neck strength for sagittal plane symmetry. Between-plane neck strength symmetry was assessed per cohort (Chapter 4.2.3). Dependent t-tests were conducted to compare the sum of Flx and Ext neck strength with the sum of LtFlx and RtFlx neck strength within each cohort. Wilcoxon Signed Rank tests were conducted to compare Flx-Ext neck strength differences with LtFlx-RtFlx neck strength differences. Neck strength symmetry were compared between male and female cohorts. Mann-Whitney U tests were conducted to compare frontal symmetry between cohorts and sagittal symmetry between cohorts.

3.10.3 Baseline Neck Strength Endurance Testing

Absolute neck strength endurance was compared between cohorts (Chapter 4.3.1) and within cohorts assessing positional differences (Chapter 4.3.2). Independent t-tests were conducted to compare average isometric neck strength endurance between male and female cohorts. A Mann-Whitney U test was conducted to compare average isometric neck strength endurance between forwards and backs within the male cohort. Similarly, an independent t-test was conducted to compare average isometric neck strength endurance between positional groups within the female cohort.

3.10.4 Cervical Range of Motion Testing

Group differences were assessed per sporting cohort; male rugby union, female rugby union and male rugby league (Chapter 4.4.1). An independent ANOVA was conducted to compare differences in average CROM between the three groups. Gabriel Post hoc tests were conducted due to unequal sample size groups.

Positional differences in CROM were assessed within each cohort (Chapter 4.4.2). A MANOVA was conducted to compare differences in Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot between forwards and backs within the male cohort. Similarly, a Kruskal-Wallis test was conducted to compare differences in directional CROM between positional groups within the female cohort.

CROM symmetry was assessed within the male and female cohorts (Chapter 4.4.3). Dependent t-tests were conducted to compare sagittal (Flx and Ext differences), frontal (L-Lflx and R-Lflx differences) and transverse (L-Rot and R-Rot differences) plane symmetry within each cohort. Dependent t-tests were conducted to compare sagittal (sum of Flx and Ext), frontal (sum of L-Lflx and R-Lflx) and transverse (sum of L-Rot and R-Rot) CROM within each cohort.

3.10.5 Integrated Analysis

Appropriate parametric (Pearson's) and non-parametric (Spearman's rho) correlational analyses were conducted to assess for associations between neck strength and CROM within the male and female cohorts (Chapter 4 and Appendix-F). Absolute average neck strength and average CROM were assessed for associations within each cohort. Likewise, average neck strength endurance and average CROM were assessed within each cohort. Absolute directional neck strength was assessed with their directional CROM counterpart within each cohort. Correlational analyses were conducted to assess for associations between average CROM and absolute neck strength symmetry in each plane; sagittal (Flx and Ext differences), frontal (L-Lflx and R-Lflx differences) and transverse (L-Rot and R-Rot differences).

3.10.6 Powers Analysis

Limited recruitment availability within the university rugby cohort lacked powers analysis for this research project.

CHAPTER 4: Results

Results Overview

Rugby player anthropometric, neck strength and CROM results are presented in Chapters 4.1, 4.2, 4.3, and 4.4 respectively. The interaction between neck strength and CROM is presented in Chapter 4.5. The novel CROM measurement method validation results are presented in Chapter 4.6. All data were screened for normality using the Shapiro-Wilk test and appropriate parametric or non-parametric tests were used accordingly. Mean ± standard deviation, and median ± interquartile range are presented for parametric and non-parametric tests respectively.

4.1 Descriptive Data and Anthropometric Results

Mann-Whitney U tests found no significant sex difference in age for rugby union players (U=123.5, p=.317). Male players, however, had significantly more years of playing experience (13.1 ± 2.5 years, range 7 to 16 years) than females (5.2 ± 3.3 years, range <1 to 15 years; U=9.5, p<0.05). Descriptive statistics of baseline anthropometrics of forwards and backs for male and female players are displayed in Table . The Mann-Whitney U test revealed males to be significantly heavier than females p<.001, U=62.000, z=-4.251. Independent t-tests revealed males to be significantly greater in height than females t(41)=9.072, p<.001. Distributions of head-neck anthropometrics of male and female rugby players are illustrated in Figure 7.

Independent t-tests revealed males to have significantly greater head circumference (t(32)=3.456, p=.002), greater neck circumference (t(44)=9.407, p<.001), and greater shoulder breadth (t(44)=7.612, p<.001) than females. The differences between the average male and female head and neck circumferences were 3.01 cm (5.5%) and 7.4 cm (17.6%) respectively. Neck circumference was calculated as a percentage of head circumference, giving 71.6 ± 3.4% for males and 62.2 ± 2.8% for females. An independent t-test showed these differences to have greater significance (t(44)=8.863, p<.001).

Independent t-tests were conducted to assess positional differences. There were no significant positional differences among females for body mass, t(7)=2.226, p=.063, or height t(17)=-.126, p=.901 (Table). For male forwards, body mass (t(24)=3.017, *p*=.006) and body height (*t*(24)=2.913, *p*=.008) were significantly greater than male backs.

There were no significant positional differences among between forwards and backs for head circumference, *t*(25)=.035, *p*=.972, or shoulder breadth, *t*(25)=1.076, *p*=.292, in males, or head circumference for females (*t*(17)=1.378, *p*=.186). Female forwards had significantly greater neck circumference (37 ± 2 cm) and shoulder breadth (40 ± 2 cm) than female backs (34 ± 1 cm, and 38 ± 1 cm respectively, *t*(17)=4.208, *p*=.001, and *t*(8)=2.337, *p*=.046 respectively).

Table 5 Body mass and height of male (n=27) and female(n=19) rugby union forwards and backs

Sex	Group	Body Mass (kg)	Height (cm)
		Mean ± SD	*Mean* ± SD
Male	Forwards	112.85 ± 27.65	189.42 ± 9.48
	Backs	88.13 ± 10.98	180.27 ± 5.85
Female	Forwards	84.01 ± 8.28	164.77 ± 5.48
	Backs	66.96 ± 5.75	165.08 ± 4.55

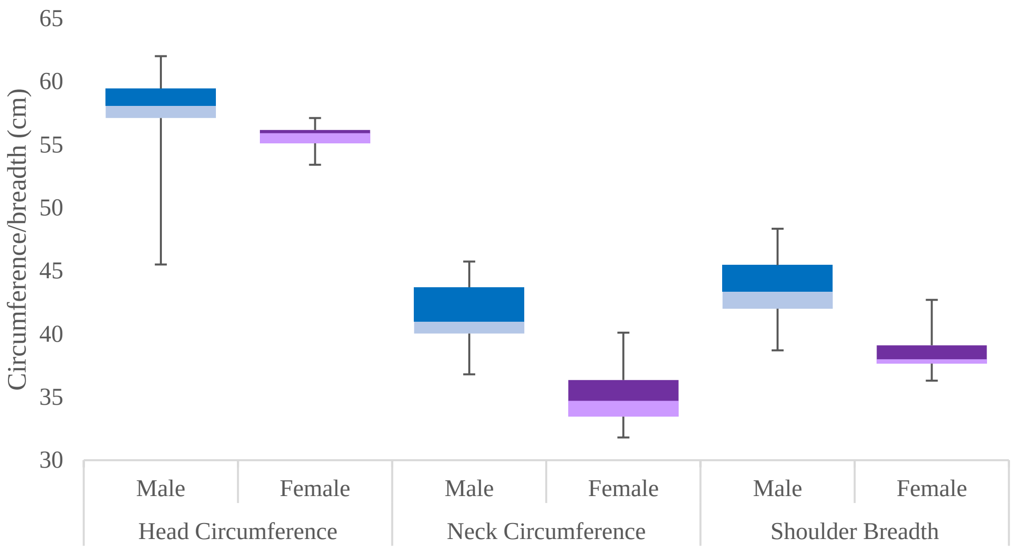

Figure 7 Baseline distribution of head circumference, neck circumference and shoulder breadth between male and female rugby union players.

4.2 Sex Differences in Neck Strength

4.2.1 Baseline Neck Strength

For rugby union participants, absolute and relative baseline neck strength values for each direction are presented in Table 6. Relative strength is calculated as Newtons per kilogram of body mass. A Mann-Whitney U test revealed males to have significantly greater absolute baseline neck strength (219 ± 64 N) than females (129 ± 23 N), *p*<.001, *U*<.001, *z*=-5.162. Independent t-tests revealed males to have significantly greater average relative neck strength (2.62 ± 0.49 N/kg) than females (2.17 ± 0.28 N/kg), *t*(41)=3.869, *p*<.001.

A Spearman's rho test showed a significant positive correlation between neck circumference and average absolute neck strength in male rugby players, (r^2(22)=0.230, *p*=.024, Figure 8). No significant associations were observed in females (r^2(16)=0.353, *p*=.180).

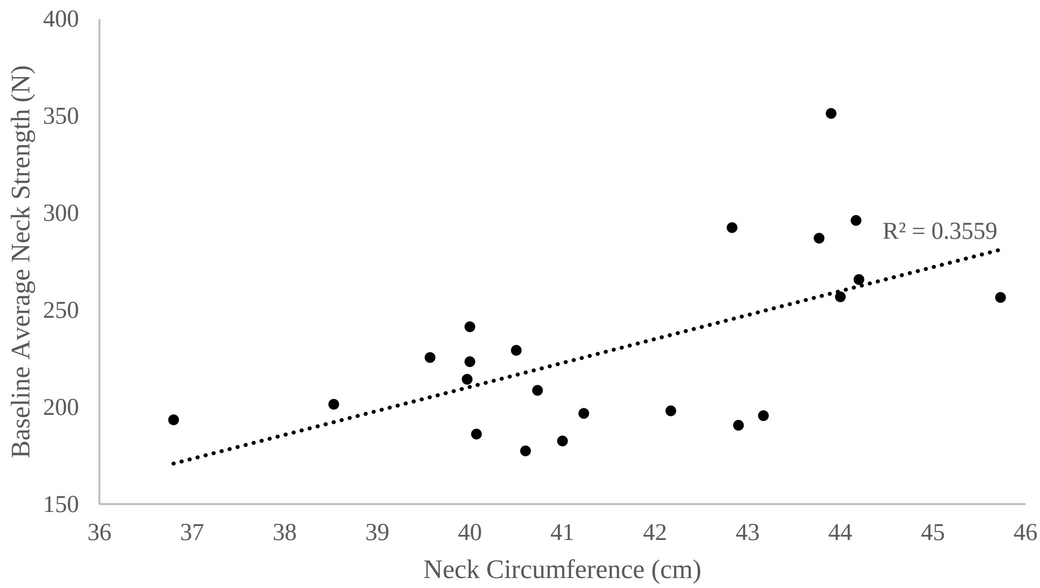

Figure 8 Spearman's rho correlation of neck circumference (cm) and baseline absolute average neck strength (N) in male rugby players.

4.2.2 Positional Differences in Absolute and Relative Directional Neck Strength

Independent t-tests revealed male forwards (254±50 N) to have significantly greater average absolute neck strength than male backs (211±32 N), *t*(20)=2.501, *p*=.021. Univariate MANOVA tests revealed forwards to have significantly greater LtFlx than backs (*F*(1,20)=10.084, *p*=.005). There were no other absolute directional neck strength differences between forwards and backs for Flx (*F*(1,20)=2.864, *p*=.106), Ext (*F*(1,20)=1.035, *p*=.321) and RtFlx (*F*(1,20)=3.740, *p*=.067). There were no significant positional differences in female players for average absolute neck strength (*t*(19)=1.435, *p*=.168). Univariate MANOVA tests confirmed no positional differences for directional strength in female players for Flx (*F*(1,19)=0.452, *p*=.509), Ext (*F*(1,19)=2.402, *p*=.138), LtFlx (*F*(1,19)=0.919, *p*=.350) and RtFlx (*F*(1,19)=0.688, *p*=.417). Thus, positional differences in neck strength were identified within males but not females.

Table 6 Absolute and relative baseline maximal neck strength between forwards and backs for male (n=22) and female (n=21) rugby union players

Direction	Position	Male		Female	
		Absolute	Relative	Absolute	Relative
		Mean ± SD *(N)*	*Mean* ± SD *(N/kg)*	*Mean* ± SD *(N))*	*Mean* ± SD *(N/kg)*
Flx	Forwards	296 ± 57	3.26 ± 0.68	149 ± 22	2.48 ± 0.35
	Backs	255 ± 58	2.95 ± 0.61	142 ± 24	2.45 ± 0.42
Ext	Forwards	256 ± 48	2.92 ± 0.53	157 ± 25	2.63 ± 0.43
	Backs	235 ± 48	2.75 ± 0.53	139 ± 26	2.35 ± 0.46
LtFlx	Forwards	241 ± 65	2.64 ± 0.78	116 ± 22	1.94 ± 0.40
	Backs	173 ± 33	2.07 ± 0.45	106 ± 23	1.80 ± 0.41
RtFlx	Forwards	224 ± 70	2.50 ± 0.75	118 ± 23	1.98 ± 0.41
	Backs	179 ± 35	2.11 ± 0.41	110 ± 20	1.87 ± 0.35

Note. Flx, Ext, LtFlx and RtFlx represent flexion, extension, left lateral flexion and right lateral flexion, respectively.

Independent t-tests revealed no difference in average relative neck strength between male forwards and backs (*t*(16)=1.937, *p*=.087). Univariate MANOVA tests revealed male forwards to have significantly greater relative LtFlx than male backs (*F*(1,20)=5.606, *p*=.026). There were no other directional relative neck strength differences between male forwards and backs for Flx (*F*(1,20)=1.504, *p*=.232), Ext (*F*(1,20)=0.680, *p*=.418) and RtFlx (*F*(1,20)=2.909, *p*=.101).

Independent t-tests revealed no difference in average relative neck strength between forwards and backs in female players, (*t*(17)=1.032, *p*=.317). Univariate MANOVA tests confirmed no directional relative strength differences between female forwards and backs for Flx ($F(1,19)=0.040$, $p=.843$), Ext ($F(1,19)=1.719$, $p=.207$), LtFlx ($F(1,19)=0.507$, $p=.486$) and RtFlx ($F(1,19)=0.381$, $p=.545$).

4.2.3 Absolute Neck Strength Symmetry

In male players, dependent t-tests found no significant difference in absolute neck strength between LtFlx (204 ± 60 N) and RtFlx (199 ± 57 N, $t(21)=0.685$, $p=.501$), but Flx (274 ± 60 N) was significantly greater than Ext (245 ± 48 N, $t(21)=2.341$, $p=.029$ in male players. Dependent t-tests found symmetry in anteroposterior and mediolateral neck strength in female players. There were no significant differences between Flx and Ext ($t(20)=-0.146$, $p=.885$), or between LtFlx and RtFlx, ($t(20)=-1.130$, $p=.272$). Anteroposterior neck strength was significantly greater than mediolateral neck strength ($t(21)=5.722$, $p<.001$). Therefore, females had greater symmetry overall than males (Figure 6).

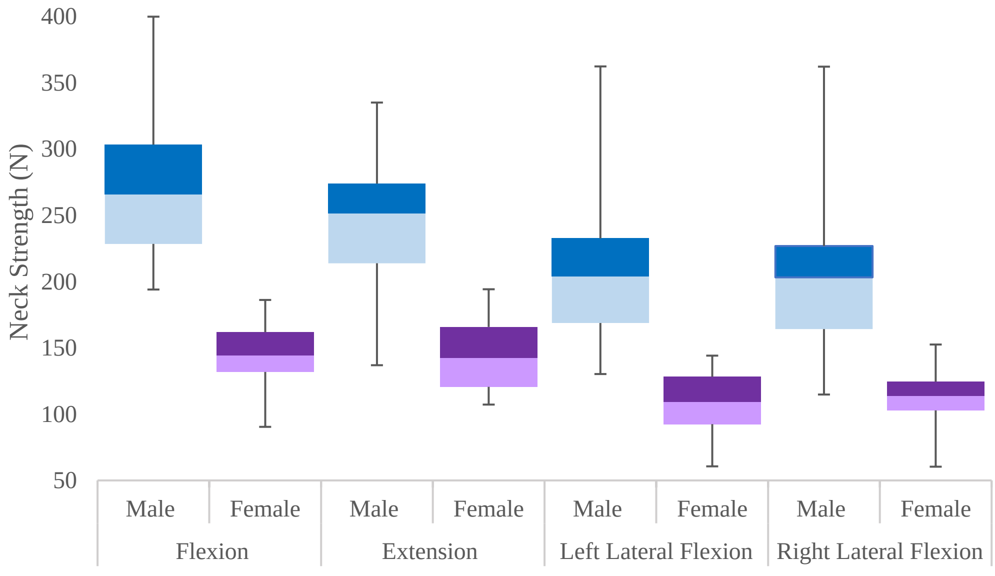

Figure 9 Distribution of absolute baseline directional neck strength (N) in male and female rugby players. Within sex, the dark colour represents the upper quartile and the lighter coloured counterpart represents the lower quartile.

Neck strength symmetry was assessed within the anteroposterior (between Flx and Ext) and mediolateral (between LtFlx and RtFlx) directions. Wilcoxon Signed Rank tests showed anteroposterior differences to be greater than mediolateral differences for both males (38 ± 37 N and 20 ± 27 N respectively, *p*=.007, *U*=43.000, *z*=-2.711) and females (6 ± 13 N and 17 ± 25 N respectively, *p*=.004, *U*=33.000, *z*=-2.868). Lateral flexion strength was significantly more symmetrical than Flx versus Ext.

Mann-Whitney U tests revealed females to have significantly greater neck strength symmetry than males in both the anteroposterior (*p*=.010, *U*=125.000, *z*=-2.575) and mediolateral (*p*=.004, *U*=111.000, *z*=-2.916) directions.

4.3 Sex Differences in Neck Strength Endurance

4.3.1 Baseline Absolute Neck Strength Endurance

Independent t-tests revealed females to have significantly greater average isometric neck strength endurance (40±12 s) than males (25±7 s), *t*(31)=-4.855, *p*<.001. Levene's test indicated unequal variances, (*p*<.05), so the degrees of freedom were adjusted from 41 to 31. Figure 10 illustrates the distribution of directional absolute neck strength endurance between males and females. Males had less variation between directions in neck strength endurance than females, illustrating greater consistency within males in.

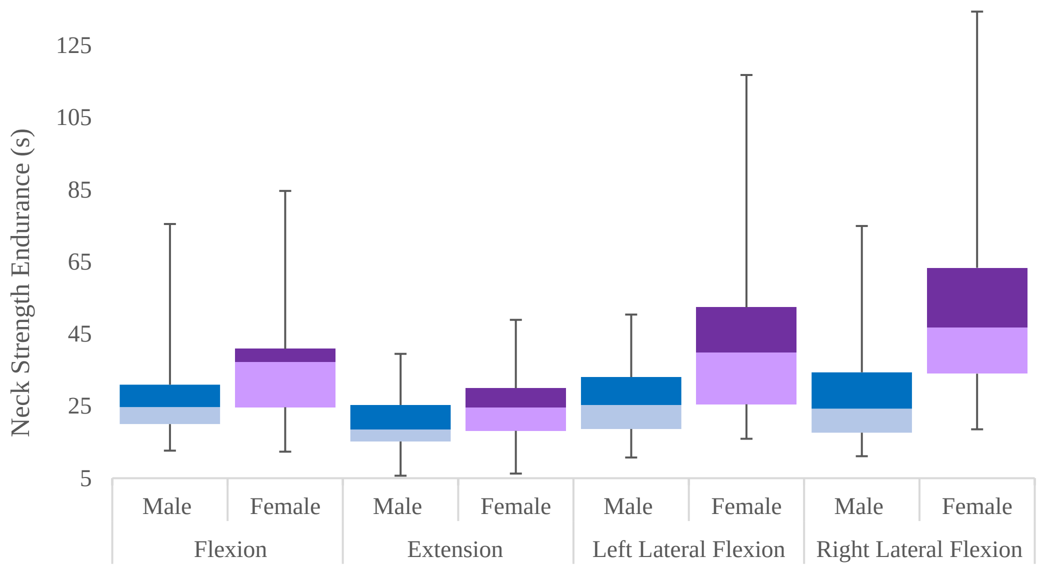

Figure 10 Distribution of baseline absolute directional isometric neck strength endurance (s) in male and female rugby players. Within sex, the dark colour represents the upper quartile and the lighter coloured counterpart represents the lower quartile.

4.3.2 Positional Differences in Absolute Neck Strength Endurance

Absolute values of baseline average neck strength endurance were assessed between forwards and backs, as displayed in Table . Results from the Mann-Whitney U test showed no significant difference between forwards (26 s±12 s) and backs (23 s±10 s) in isometric neck strength endurance in male players (p=.581, U=102.000, z=0.586). Independent t-tests revealed no significant differences between forwards (37 s±8 s) and backs (41±14 s) in isometric neck strength endurance in female players ($t(19)$=-0.790, p=.439).

Table 7 Absolute baseline isometric neck strength endurance (s) between forwards and backs for male (n=22) and female (n=21) rugby union players

Direction	Position	Male	Female
		Mean ± *SD (s)*	*Mean* ± *SD (s)*
Flx	Forwards	27 ± 8	35 ± 22
	Backs	27 ± 15	37 ± 12
Ext	Forwards	22 ± 10	27 ± 13
	Backs	18 ± 7	26 ± 10
LtFlx	Forwards	29 ± 12	39 ± 17
	Backs	26 ± 11	47 ± 26
RtFlx	Forwards	29 ± 18	47 ± 18
	Backs	27 ± 13	56 ± 33

Note. Flx, Ext, LtFlx and RtFlx represent flexion, extension, left lateral flexion and right lateral flexion, respectively.

4.4 Sex Differences in Cervical Range of Motion

4.4.1 Group Differences in Cervical Range of Motion

Directional CROM between male union, female union and male league players are displayed in Table 8. Female union and male league had greater CROM in each direction than male union.

Table 8 Directional cervical range of motion in male union (n=23) female union (n=14) and male rugby league players (n=10)

Direction	Male Union	Female Union	Male League
	Mean ± *SD* (º)	*Mean* ± *SD* (º)	*Mean* ± *SD* (º)
L-Lflx	35 ± 9	42 ± 8	40 ± 12
R-Lflx	37 ± 8	43 ± 8	42 ± 11
Flx	51 ± 14	63 ± 11	67 ± 10
Ext	52 ± 15	68 ± 9	69 ± 13
L-Rot	58 ± 12	64 ± 8	60 ± 8
R-Rot	60 ± 11	63 ± 8	63 ± 9

Note. Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot represent flexion, extension, left lateral flexion, right lateral flexion, left rotation and right rotation respectively.

Male rugby union, male rugby league and female rugby union were assessed in average CROM. Levene's test for equality of variances between groups was found to be significant, p=.031. Owing to the violated assumption of ANOVA, the Brown-Forsythe test found a significant difference between groups (F(2,25)=7.403, p=.003). The Gabriel Post hoc test was chosen due to the unequal male union (n=23), female union (n=14) and male league (n=10) sample groups. Gabriel Post hoc tests revealed female union (56±4º) and male league (57±8º) average CROM to be significantly greater than male union (49±7º) average CROM (p=.007 and p=.010, respectively). There were no significant differences between female union and male league average CROM (p=.999). Therefore, male union had significantly lower average CROM than female union and male league players (Figure 11).

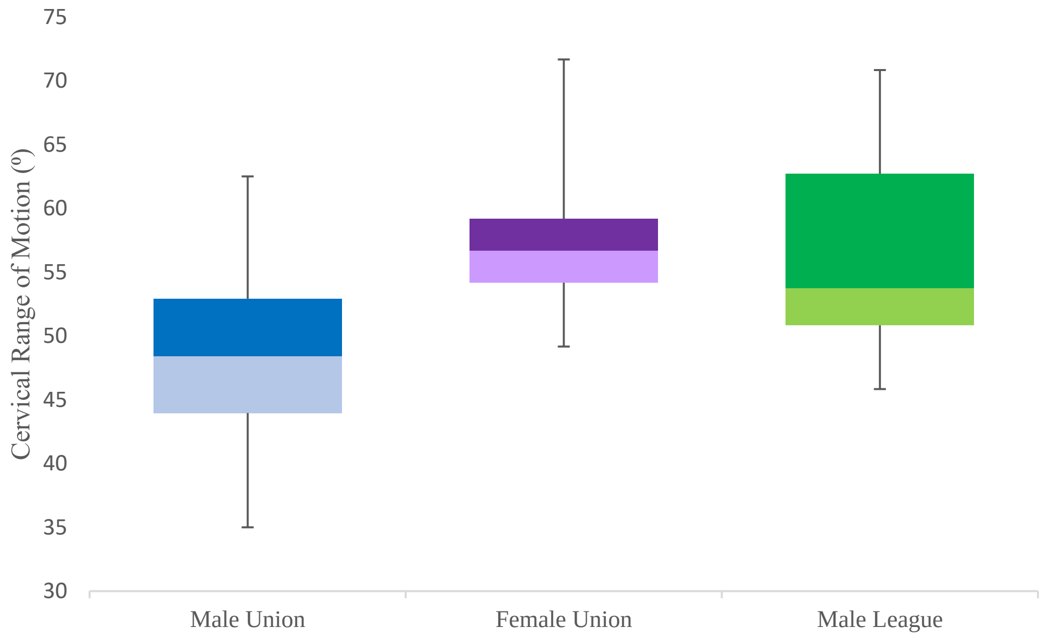

Figure 11 Distribution of average cervical range of motion (º) in male rugby union (n=23), female rugby union (n=14) and male rugby league (n=10) players. Within groups, the dark colour represents the upper quartile and the lighter coloured counterpart represents the lower quartile.

4.4.2 Positional Differences in Directional Cervical Range of Motion

Directional CROM between forwards and backs in male and female players are displayed in Table . Differences in directional CROM were assessed between forwards and backs using a MANOVA. Levene's test for homogeneity of variances was met for Flx (F(1,17)=0.874), Ext (F(1,17)=0.822), L-Lflx (F(1,17)=0.001), R-Lflx (F(1,17)=2.725), L-Rot (F(1,17)=0.242) and R-Rot (F(1,17)=0.141), p>0.05. Pillai's trace found no effect of position on directional CROM (V=0.417, F(6,12)=1.428, p=.282) in male players. The Kruskal-Wallis test revealed no significant differences in Flx (H(1)=0.278, p=.598), Ext (H(1)=0.111, p=.739), L-Lflx (H(1)=2.260, p=.133) and R-Lflx (H(1)=1.213, p=.271), L-Rot (H(1)=0.173, p=.677) and R-Rot [H(1)=0.299, p=.585] across positions in females. Therefore, directional CROM was not influenced by playing position when grouped into forwards and backs within male and female player groups.

Table 9 Directional CROM between forwards and backs in male (n=23) and female (n=14) rugby union players

Direction	Position	Male	Female
		Mean ± *SD* (º)	*Mean* ± *SD* (º)
L-Lflx	F	29 ± 6	66 ± 9
	B	35 ± 6	63 ± 7
R-Lflx	F	34 ± 4	66 ± 11
	B	38 ± 8	64 ± 10
Flx	F	45 ± 16	44 ± 7
	B	51 ± 14	38 ± 9
Ext	F	46 ± 14	47 ± 6
	B	56 ± 17	43 ± 7
L-Rot	F	52 ± 11	62 ± 4
	B	61 ± 11	63 ± 10
R-Rot	F	57 ± 13	62 ± 8
	B	63 ± 10	60 ± 11

Note. Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot represent flexion, extension, left lateral flexion, right lateral flexion, left rotation and right rotation respectively. F and B represent forwards and backs, respectively.

4.4.3 Cervical Range of Motion symmetry

Dependent t-tests were conducted to assess CROM symmetry within male and female players. CROM was assessed for symmetry in each plane; sagittal (Flx and Ext differences), frontal (L-Lflx and R-Lflx differences) and transverse (L-Rot and R-Rot differences). There were no significant differences between Flx and Ext (t(22)=-0.607, p=.550), L-Lflx and R-Lflx (t(22)=-1.767, p=.091) or L-Rot and R-Rot (t(22)=-0.973, p=.341) in male players. This indicated within-plane symmetry. Transverse plane CROM (59±10 º) was significantly greater than frontal (M=36 º, SD=8 º) and sagittal (52±13 º) plane CROM in male players, t(22)=-8.709 and t(22)=-2.494, p<.05, respectively. For female players, dependent t-tests revealed transverse and sagittal plane symmetry in CROM. There were no significant differences between Flx and Ext (t(13)=-.213, p=.834) or between L-Rot and R-Rot (t(13)=0.556, p=.588). Frontal plane CROM was found to be unsymmetrical with L-

Lflx (44±7 º) to be significantly greater than R-Lflx (40±8 º) (t(13)=-3.015, *p*=.010). Sagittal plane (65±6 º) and transverse (62±6 º) CROM were significantly greater than frontal plane (42±7 º) CROM, (*t*(13)=-10.006 and *t*(13)=-7.826, p<.05, respectively). Therefore, males showed greater within-plane CROM symmetry than females (Figure 12).

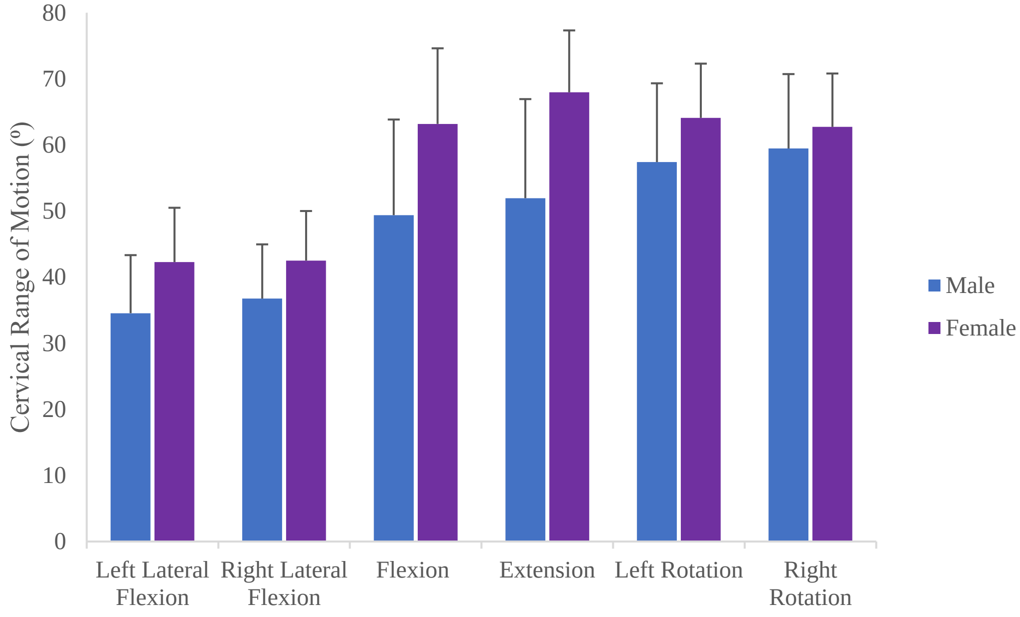

Figure 12 Directional cervical range of motion (º) in male and female rugby players.

CROM symmetry was assessed by comparing sagittal (sum of Flx and Ext), frontal (sum of L-Lflx and R-Lflx) and transverse (sum of L-Rot and R-Rot) CROM. Paired t-tests revealed all planes of CROM to be significantly different in male players. Transverse CROM (*M*=118 º, *SD*=20 º) was significantly greater than frontal CROM (*M*=103 º, *SD*=26 º), *t*(22)=-2.494, *p*=.021. Sagittal CROM (*M*=103 º, *SD*=26 º) was significantly greater than frontal CROM (*M*=72 º, *SD*=16 º), *t*(22)=6.126, *p*<.001. Paired t-tests revealed sagittal CROM (*M*=129 º, *SD*=12 º) to be significantly symmetrical with transverse (*M*=123 º, *SD*=22 º) CROM in female players, *t*(13)=-1.270, *p*=.226. Sagittal and transverse CROM were significantly greater than frontal CROM (*M*=85 º, *SD*=14 º), *t*(13)=-10.006, *p*<.001 and *t*(13)=7.826, *p*<.001, respectively. Therefore, females had greater CROM symmetry between planes than males.

4.5 Integrated Analysis of Neck Strength and Cervical Range of Motion in Male and Female Rugby Players

4.5.1 The Relationship Between Average Neck Strength and Average Cervical Range of Motion

No significant relationships between average neck strength and average CROM were observed for males or females (Appendix-F). Directional CROM and directional neck strength associations, however, were observed in females. Pearson's correlation was significant between baseline Ext neck strength and Ext CROM in females (r^2=0.295, p=.044). Mid-season Flx neck strength and Flx CROM were significantly negatively correlated in females (r^2=0.368, p=.021). There were no other relationships between directional neck strength and their directional CROM counterpart in males or females (Appendix-F).

4.5.2 Planar Neck Strength Symmetry and Cervical Range of Motion

No significant relationships between planar neck strength imbalances and average CROM were observed for females (Appendix-F). Negative correlations were identified in males between average CROM and pre-season mediolateral neck strength imbalances (r^2=0.338, p=.009) and mid-season anteroposterior neck strength imbalances (r^2=0.235, p=.035) using Pearson's correlation and Spearman's rho respectively. Similarly, there were no relationships between isometric neck strength endurance imbalances and average CROM in males or females (Appendix-F).

4.6 Cervical Range of Motion Validation Data

4.6.1 Intratester Repeatability

The purpose of this sub-study was to validate the ImageJ neck mobility board method as a measure of CROM in all planes of motion (flexion, extension, rotation and lateral flexion) using the CROM device as a reference standard (Williams et al., 2010). CROM repeatability analysis was performed on two participants, both of which being measured using the CROM device and ImageJ technique. The participants performed three trials per CROM direction (L-Lflx, R-Lflx, Flx, Ext, L-Rot and R-Rot) per measurement method and were assessed twice for test and re-test analysis. The normally distributed data, (p>0.05), was analysed using the ICC. A two-way mixed-effects model based on single measures and absolute agreement assessed the intratester repeatability for the CROM device and ImageJ. Mean estimations along with 95% confidence intervals (CI) were reported for each ICC. Interpretation was as follows: "poor" (ICC < 0.5), "moderate" (0.5–0.75), "good" (0.75–0.9) and "excellent" (ICC > 0.9). Bland-Altman analysis determined the systematic bias and 95% limits of agreement (LOA) in CROM test (trials 1–3) and re-test trials (trials 4–6) per measurement method. One-sample t-tests per CROM method found no significant difference between zero and the mean difference of CROM between test and re-test trials, p>0.05, indicating a level of agreement within methods. Statistical results from Bland-Altman plots and Pearson correlation coefficients (R^2) are presented in Table .

Table 10 CROM Device and ImageJ intraclass correlation coefficients (ICC), their 95% confidence intervals (CI), coefficients of determination (R^2), systematic bias and the upper and lower 95% limits of agreement (LOA)

Measure	ICC	Single 95% Cl	SEM	R²	Systematic Bias	Lower LOA	Upper LOA
CROM Device	.999	0.999-1.000	0.963	0.999	0.028	-1.070	1.125
ImageJ	.995	0.988-997	2.423	0.989	-0.444	-3.739	2.850

4.6.2 CROM Device Repeatability Between Testing Trials

An excellent degree of repeatability was found between CROM device test (trials 1–3) and re-test trials (trials 4–6). The single measure ICC was 0.999 with a 95% confidence interval from 0.999 to 1.000 (F(35,35)= 2957.010, p<.001). The scatter plot (Figure 13) shows a strong positive correlation between test and retest trials for directional CROM measurements using the CROM device, supported by an ICC of 0.999. The Bland-Altman plot (Figure 14) indicates a narrow limits of agreement estimate (LOA) between -1.070º and 1.125º, with a low average discrepancy of 0.028º. This suggests that the measurements between baseline and retest trials for the CROM device are similar. Trends are not present along the x-axis due to the inherent differences in directional CROM values (Chapter 4.4), as opposed to what might be observed for average CROM. The agreement among test and retest directional CROM measurements supports previous validation research (Audette, Dumas, Côté,

& De Serres, 2010) for the CROM device to be of a gold standard measure, thus appropriate to be compared against ImageJ.

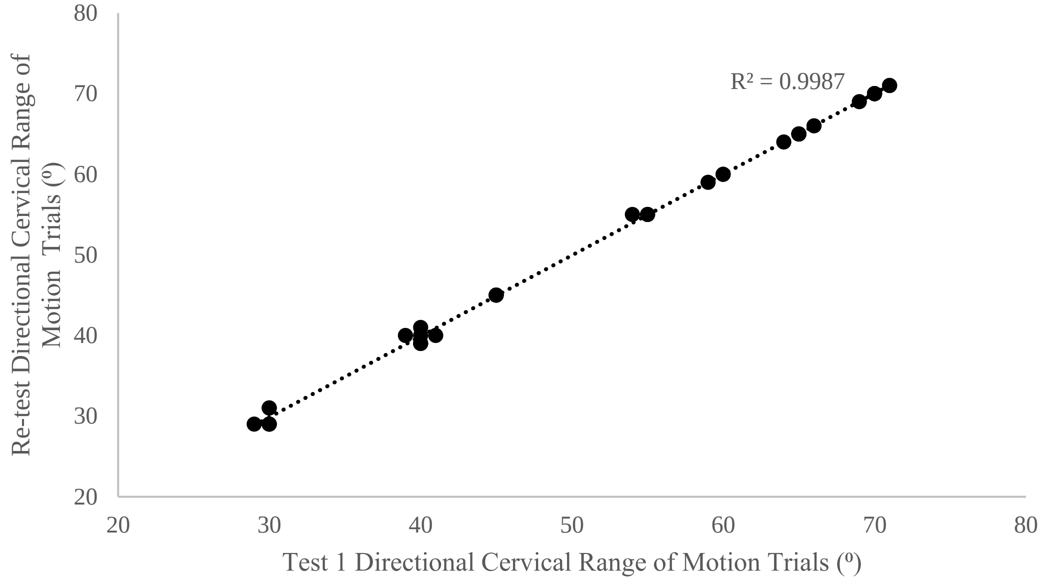

Figure 13 Scatter plot comparing CROM device test (trials 1-3) and retest (trials 4-6) trials per cervical range of motion direction. Dotted Black represents a linear trendline. Directional cervical range of motion entailed flexion, extension, left lateral flexion, right lateral flexion, left rotation and right rotation.

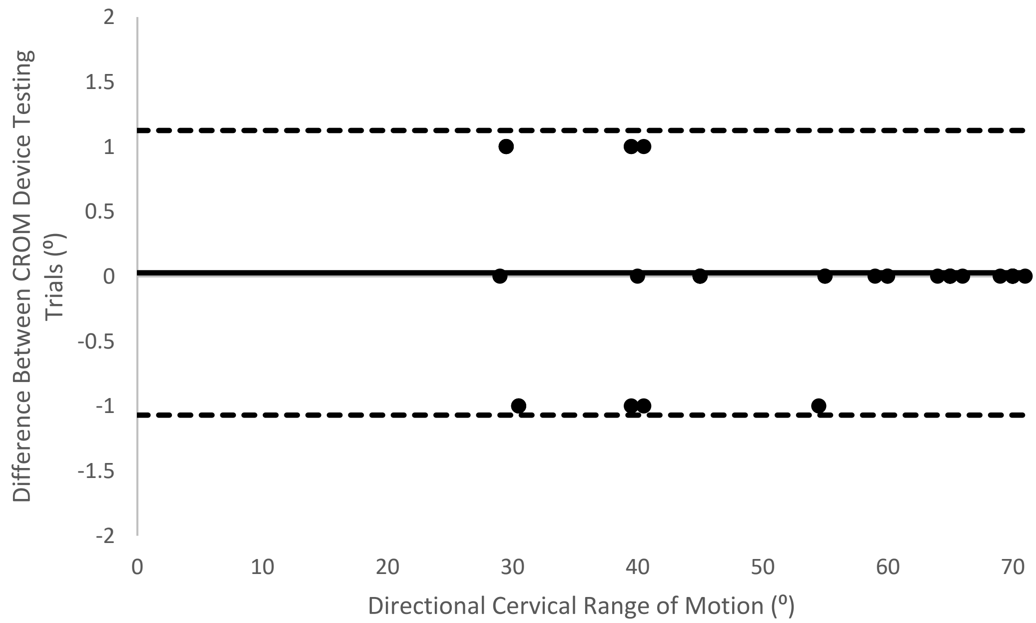

Figure 14 Bland-Altman plot comparing CROM device test (trials 1-3) and retest (trials 4-6) trials per cervical range of motion direction. Solid black lines represent systematic bias and dashed lines represent the upper and lower 95% limits of agreement. Directional cervical range of motion trials entailed flexion, extension, left lateral flexion, right lateral flexion, left rotation, and right rotation.

4.6.3 ImageJ Repeatability Between Testing Trials

An excellent degree of repeatability was found between ImageJ test (trials 1–3) and re-test trials (trials 4–6). The single measure ICC was 0.994 with a 95% confidence interval from 0.988 to 0.997 ($F(35,35) = 346.222$, $p < .001$). The scatter plot (Figure 15) indicates a strong positive correlation between test and retest trials for directional CROM measurements using ImageJ, supported by an ICC of 0.995. The Bland-Altman plot (Figure 16) indicates a lesser agreement in ImageJ measurements compared to the CROM device, with an average discrepancy of -0.444º and LOA between -3.739º and 2.850º. Nonetheless, these discrepancies are low, suggesting the measurements between test and retest trials for the ImageJ are similar.

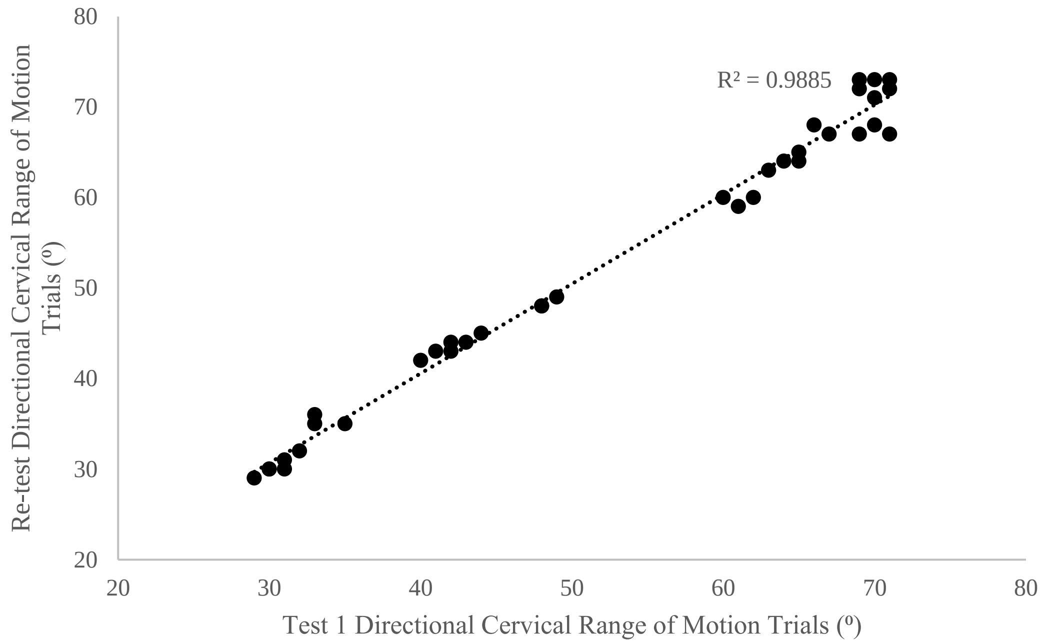

Figure 15 Scatter plot comparing ImageJ test (trials 1-3) and retest (trials 4-6) trials per cervical range of motion direction. Dotted Black represents a linear trendline. Directional cervical range of motion trials entailed flexion, extension, left lateral flexion, right lateral flexion, left rotation and right rotation.

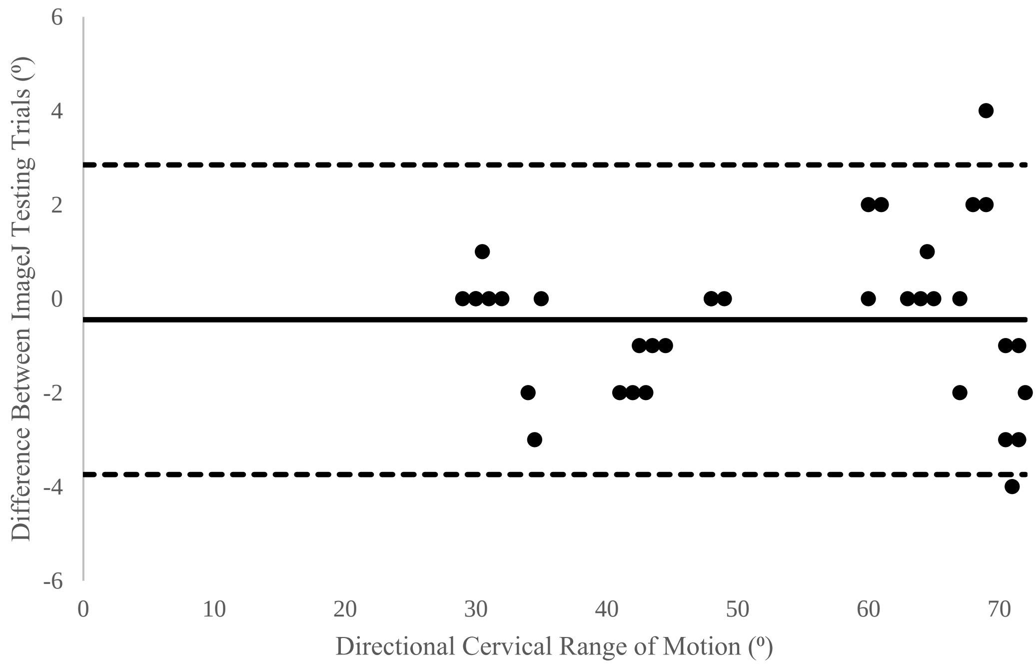

Figure 16 Bland-Altman plot comparing ImageJ test (trials 1-3) and retest (trials 4-6) trials per cervical range of motion direction. Solid black lines represent systematic bias and dashed lines represent the upper and lower 95% limits of agreement. Directional cervical range of motion trials entailed flexion, extension, left lateral flexion, right lateral flexion, left rotation, and right rotation.

4.6.4 Coefficient Variation

The calculation of a coefficient of variation (CV) further identifies agreement between methods. All individual CVs for directional CROM per participant were below <5% for each method of measurement across testing sessions, presented in Table . All combined CVs for directional CROM per participant were below <5% across testing sessions, presented in Table .

4.6.5 Intratester Reliability

A two-way mixed-effects model based on single measures and absolute agreement assessed the intratester reliability between the CROM Device and ImageJ method. Bland-Altman analysis determined the systematic bias and 95% limits of agreement (LOA) in average CROM between the CROM device and ImageJ. A one-sample t-test found no significant difference between zero and the mean difference in mean directional CROM for the CROM device and ImageJ, p>0.05, indicating a level of agreement between methods. Statistical results from Bland-Altman plots and Pearson correlation coefficients (R^2) are presented in Table .

Table 11 Individual CROM Device and ImageJ coefficient variation for mean directional cervical range of motion per participant

Method	PPT	Individual Coefficient Variation (%)					
		L-Lflx	R-Lflx	Flx	Ext	L-Rot	R-Rot
ImageJ	1	2.6	2.3	1.8	1.0	1.6	2.2
	2	3.2	3.1	2.2	1.1	1.7	2.1
CROM Device	1	2.3	2.5	0.0	0.7	0.8	0.7
	2	1.4	1.7	0.0	0.0	1.3	1.2

Note. L-Lflx R-Lflx, Flx, Ext, L-Rot and R-Rot represent left lateral flexion, right lateral flexion, flexion, extension, left rotation, and right rotation.

Table 12. Combined method coefficient variation for mean directional cervical range of motion per participant

PPT	Combined Coefficient Variation (%)					
	L-Lflx	R-Lflx	Flx	Ext	L-Rot	R-Rot
1	3.1	2.4	1.5	6.4	1.4	2.0
2	7.8	3.7	2.3	1.2	1.8	1.9

Note. L-Lflx R-Lflx, Flx, Ext, L-Rot and R-Rot represent left lateral flexion, right lateral flexion, flexion, extension, left rotation, and right rotation.

Table 13 Intraclass correlation coefficients (ICC) between the CROM Device and ImageJ, their 95% confidence intervals (CI), coefficients of determination (R^2), systematic bias and the upper and lower 95% limits of agreement (LOA)

ICC	Single 95% Cl	SEM	R^2	Systematic Bias	Lower LOA	Upper LOA
.982	0.960-0.992	4.142	0.967	0.75	-4.920	6.420

An excellent degree of reliability was found in directional CROM measurements between the CROM device and ImageJ. The single measure ICC was 0.982 with a 95% confidence interval from 0.960 to 0.992 ($F(23,23)=113.900$, $p<.001$). The scatter plot (Figure 17) indicates a strong positive correlation between mean directional CROM measured by the CROM device and ImageJ, supported by an ICC of 0.982. The Bland-Altman plot (Figure 18) indicates a narrow LOA between -4.920º and 6.420º, with a low average discrepancy of 0.75º, suggesting the measurements between the CROM device and ImageJ are similar. Trends are not present along the x-axis due to the inherent differences in mean directional CROM values (section 4.4) as opposed to what might be observed for average CROM.

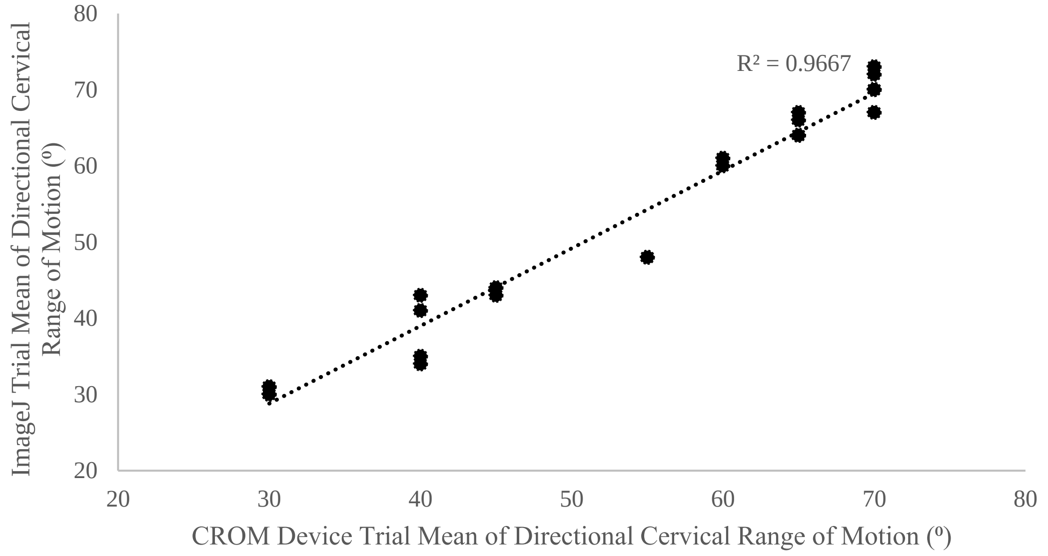

Figure 17 Scatter plot comparing mean directional cervical range of motion measured by the CROM device and ImageJ. Dotted Black represents a linear trendline. Directional cervical range of motion entailed flexion, extension, left lateral flexion, right lateral flexion, left rotation, and right rotation.

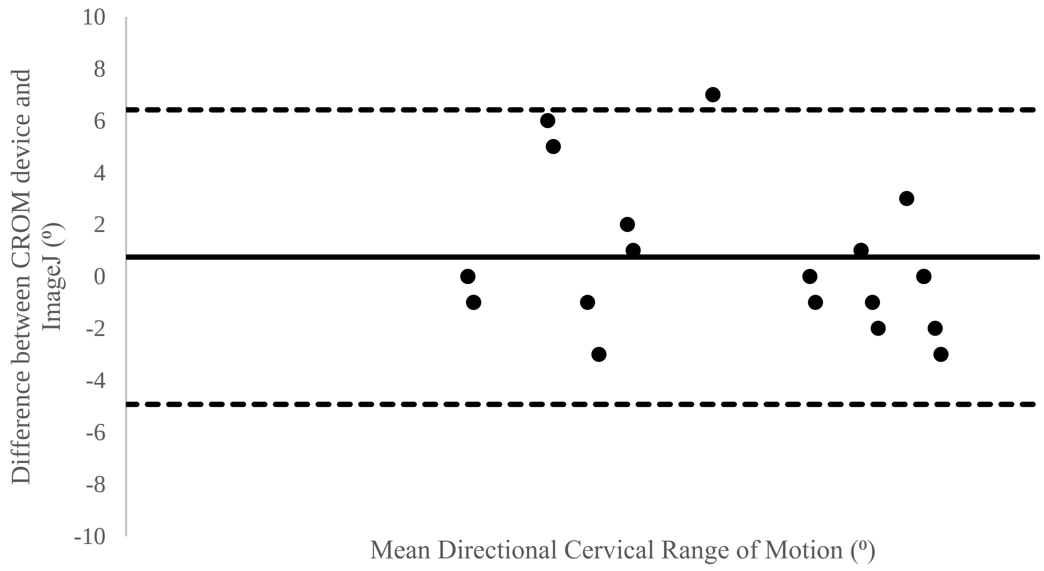

Figure 18 Bland Altman plot comparing mean directional cervical range of motion measured by the CROM device and ImageJ. Solid black lines represent systematic bias and dashed lines represent the upper and lower 95% limits of agreement. Directional cervical range of motion entailed flexion, extension, left lateral flexion, right lateral flexion, left rotation, and right rotation.

4.6.6 Cervical Range of Motion Validation Summary

Both methods using the CROM device and ImageJ had excellent intratester repeatability and reliability. Despite validating a new method of measuring CROM using ImageJ with the neck mobility board, the CROM device was chosen for this research project. This method was modified with the addition of the harness board to eliminate extraneous variables caused by upper body movement.

CHAPTER 5: Discussion

5.1 The Gender Data Gap

5.1.1 Female Representation in Sport Science and Medical Literature

Women have been chronically understudied in sport science and medical research resulting in a gender data gap (Costello et al., 2014). Findings from androcentric studies are routinely generalised to females, with a lack of evidence to support this. Only recently have governmental guidelines begun advocating for the inclusion of women in clinical research (National Institutes of Health, 2019).

There is a growing consensus in the non-rugby literature that women are more susceptible to brain injury under comparable loading conditions (Dollé et al., 2018). Female athletes are reported to take longer to recover from sports related brain injury than their male counterparts (Antona-Makoshi et al., 2018), and suffer a greater symptom burden (Dollé et al., 2018; McGroarty, Brown, & Mulcahey, 2020). Despite this, and the women's game being the fastest growing area of rugby globally, training and injury surveillance strategies are based on male data (Hendricks et al., 2020).

Due to the high-impact nature of rugby union, it is an extreme and visible example of the consequences of the gender data gap for females. The current consensus in sporting literature supports the link between greater neck strength and lower head impact magnitudes (Peek et al., 2020; Salmon et al., 2018). The findings from this thesis show significantly lower neck strength in female players relative to their male counterparts. Overall, the sex and gender differences identified in this study do not support the generalisation of male-derived data to female rugby players, particularly regarding injuries to the head and neck.

5.1.2 Training Injury Implications of Playing Age Discrepancies

The male and female rugby union cohorts in this study were clearly physically disparate populations. The differences between cohorts, however, were not limited to physical characteristics. Despite no sex differences in chronological age, male players had an average of eight years more rugby playing experience than their female counterparts. In addition, male players had at least seven years rugby experience at the commencement of the study, while many females had fewer than two. As the study progressed, sociological issues such as playing opportunities prior to starting university became increasingly apparent. Most females lacked the systematic age-grade physical conditioning, which most males progress through from a young age. The lack of rugby and position-specific physical conditioning among females was evident in the results in this thesis.

When transitioning from school level rugby to university level rugby, the younger players may be more susceptible to injury amongst stronger and more experienced counterparts. It would be beneficial for coaches to screen players before participation to ensure sufficient physical conditioning is met to safely perform the role. Neck strength conditioning programmes should be tailored for players when transitioning between playing positions or higher playing levels. The significant discrepancies between male and female neck strength in this thesis support the need to female-specific neck strength training, based on female-derived data.

5.2 Anthropometric Measures

5.2.1 Anthropometric Sex Differences

Males exhibited greater body mass, height, neck and head circumference and shoulder breadth than females. There was only a 3.01 cm (5.5%) difference between the average male and female head circumference, yet a 7.4 cm (17%) difference in neck circumference. For males the neck circumference was 71.6 ± 3.4% of head circumference, whereas in females this was 9.4% less, at 62.2 ± 2.8%. This is in accordance with previous reports of dimorphisms in spinal anatomy, linked to increased head-neck movement in vehicle collisions (Stemper, Pintar, & Rao, 2011), increasing female susceptibility to whiplash and concussive injuries (Janssen, Drevelle, Humbert, Skalli, & Castelein, 2009; Mohan & Huynh, 2019). Males also exhibited greater morphological positional specificity relative to females, with greater differences in neck circumference between male forwards and backs than female. It is likely that the underlying sex dimorphisms in the cervical spine do increase female susceptibility in rugby also. This appears to be extenuated by the gender-based playing age discrepancy and access to expert coaching.

5.3 Neck Strength and Stability

5.3.1 Sex Differences in Neck Strength

To maintain cervical spine alignment and reduce head accelerations during impact, sufficient neck strength is required (Peek, Elliott, & Orr, 2020). Greater neck strength has been found to reduce the head's inertial loading during impact (Eckner et al., 2014). In the current study, males were found to have significantly greater absolute neck strength than females, supporting most existing literature (Collins et al., 2014; Eckner et al., 2014). When calculating neck strength relative to body mass as Newtons per kilogram, males remained significantly stronger than females.

5.3.2 Positional Trends in Neck Strength

Forwards and backs were assessed to identify whether differences in positional requirements influence scores in neck strength. The male forwards had significantly greater absolute neck strength than male backs. The results are consistent with research (Hamilton & Gatherer, 2014), however, when accounting for body mass, these authors found no positional differences in relative neck strength. Despite the high incidence of SRC in females (Zuckerman et al., 2015), there is scarce female rugby union research investigating neck strength of forward and back players for comparisons to be made with the current study. There were no significant differences in neck strength between positions among the female rugby players. The lack of positional differences may be due to a lack of playing experience and regular changing of positions.

In the female cohort, one participant played position number seven during the previous season and changed to number three for the current season. Lack of expert coaching resulted in the female player not being front row trained, whereas male players did receive specialist front row training. According to World Rugby laws, all front row players and any substitutes must be suitably trained for the role (Methenitis, 2020). Injuries often occur to players who frequently change playing positions to ones they have less experience in (Bohu et al., 2009). Players should be physically and technically trained for front row positions as they are vulnerable to catastrophic injuries, especially when playing in high competition British University College Sport (BUCS) leagues. Transitioning to a front row position places the player at risk of injury from opposing experienced players in the scrum with stronger necks and shoulders.

5.3.3 Sex Differences in Neck Strength Endurance

Increasing deep cervical flexor and extensor endurance capability has been suggested to decrease head accelerations (Vibert et al., 2001). Authors suggest that enhancing deep cervical stability increases cervical posture and releases stress and reliance on the superficial muscles for head-neck stability. Females were greater in absolute average neck strength endurance than males. Males exhibited greater consistency as they had less variation between directional neck strength endurance than females. The differences between sex could be argued that poorer performance of neck strength at the time of testing would result in lower strength endurance targets relative to their actual ability. Nonetheless, this possible limitation would be consistent across all individuals, not between sex. There were no positional differences between forwards and backs in neck strength endurance for males and females in the current study. Neck strength endurance scores were calculated relative to ability as 70% of their MVC scores. Therefore, smaller differences between groups may be expected as each player had different targets to reach relative to their ability.

5.3.4 Sex Differences in Neck Strength Symmetry

Imbalances in neck muscle coordination have been suggested to account for higher head accelerations during heading actions in novice football players (Riches, 2006). Male players exhibited frontal symmetry with no significant differences between LtFlx and RtFlx. Whereas sagittal plane neck strength was unsymmetrical, with Flx being significantly greater than Ext. Sagittal plane asymmetry was expected due to the implications of the head mass and position, contributing to greater Flx values and impeding Ext values. While the INSTA was set up in this configuration intentionally, an upright position where accessory muscles were restricted, may in future, provide less positional bias between Flx and Ext. Authors have suggested that frontal plane neck strength symmetries have greater protective effects on the head and neck during impact (Dezman et al., 2013; Hildenbrand & Vasavada, 2013). Flx-Ext neck strength ratios closest to one were associated with lower head accelerations during soccer heading in both male and female players (Dezman et al., 2013).

Female players exhibited greater symmetry in both the frontal and sagittal planes. Their sagittal plane symmetry may, in fact, suggest asymmetry when accounting for head mass. Therefore, given the INSTA configuration, it may be possible that the female players have relatively greater Ext strength and may therefore be at greater risk of sustaining greater head accelerations. The asymmetry among females may be due to undeveloped neck strength in all directions from a lack of playing experience.

Shoulder strengthening exercises practised in rugby improve UT strength, which aids neck extensor strength (Peek et al., 2020). Shoulder strength exercises have less influence on neck flexor strength, which may explain the discrepancies among females. Females lacked the systematic age-grade progression of physical conditioning that males underwent from a young age throughout their rugby career. Specific training may be required in targeting the SCM for flexor strength.

In the current study, sagittal plane, or anteroposterior neck strength was significantly greater than frontal plane, or mediolateral neck strength in male and female players. Studies have demonstrated the benefits of within-plane neck strength symmetry (Dezman et al., 2013; Hildenbrand & Vasavada, 2013; Streifer et al., 2019). Further research is required to investigate the effect of between-plane symmetry on head acceleration. An effective technique in reducing the risks associated with head impacts could be the design of a training intervention, focusing on improving within-plane and between-plane neck strength symmetry.

5.4 Neck Length and Head Mass Measurement

5.4.1 Neck Length Screening

Measuring neck length is important for the calculation of head and neck moments when quantifying head impacts. There is no ISAK anthropometric standard of measuring neck length (Norton, 2019). This has resulted in varying methods of measuring neck length and head-neck segment length in literature. The in-vivo nature of the current study using rugby players deemed experimental methods of measuring neck length as the most appropriate component for calculating the head-neck segment moment arm.

Screening anthropometric variables prior to participation can inform coaches of which players are more vulnerable in comparable loading conditions. In the current study, neck circumference was found to be correlated with neck strength in males. These results suggest that neck circumference may be an indicative measure of which players require specific neck strength training to improve head-neck stability. There were no correlations between neck circumference and neck strength in females, meaning screening parameters may differ between sex. Males exhibited positional differences in height, weight, neck circumference and shoulder breadth. Whereas there were no observed positional differences in female players. The anthropometric disparities between sex highlight the importance of bespoke programmes and equal training opportunities.

Neck length may be an important screening variable in rugby. A longer neck could mean greater difficulty in stabilizing the head-neck segment resulting in greater accelerations. This hypothesis could not be assessed with the measurement of neck length due to COVID-19 restrictions. Coaches can utilise these anthropometric screening methods to objectively create bespoke programmes for individuals. In the current study, the purpose of the neck length validation study was to design a reliable measure of neck length that was inexpensive, accessible and efficient in application. Practicality appeals to coaches given their demanding schedules and pitch-side surroundings. Additionally, club level teams do not have the funds for expensive equipment or specially trained personnel. Therefore, the new neck length measure is of greater suitability in comparison to MRI methods used in previous research (Ahmed et al., 2020; Taha et al., 2014).

5.4.2 Head Mass

There is no standard measure of head weight in the current international guidelines (Norton, 2019). Roush (2010) stated that head mass, along with centre of gravity and principle moments of inertia are important when studying head impacts. Given the context of the current study, it was imperative that such a method was devised and validated. Previous studies (Caccese et al., 2018; Mansell et al., 2005; Tierney et al., 2008) have reported a wide range of estimated head weights using body mass in collegiate soccer players. It was hypothesised that variabilities in estimated head weights would be accentuated in rugby populations given the variability in body mass between positions. For example, the men’s front row (106 ± 4 kg) were considerably heavier than the backline players (84 ± 4 kg), which does not necessarily mean they would have considerably heavier heads. Moreover, front row players do not represent the 50th percentile male, so estimates of head mass using percentage values of body mass is unreliable.

Alongside quantifying head impacts and neck injury thresholds (Roush, 2010), head weight was an important variable to measure as it affected the INSTA data. The INSTA required the participant to lie prone with force transducers positioned anteriorly, posteriorly, as well as to the left and right sides of the head. The implications of head weight in the frontal plane impeded Ext scores and assisted Flx scores. The Flx-Ext relationship was imbalanced and not representative of true MVC scores. Similarly, the implications of head weight in the sagittal plane impeded lateral Flx scores, although to a much lesser extent. The left-right lateral Flx relationship was not affected to the same extent as Flx-Ext because head weight was acting perpendicularly. Therefore, the implications of head weight on left and right lateral Flx would be theoretically balanced. Research using a similar INSTA subtracted relaxed head weight values from MVC scores to account for head weight pressure on the force transducers (Salmon et al., 2015). Resting head weight was measured against the force transducers for this research project. However, the head weight values were unrealistic with large discrepancies between players. These values proved unreliable and were not used.

With the head weight data from the INSTA excluded, the secondary measure of head weight was the use of infant weighing scales. Infant weighing scales are practical, inexpensive and available to researchers. Easy application was of importance because locating and measuring players alongside their busy university schedules proved challenging. COVID-19 restricted any measurements being taken, so head weight could not be assessed for this research project. This is a key component for future head impact research.

5.5 Cervical Range of Motion

5.5.1 Sex Differences in Cervical Range of Motion

Females had significantly greater average CROM than males. Given that age has been found to be inversely proportional to CROM (Budelmann, Piekartz, & Hall, 2016), significant age effects would be difficult to identify in young students aged between 18-23 years. Moreover, research has found no effect of sex on CROM for individuals in their 20s (Pan et al., 2018). Therefore, the third influential factor affecting CROM between sex may be due to rugby playing experience. Greater exposure to the game's physical demands from a younger age may suggest that males may have experienced more cumulative decrements in CROM than females. A conflicting argument may propose that a lack of player experience among females should in fact display greater instantaneous decrements in CROM. Previous sporting history was not recorded prior to rugby participation and whether these sports were full contact, such as martial arts or kickboxing. Previous sporting history may have exposed players to cumulative stressors on the cervical spine, affecting CROM results. Although females may lack rugby playing experience, they may have experienced similar cervical spine degeneration from alternative contact sports from a young age.

Female rugby union players have been found to experience greater head impact accelerations and observed to fall head-to-ground as opposed to a shoulder-roll observed in males (Petrie et al., 2020). These authors reported greater average linear head accelerations (14.5 g) and comparable maximum linear head accelerations (44 g) in females (Petrie et al., 2020) than males (14 g and 50 g, respectively) (Pennington et al., 2020). Females experienced greater average (1030 rad•s^{-2}) and maximum (4000 rad•s^{-2}) rotational head accelerations (Petrie et al., 2020) than that of the males (940 rad•s^{-2} and 3000 rad•s^{-2}, respectively) (Pennington et al., 2020). The poor falling technique from a lack of playing experience may cause greater injury to the cervical spine among females in a shorter time frame. Moreover, the physiological sex differences of smaller vertebrae and lower neck strength suggests why females may be more susceptible to injury and exhibit greater decrements in CROM (Antona-Makoshi et al., 2018; Vasavada et al., 2008).

5.5.2 Sex Differences in Cervical Range of Motion Symmetry

Males exhibited CROM symmetry within the frontal, sagittal and transverse plane. Females exhibited CROM symmetry in the sagittal and transverse plane, but not within the frontal plane as L-Lflx was significantly greater than R-Lflx. The frontal asymmetries could be due to a lack of neck strength and inability to stabilize the head as sufficiently as males during impact. Females typically have greater ligamentous laxity (Quatman et al., 2008), narrower vertebral body (Stemper et al., 2008) and inconsistent vertebral coupling (Stemper et al., 2008), which authors have indicated to reduce cervical spine stability (Stemper et al., 2009). Future research should investigate whether lower CROM values on a particular side correlate with the direction of received side-on tackles.

5.5.3 Front Row Vulnerability

Given the complexities of the cervical spine axis of rotation (Swartz et al., 2005) and the impact location considerations described by Nightingale et al., (2000), it has been hypothesised that front row players are particularly vulnerable to cervical spine degeneration. This was reflective in the current study as front row players exhibited lower average CROM than backline players, all of whom had similar playing experience and level. Factors which may predispose decrements in CROM occur within the scrum engagement formation. Hookers wrap their arms around the loose-head and tight-head prop for support, limiting their ability to make cervical spine positional adjustments to reduce stress acting on the neck (Trewartha et al., 2014). Interestingly, front row average CROM was marginally greater than backline average CROM in female players. This may be due to lack of playing experience for positional differences to emerge. Authors suggest a reduced CROM is a product of cumulative rugby impacts as opposed to distinctive traumatic incidences (Lark & McCarthy, 2010). Accordingly, female players had significantly greater average CROM than male players. Greater exposure to the game's physical demands from a younger age may suggest why males may have experienced decrements in CROM over time, exhibiting lower values.

5.5.4 Male Positional Differences

The functional capacity of the neck has been found to be influenced by playing position (Hemelryck et al., 2018). The positional requirements of the forwards engaging in scrums and forceful tackles would suggest greater cervical trauma, resulting in greater CROM decrements than the backs (Hemelryck et al., 2018). The current study revealed no significant differences in directional CROM between forwards and backs in male players. The findings in the current study support the lack of positional differences seen in junior (15-18 years) and senior (19-35 years) first division rugby club players (Hemelryck et al., 2018). The only significant difference in CROM was found between front row and backs for Flx in senior players, but not between forwards as a group (Hemelryck et al., 2018).

Lark and McCarthy (2007) investigated 46 male semi-professional rugby players and found significant positional differences in Ext, R-Lflx and L-Rot. The players had mean age of 25 years with 14 years of playing experience and exhibited similar CROM values to the university forwards in the current study for Flx, Ext and L-Lflx (-2%, 7% and -3%, respectively). Greater positional differences were observed in the university forwards for R-Lflx, R-Rot and L-Rot (-19%, -20% and -10%, respectively) when compared to the semi-professional forwards (Lark & McCarthy, 2007). The university backs in the current study were similar in Flx, Ext, L-Lflx and

L-Rot (0%, 2%, -7% and -6%, respectively) when compared to the semi-professional backs (Lark & McCarthy, 2007). Larger differences were observed between the university backs and semi-professional backs for R-Lflx and R-Rot (-13% and -14%, respectively) (Lark & McCarthy, 2007).

Hamilton and Gatherer (2014) compared the forwards and backs of professional male rugby players with a mean age of 23 years. The backs were significantly greater in Flx, L-Rot and R-Rot (Hamilton & Gatherer, 2014). Across CROM directions, the current study's male university players exhibited 17-38% less CROM than professional ruby players. Given that age was relatively similar between studies, the influential factor affecting CROM could be playing level. Greater similarities were observed between semi-professional rugby players (Lark & McCarthy, 2007) than professional rugby players (Hamilton & Gatherer, 2014) as ability was more closely matched. Discrepancies in CROM values from playing level could be due to different impact severities, previous injuries, technique, training frequency and intensity.

The studies mentioned above (Hamilton & Gatherer, 2014; Lark & McCarthy, 2007) used the CROM device to measure maximal active range of motion of rugby players in an upright seated position. The static chair was adjustable in height for hip flexion at 90°, however, no objective measure was used to ensure this other than by observing which may have produced unreliable and results. In addition, movement of the upper body for CROM facilitation was not controlled for which may have produced invalid measures. Furthermore, Lark and McCarthy (2007) recorded one single repetition per CROM direction without calculating averages, limiting the possibility of identifying anomalies. In the current study, participants were stood upright with the trunk restrained to the harness board. Controlling trunk movement limits the implications of spinal twisting and curvature, which would have facilitated greater CROM values. This technique provides reliable and valid measures that are representative of true maximum CROM values.

5.5.5 Female Positional Differences

The current study revealed no significant differences in directional CROM between forwards and backs in female rugby players. The lack of playing experience among females may result in uniform CROM decrements from poor tackle and landing techniques. The lack of experience resulted in female players changing positions during the season to find roles best suited to their developing skillsets. The changing of positions could have contributed to the lack of positional differences. The androcentric nature of previous research in this area has restricted any meaningful comparisons with the current study. Thus, it is crucial for health and safety that future investigations in this area include female rugby populations of different ages and playing experience.

Due to the gender data gap in research, there are no female rugby CROM values to compare positional differences with. The results can only be compared with age-matched female controls that have not participated in contact sports. Here, we can identify if rugby exposure is a contributary factor towards decrements in CROM. Scarce research distinguished between sex when measuring CROM. Additionally, scarce research measured females using a CROM device to make reliable comparisons with the current study. The only comparable study measured CROM of 15 healthy females, of whom were medical students and therapy clinic employees, aged between 20-30 years and assessed using a gravity goniometer (Kuhlman, 1993). A comparison of mean CROM values between the two groups found female rugby players to exhibit 41% less Flx, 44% less Ext, 36% less R-Rot and 34% less L-Rot. Interestingly, the female rugby players exhibited 27% greater R-Lflx and L-Lflx than the female controls (Kuhlman, 1993). These results suggest that exposure to rugby may be a major factor contributing to shoulder and neck injuries.

5.5.6 Sporting Group Differences

There is a scarcity of CROM research comparing rugby union and rugby league. The current study found male league to have a significantly greater average CROM than male union. Rugby league is typically greater in aerobic power with fewer players on the pitch with the absence of scrummaging, mauls and rucks (Play Rugby League, 2019). The rugby union events causing acute cervical traumas may suggest differences in average CROM between sports (Kuster et al., 2012). There was no female university rugby league team to recruit for comparisons to be made with female rugby union players in the current study. This further highlights the gender gap in equal playing opportunities.

Due to the development process of the CROM methodology, pre-season measures could not be recorded. Therefore, changes in CROM over half a playing season could not be identified. Only rugby union players underwent the neck strength training intervention, which may have had protective effects on the cervical spine, reducing decrements that may have occurred. Likewise, rugby league players may have exhibited greater decrements in CROM through lack of neck strength training. These hypotheses cannot be determined without pre-season measures.

Similarly, individual CROM differences could not be assessed without pre-season measures. All participants were university students, typically computer-based and spending large amounts of time on phones and smart devices. The weight bore by the spine significantly increases when flexing the head to view phone content (Hansraj, 2014; Lin et al., 2020). Additionally, poor sitting posture with a tilted head, typically during computer-based work, can affect the cervical spine (Strimpakos, 2011a). Low mid-season CROM values could be due to these cumulative stresses placed on the cervical spine during a university degree and not necessarily the sole effect of rugby.

5.6 Integrated Components

5.6.1 The Effect of Neck Strength on Average Cervical Range of Motion

No published research is available on the direct relationship between neck strength and CROM in rugby populations. Sufficient neck strength is required to sustain cervical spine biomechanical alignment during impacts and contact events in rugby (Geary et al., 2014). Neck pain has been linked to lower neck strength and less cervical spine mobility (Kauther et al., 2012). The efficacy of neck strength training in rehabilitation interventions suggests associations between neck strength and CROM. In the current study, there were no correlations between average neck strength and average CROM in males or females. Faster neck muscle activation may be more influential than sole neck strength in protecting the cervical structures (Eckner et al., 2014), or both factors in conjunction.

5.6.2 The Effect of Neck Strength on Directional Cervical Range of Motion

Isometric neck strength training has been found to reduce match-related neck injuries in professional rugby union players (Hrysomallis, 2016). Yet, even with significant neck strength increases between pre-season and mid-season testing, still, no relationship was formed with average CROM. Correlational analysis was conducted to assess whether directional neck strength plays a protective role in preventing directional decrements in CROM. Interestingly, baseline absolute Ext neck strength was negatively correlated with Ext CROM in females. Similarly, mid-season Flx neck strength was negatively correlated with Flx CROM in females. The results support studies in the association between reduced cervical Flx and greater neck strength (Hamilton & Gatherer, 2014). Neck Flx is a prominent movement in rugby across all positions. The tackler typically performs frontal tackles, with the neck in a braced flexed position (Sayers & Ballon, 2017). Typically, the buckling mechanism occurs in Flx-Ext causing injury to the cervical spine (Nightingale et al., 2000). These in-play characteristics may explain differences in trends and why there are no other associations between directional neck strength and their directional CROM counterpart in females. Though, neck musculature is complex and overlapping, so it is simplistic to define strength as left or right. Moreover, isolating neck strength into directions and associating its effects on directional CROM further simplifies a complex mechanism.

Unlike females, there were no associations between directional neck strength and their directional CROM counterpart in male players. Biomechanical modelling of the neck identified sex differences in the centre of rotation for Flx and Ext (Zheng, 2011). Sex differences in the centre of rotation may explain why females are at greater risk as particular locations on the cervical spine are more susceptible to injury (Tencer, Huber, & Mirza, 2003). A greater head mass requires greater neck strength to stabilize the head during perturbation (Debison-Larabie, 2016). Females typically have less neck strength with a greater neck circumference-head mass ratio than males (Vasavada et al., 2008). Thus, females with smaller necks have greater difficulty supporting the mass of the head and are more susceptible to cervical injury than males. Moreover, greater magnitudes of static muscle activity are needed to support the head, which may induce fatigue more readily (Debison-Larabie, 2016). The current study confirmed these anthropometric sex differences as males exhibited greater average head circumference, neck circumference and shoulder breadth than females. These anthropometric factors predispose males to safer impact responses than females.

5.6.3 The Effect of Neck Strength Symmetry on Cervical Range of Motion

Neck strength symmetry has been found to reduce angular head acceleration (Dezman et al., 2013). In the current study, there were no significant associations between neck strength symmetry and average CROM in females. Frontal baseline neck strength imbalances and mid-season sagittal neck strength imbalances were negatively correlated with average CROM in males. The findings suggest that greater neck strength symmetry may reduce decrements that occur in CROM. However, these correlations were not consistent between baseline and mid-season neck strength, nor between planes. Additionally, baseline CROM values were not measured to determine if decrements occurred or if neck strength prevented these decrements. Player position may have influenced frontal plane differences when playing on the pitch's left or right side. For example, a left wing would predominantly sustain impacts to the right side of their body and rotate their head to the right for ball handling actions and field-scanning. This may cause greater frontal plane asymmetries in comparison with a number eight who plays evenly across the pitch, scanning play and sustaining impacts from all directions.

5.7 Study Limitations

5.7.1 COVID-19

As noted throughout this study, COVID-19 restricted data collection in post-season neck strength, post-season CROM, head mass measurement, neck length measurement and neck length validity testing. The implications of COVID-19 prevented predominantly all hypotheses to be tested.

5.7.2 Participants

The primary limitation of this thesis was the cohort of participants. The rugby players available for recruitment were limited, meaning the small cohort of male and female participants lacked powers analysis. The lack of participants limited investigation between specific positions so case studies were conducted without levels of statistical significance. Non-intervention rugby union control groups were not available for both sexes. Male rugby league players were representative of the male union control group. No female rugby league players were available to be representative of the female union control group. Additionally, comparing findings of rugby league with rugby union came with limitations. Differences in post-season CROM would be difficult to compare given the collisional-contact differences between sports. Nonetheless, COVID-19 restricted post-season CROM data collection for these issues to become evident.

Lastly, rugby training compliance was difficult to control. Strength and conditioning sessions were compulsory, although the absence of players was common during Phase 1 of the intervention. The inconsistency of attendance in field and gym training sessions may have affected neck strength scores among the cohort. Additionally, players were instructed by coaches to complete a training programme throughout the Christmas holiday period to maintain fitness. Compliance to the training programme could not be controlled and was entrusted by the player to complete with honesty. Mid-season neck strength results may have been affected by the loss of fitness. Greater overall improvements may have been regained and identified in post-season neck strength testing.

5.7.3 Testing Apparatus

A strength of this thesis was the design of a neck length measurement procedure and CROM measurement procedure. Key components of both procedures were efficiency, low cost and accessibility to researchers. Due to COVID-19 restrictions, the neck length measurement procedure could not be validated. The CROM methodology using ImageJ, designed with a board apparatus, was validated with excellent reliability (ICC=0.982) and repeatability (ICC=0.995). Limitations of using the CROM device are availability and expense. The current study revealed ImageJ to be a valid and inexpensive alternative of using the CROM device. Previous research using the CROM device did not objectively control accessory upper body and trunk movement when performing maximal CROM (Hamilton & Gatherer, 2014; Lark & McCarthy, 2010, 2007, 2009). The new CROM measurement procedure restrained the upper body and trunk to a board apparatus that limited spinal twisting implications. This method provides reliable and valid measures that are representative of true maximum CROM values. A limitation of CROM testing was the recording absence of opened or closed eyes during measurement. Authors have suggested that visual stimulation may affect range of motion and can be used to attain higher values (Dvir, Werner, & Peretz, 2002). Additionally, the handedness or tackle shoulder preference of players was not recorded, which may have influenced scores in CROM or explain differences between players.

5.7.4 Endurance Testing

All three male players who underwent post-season testing exhibited lower neck strength endurance times, which firstly, should be interpreted with caution due to the small sample size. Secondly, neck strength endurance scores were calculated relative to ability as 70% of maximum isometric neck strength. Therefore, pre-season and post-season endurance times are incomparable due to differences in relative neck strength endurance targets. Future research should use pre-season neck strength endurance targets for post-season testing and compare the differences.

5.8 Considerations for Future Research

5.8.1 Changes for Women's Rugby

The findings of the current study demonstrate a lack of neck strength among females in comparison with males. Additionally, the lack of positional differences among females suggest forwards may be at risk of injury when playing against stronger, more experienced players. When accounting for head mass implications, females exhibited less frontal symmetry, which has been found to impede head-neck stability (Dezman et al., 2013). Although, females did exhibit greater frontal plane symmetry than males.

Petrie et al, (2020) observed that university level female rugby players exhibit whiplash style head-to-ground falling techniques instead of controlled body rolls observed in males. The current study, along with the findings of Petrie et al., (2020) inspired a global women's rugby survey, aimed at bridging the gender data gap in research (World Rugby, 2020). This survey was launched on the 24th of August 2020 and distributed globally. Based on information provided by the survey research team, it is hypothesised that women players and coaches are likely to express requests for sex-specific training equipment (Williams et al., 2020). The design of smaller tackle pads would help female players learn how to tackle and be tackled safely. Equally, poor falling and tackle techniques have been reported in women's university rugby (Petrie et al., 2020). Thus, survey researchers anticipate responses stating the need for more funding and resources to be dedicated to tackle and fall coaching for women's rugby at the lower levels (Williams et al., 2020). Future coaching recommendations should implement training drills to instil controlled head-neck stability through body rolls when falling to the ground and training equipment designed appropriately for women. The geometric and physiological characteristics in females warrant sex-specific training programmes to reduce the risk of cervical injury and SRC.

At the elite level, men's rugby teams typically play and warm up on more manicured professional pitches than women. Women are regularly assigned the lesser-quality alternative pitch for championship events. In the 2020 Six Nations, for example, the Wales men played their matches in Principality stadium whereas the women played on the 4G artificial surface at Cardiff Arms Park (Sands, 2020). Therefore, equal opportunities in infrastructure usage should be instilled in women's rugby.

5.8.2 Cultural and Behavioural Changes

The evolution of women's rugby is far behind men's rugby, stemming from a lack of opportunity at an early age. The current study reflects these discrepancies in playing opportunities from a lack of female participation, neck strength and positional differences. The university had five men's rugby teams and just two women's rugby teams. This explains why the women's 1st university team had both international and novice players, who are susceptible to injury if inadequately trained. Discrepancies in playing level within female university teams would be reduced if there were greater pools of women to choose from for team selection. Cultural changes should be made to remove the stereotype of rugby being a 'boys' game at school and introduce female role models for schoolgirls to aspire to. Women would be safer to play rugby had they been given equal opportunities at school and progressed through age-grade systematic training that males typically follow.

5.8.3 Modifiable Risk Factors

Rugby players should focus on improving neck strength and neck strength symmetry to reduce cervical injuries and SRC risk. The current study found neck circumference to be positively correlated with neck strength in male players. This is an inexpensive and efficient screening variable coaches can administer readily to identify vulnerable players. While head mass is a non-modifiable risk factor, it could also be a useful screening variable. Infant weighing scales were proposed as a quick and available measure of head mass for coaches to administer. COVID-19 restricted methodology development and measurements using this apparatus, so future research should validate this technique. Research has highlighted the importance of Flx-Ext symmetry exhibiting lower head accelerations (Dezman et al., 2013). The implications of head mass on the INSTA impeded reliable comparisons between frontal and sagittal neck strength. Future research should investigate the importance of neck lateral flexion strength in comparison to flexion and extension, in reducing head acceleration magnitudes. Lastly, rugby players should be educated on the long-term consequences of poor cervical posture when on smartphones (Hansraj, 2014; Lin et al., 2020) and encouraged to make lifestyle changes.

5.8.4 Clinical and Coach Recommendations

The current study's prominent findings highlight sex disparities in SRC risk factors and the importance of sex-specific training programmes that are optimal for particular playing level cohorts. The gender data gap in research warrants sex-specific normative values for female neck strength and CROM. Normative values would help coaches screen athletes of risk factors associated with neck injuries and SRC. Screening strategies before participation can inform coaches on the level of physical conditioning each athlete requires. Screening anthropometric variables are quick alternative measures when grouping players, as in the current study, neck circumference was correlated with neck strength in males. No correlations were observed in females, which may be due to sex disparities in physiology and equal training and participation opportunities. Tailored programmes can be designed for specific players and prepare athletes for the physical demands of playing positions, such as front row. In the future, sporting governing bodies could collaborate with research and coaching groups to design and implement appropriate neck strength programmes for players at all levels and ages. It is hypothesised that women's concussion is not taken as seriously as men's and questions on this topic are included in the ongoing global survey in women's rugby (Williams et al., 2020). Women have expressed to survey researchers prior to the survey's release that they do not receive the same level of medical attention as their club's or university's men's teams (Williams et al., 2020). The current study demonstrates that women are different from men and are more susceptible to injury. Thus, it is recommended that women are treated more seriously by medical staff.

5.8.5 Conclusion

There is a significant gender data gap in sports science and medical research. Androcentric rugby union research may implicate the safety and welfare of female players. Concussion is a high profile and common injury in rugby. Women are more susceptible to SRC in comparable loading conditions than men due to their physiological and geometric differences. The data in the current study demonstrated sex differences in anthropometry, neck strength and CROM. Anthropometric differences between sex found males to exhibit significantly greater neck circumference, shoulder breadth and head circumference. Physiological differences between sex found males to be significantly greater in neck strength and females significantly greater in neck strength endurance. Females exhibited greater within-plane and between-plane neck strength symmetry than males. Sex differences in CROM found females to exhibit greater neck mobility than male players. These baseline sex disparities show that females should not be generalised to males. Females should not undergo training and injury prevention strategies based on androcentric research.

As the study progressed, differences in previous playing opportunities became increasingly apparent as females lacked the systematic age-grade physical conditioning for positional differences to emerge. Male forwards had significantly greater neck strength than male backs, with females exhibiting no positional differences. Interestingly, neither cohort exhibited significant positional differences in CROM. Nevertheless, the current study helped bridge the gender data gap by adding female rugby union CROM data to sports science research. The study was the first to assess the direct relationship between neck strength and CROM in male and female rugby populations. There were no significant associations between neck strength and CROM in male players. Whereas in females, there were significant correlations between pre-season Ext strength and Ext CROM, as well as mid-season Flx strength and Flx CROM.

The degenerative cervical injuries that rugby players exhibit from sustaining cumulative impacts could not be assessed due to COVID-19 restrictions. Similarly, the efficacy of phase 2 of the neck strength training intervention and the impact it had on preventing decrements in CROM could not be assessed. Thus, this study's results are based on pre-season to mid-season neck strength values and mid-season CROM values. Future research should collect post-season data to assess the relationship between neck strength and CROM over a whole playing season for both male and female players. The development of new neck length and CROM measures with validation studies were conducted. The harness board apparatus with the ImageJ procedure demonstrated excellent reliability as a measure of CROM. However, validation of the neck length methodology was restricted due to COVID-19.

Based on the COVID-19 restrictions, future directions should further explore the parameters and hypotheses intended for this research project. Women are more vulnerable to cervical injuries and concussion than men, so the design of sex-specific and cohort-specific training programmes are advised for coaches to improve player safety. Within these training programmes, attention should be focused on improving neck strength and neck strength symmetry. Social behaviours should be steered towards advocating women in rugby by providing equal playing opportunities and appropriate training. The gender data gap in research warrants sex-specific normative values for female neck strength and CROM. The current study was one of three projects which lead to the development of a global female rugby survey, bridging the gender data gap in research. Future research should investigate symptoms of concussion in women and how they respond differently to men.

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Appendix-A: Specifications of the INSTA

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Overview

The objective of this project is to measure the isometric neck strength and strength endurance of rugby athletes. This forms part of a wider initiative to minimise head inertial loading in training and competition. A test rig has been constructed to enable this testing. This rig is designed to facilitate repeatable test measures, ensuring that accessory muscles are restricted, so that only the muscles of the neck can be recruited. Four 35 kg Tedea-Huntleigh load cells have been used to measure neck strength in four directions; flexion, extension, left and right lateral flexion. This document describes the mechanical specifications of the rig as part of the risk assessment required to carry out testing protocols.

Figure 1: The neck strength test rig with a person demonstrating the required position

Requirements of the Rig

The testing position is shown in Figure 1. The participant is in a prone position, with their torso strapped to the horizontal bench with a car racing harness. Feet will be off the ground with their knees resting on a cushion with the height adjusted for each person. The head is positioned in the centre of the four inward-facing load cells and each load cell has a neoprene pad attached via a 85*60 mm aluminium platform. For testing, participants will push with maximum effort against each load cell in the specified direction. These efforts will be sustained for durations of between 2 and 6 seconds and will be repeated between three and five times per direction for each testing session.

The frame of the rig (Figure 1) must be able to support the body weight of the heaviest rugby athletes, without flexing at all. The heaviest elite rugby player in the world currently is 142 kg. The average weight of our current university study population is 97.4 kg (SD 11.9, range 70 – 117) for men and 68.3 kg (SD 8.3, range 53.5 – 85 kg) for women.

The rig must also accommodate athletes ranging in height from 150 cm to 195 cm. The horizontal bench is adjustable in a forwards and backwards direction. The entire headset, in the box marked B in Figure 2, can also be adjusted forwards and backwards. The portion of the headset in box C in Figure 2 can be adjusted in a vertical direction. When adjusting for each individual, the position of the neoprene pads must be positioned to the same location on each person's head.

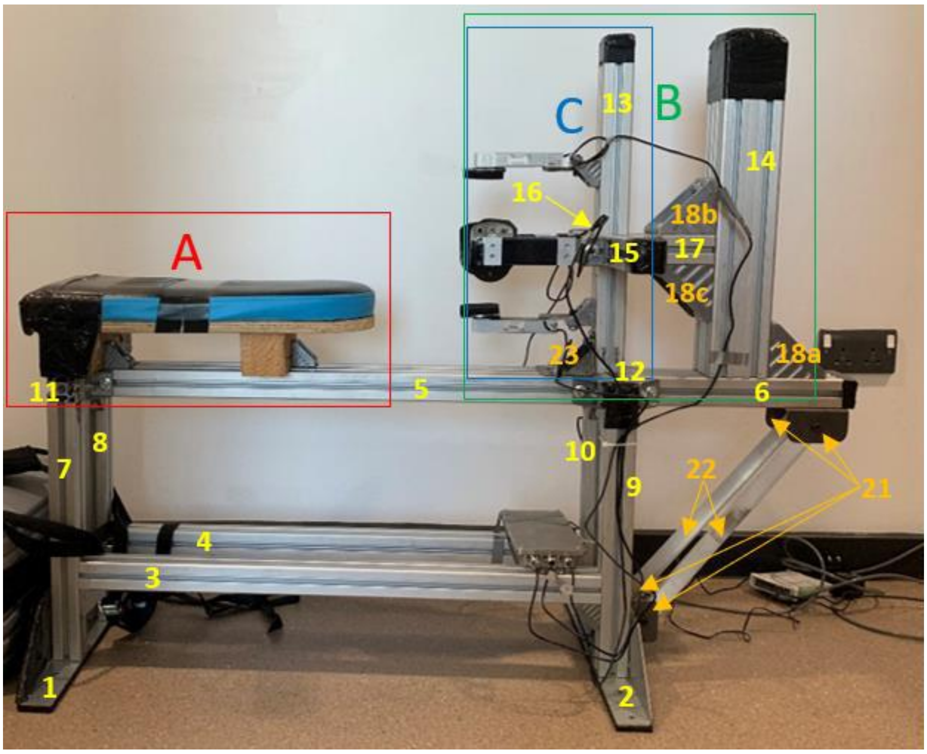

Figure 2: A side view of the neck strength rig showing the position of the bench and the headset with the mounted load cells. A indicates the horizontal bench with forwards-backwards adjustment. B indicates the entire head piece which can be adjusted forwards and backwards. C indicates the headset which can be adjusted vertically. Yellow numbers relate to frame components listed in Table 1 and orange numbers relate to the connectors listed in Table 1.

The framing for the headset and bracketing for each load cell must be able to withstand repeated force up to 50 kg (490 N) being applied. The value of 490 N is the highest reported by a previous study (Salmon, 2014) where a similar rig was used to test professional male rugby athletes. The rig used by these authors, however, enabled accessory muscles to be recruited which is expected to result in higher neck strength readings.

Rig Design and Construction

The design and construction of this neck strength test rig has been completed with the assistance of Roberto Sotgiu, who is a qualified mechanical design engineer (MEng (hons), Bath, 2000). Roberto has significant experience in the special purpose machinery industry, primarily in the design of bespoke test/assembly/feature-checking machines for the manufacturing sector.

The frame of the neck strength rig has been entirely constructed with Bosch Rexroth aluminium profile extrusion products, which can be viewed here:

(https://www.boschrexroth.com/en/xc/products/product-groups/assembly-technology/topics/aluminum-profiles-solutions-components/aluminum-profiles-products/index

Each strut is fastened with a minimum of two rigid brackets and fasteners have been torqued to the required manufacturer's specification. This makes the frame completely rigid and capable of withstanding the loads required for the testing of rugby athletes neck strength. This will be the case so long as all fastenings are torqued to 100% and positioned as per the specifications in Figure 2. Table 1 provides a list of all structural components shown in Figure 2.

Table 1: List of all structural components which are indicated in Figure 2

Item No.	Description
	Frame length components
1	Steel foot stand bracket 500*100*45mm
2	Steel foot stand bracket 500*100*45mm
3	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 800mm length
4	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 800mm length
5	Bosch Rexroth extrusion 90*45 mm, 10mm slot, 800mm length
6	Bosch Rexroth extrusion 90*45 mm, 10mm slot, 340mm length
7	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 450mm length
8	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 450mm length
9	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 450mm length
10	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 450mm length
11	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 200mm length
12	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 200mm length
13	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 500mm length
14	Bosch Rexroth extrusion 90*90 mm, 10mm slot, 500mm length
15	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 220mm length
16	Bosch Rexroth extrusion 45*45 mm, 10mm slot, 220mm length
17	Bosch Rexroth extrusion 90*45 mm, 10mm slot, 120mm length
	Angle Brackets and Connectors
18	Bosch Rexroth Strut Profile Angle Bracket, strut profile 90 mm
	3 brackets: joining 14 to top of 6 (a), 14 to top of 17 (b) and 14 to bottom of 17 ©
19	Bosch Rexroth Strut Profile Angle Bracket, strut profile 45 mm
*4	20 brackets: 1 each joining 7, 8, 19 a 10 to 3 and 4 respectively
*4	joining 7, 8, 9 & 10 to the inside of 11 and 12 respectively
*4	joining 11 & 12 to 5 respectively, with one on either side of 5
*2	joining 12 to either side of 6
*2	joining 2*4 timber supports of flat bench (A) to both grooves of 5
*4	joining each load cell to items 13, 15 and 16 via the mild steel fittings
20	Bosch Rexroth Strut Profile T-Head Bolt
	4* each of 18a, b and c (12)
	2* each of item 19(40)
	*4 joining 1 and 3 & 4 and 2 with 9 and 10
	*4 joining 23 with 13 and 5
21	Purpose-built steel angle brackets to secure 45 degree support struts
22	Aluminium angle support struts (420*24*12)
23	Purpose built steel angle bracket supports
24	M6 machine screws
	*4 connecting each load cell to aluminium head support and mild steel fittings (16)

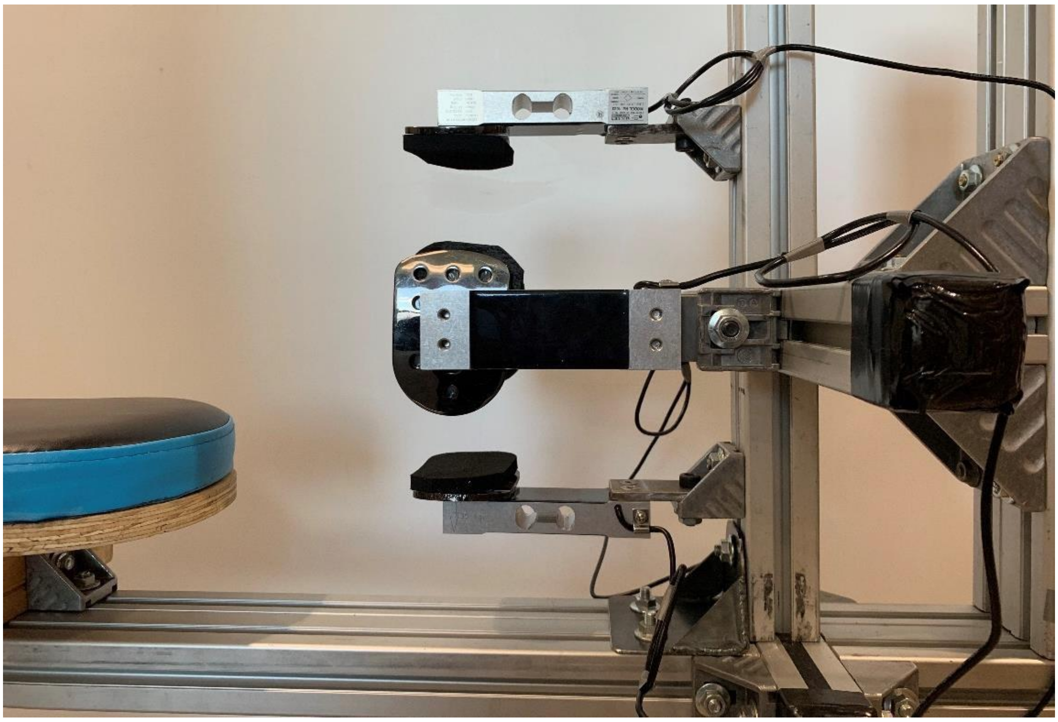

Figure 3: Side view of the load cells fixed to the head piece frame with brackets. Neoprene foam pads are visible on the inside of the aluminium platforms where force is applied

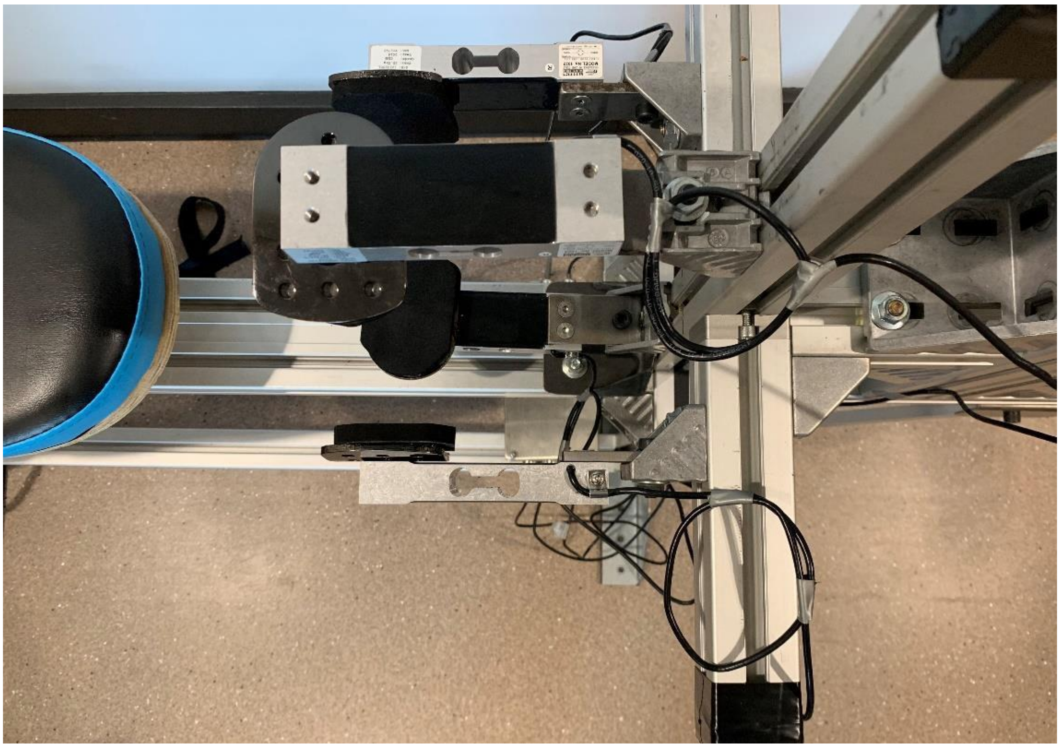

Figure 4: Top view of the head piece, showing the brackets used to fix load cells to the head piece

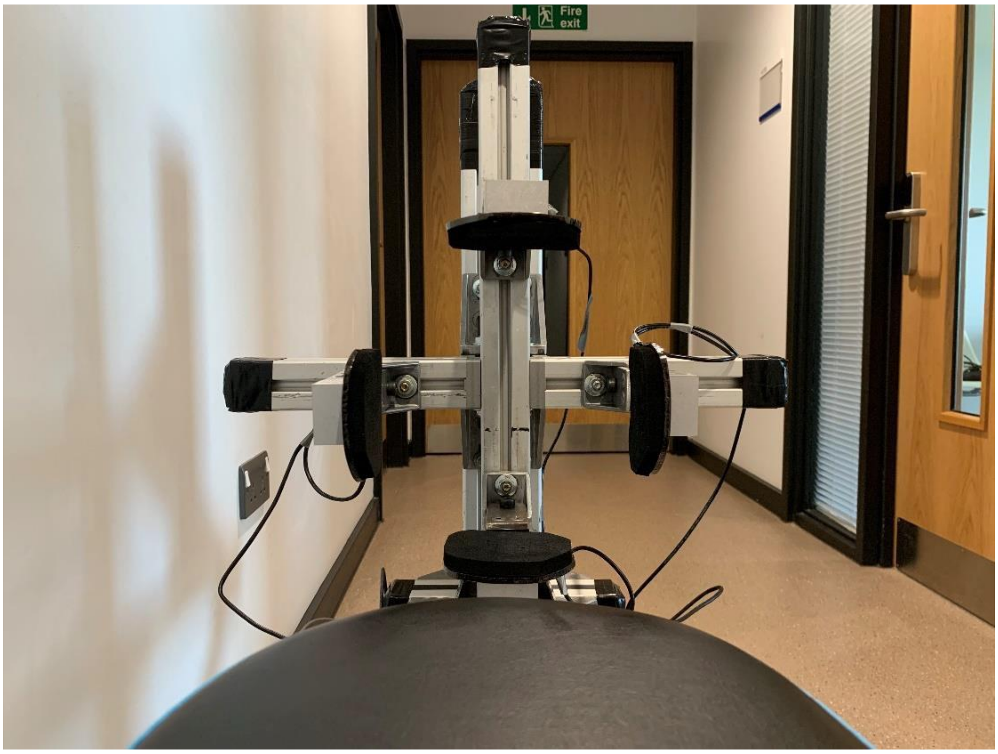

Figure 5: End-on view showing the head piece with load cells, also visible is the horizontal bench where the participant's torso will be strapped down

Headset Specifications and Technical Data

The four Tedea-Huntleigh Load Cells were positioned as per Figures 3, 4 and 5, so that when the participant's head is positioned as per Figure 1, neck flexion, extension and lateral flexion can be measured. Each load cell is mounted to the Rexroth frame using Rexroth brackets, the technical data for these is provided in Figure 7. The angle of force applied to these brackets via the load cells is consistent with the third position shown in Figure 7, which can withstand 160 Nm. Figure 6 shows that the moment arm in question is 0.16 m long and as stated above, the maximum expected force is 490 N. There expected maximum load on these brackets is therefore 78.4 Nm. The capacity of these brackets is more than double what the maximum expected load.

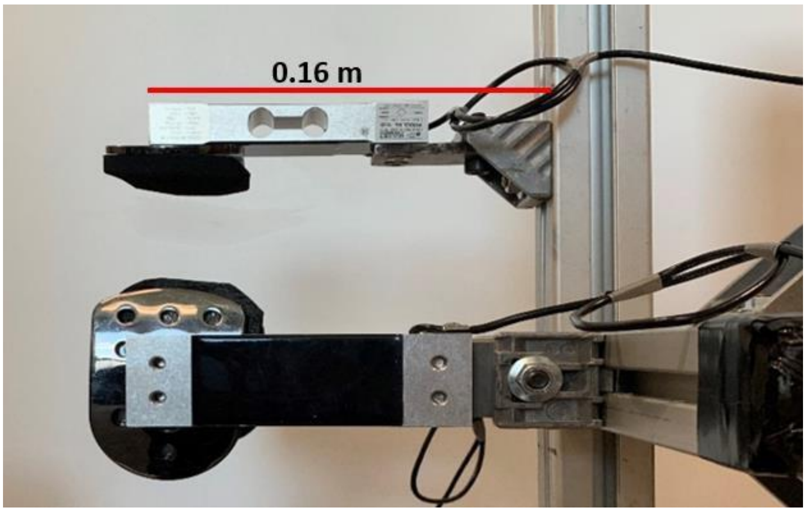

Figure 6: Distance from bracket mount to distal end of load cell where force is applied

Technical data

	Groove	ESD	Material entry	F_{max}	M_{max}	M_{max}
				N	Nm	Nm
Bracket	10	⊛	Bracket: Diecast aluminum, vibratory ground Fastening material: steel; galvanized	3000	60	160
	10	⊛	Bracket *designLINE*: Diecast aluminum; vibratory ground, painted (RAL 9006) Fastening material: steel; galvanized	3000	60	160
	10	⊛	Bracket: Diecast aluminum, vibratory ground	3000	60	160

Figure 7: Technical data for the brackets used to fix load cells to extrusion

The load cells are mounted to the brackets using 35*6mm, 66mm lengths of mild steel, machined for this purpose. The mechanical properties of mild steel can be found here:

https://www.azom.com/article.aspx?ArticleID=6115

Importantly, the ultimate tensile strength of mild steel is 400 MPa and the yield tensile strength is 370 MPa (200-300 kg). Given the loads to be applied to this apparatus, this is well over-engineered.

The load cells themselves have a rated capacity of 35kg, a safe overload capacity of 150% of this rated capacity, maximum overload 200% and ultimate overload 300% (so ultimate overload being 105 kg). This data is available here: https://www.loadcells.com/products/load-cell-1022/

The ultimate overload of these load cells is more than double the expected maximum load to be applied to each load cell.

Safety of Electronic Components

A Type B 12V power supply is required to power the load cell amplifiers. Electronics engineer Mr David Moody (Swansea University) has checked all electronic components and wiring and has considered them safe. An email from Mr Moody states "I can confirm that the rig is electrically safe as the load cells are low voltage and correctly connected to a low powered amplifier powered by a class 2 device. This Class 2 device will need the usual insulation resistance test in a PAT test as it's a plug-in power supply, but this is carried our annually by a contractor for estates". It has been registered online with states to be added to the annual PAT testing list.

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Appendix-B: Neck Strength Testing Protocol

Protocol Objectives:

1. Inform the participant of the neck strength protocol (measuring maximal isometric neck strength for 3x3 seconds in each direction – Flx, Ext, LtFlx and RtFlx).
2. Endurance testing will occur 20 minutes after maximal strength testing
3. Measurements will be taken pre, mid and post* rugby season.
4. Assure the participant that all data will be kept anonymous through assigned ID codes

Standardized Warm-up:

5. Row on a rowing ergometer for five minutes.
6. 3x10 repetitions of shoulder shrugs, shoulder circumduction, shoulder protractions and retractions, neck half circles (each direction) (Salmon et al.,2018)
7. Instruct the participant to perform 3x10 second prone chin-tuck isometric protractions and retractions

Rig Adjustments:

8. Ask the participant to lie prone on the rig by sliding the head between all four load cells
9. Ensure the load cells are close to the head but not touching any in the neutral position
10. Ask the participant to slide out of the rig and make any adjustments if needed
11. Record the measurement of the load cell location using the scale on the rig for each participant
12. Ensure the bottom load cell is positioned inferiorly on the supraorbital ridge
13. Ensure the top load cell is positioned above the external occipital protuberance
14. Ensure the lateral load cells are positioned above the external auditory canal
15. Ensure the trunk is vertical by adding a platform below the knees using weights

Rig Set-up:

16. Instruct the participant to slide back into the rig with head in the correct position between the load cells as stated earlier
17. Fasten the harnesses to ensure no movement of the upper body and trunk can occur
18. Fasten the harness around the legs
19. Ensure legs are crossed over not touching the ground for assistance

Familiarisation Trials:

20. Instruct the participant to perform 50% maximal effort isometric contraction in each direction – 2x3 seconds with 20 seconds rest between each repetition.

Maximal Strength Testing Trial:

21. Inform the participant that testing will commence
22. Inform the participant of the Maximal voluntary contraction (MVC) trial
23. Direction of MVC will be randomly ordered
24. 3x3 seconds will be performed per direction
25. 30 seconds rest between each repetition and 60 second rest between each direction

Endurance Strength Testing Trial:

26. Inform the participant that testing will commence
27. Inform the participant of the strength endurance trial
28. Direction of endurance trial will be randomly ordered
29. 70% of MVC will be calculated per direction
30. 1 repetition of 70% MVC will be performed for as long as can be sustained by the participant
31. Two-minute rest between each direction

Testing De-brief

32. Cool down and stretch as per the standardized warm-up

Appendix-C: CROM Device Testing Protocol

Inform Participant of the Process:

1. Inform participant of the CROM protocol (Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot). Measurements will be taken pre and post rugby season.
2. CROM will be measured using the CROM device (Williams et al., 2010)
3. All data will be kept anonymous through assigned ID codes

Standardized Warm-up:

4. Instruct participants to warm up by rowing on an ergometer for five minutes
5. 3x10 repetitions of shoulder shrugs, shoulder circumduction, shoulder protractions and retractions, neck half circles (each direction)
6. 3x10 prone chin-tuck isometric protractions and retractions
7. Demonstrate movements required for testing. Allow participants to implement movements as a familiarisation warm-up
8. **Protocol Set-up:**
9. Adjust harness board to the shoulder height of the participant, held in place with clamps against the squat rack bars. Ensure the harness board is the correct height to allow for full CROM in the sagittal plane.
10. Ask the participant to stand upright with a straight back against the wooden board with arms relaxed hanging at the sides. Enclose the harness and adjust the straps so shoulders remain in a fixed position throughout testing.
11. Instruct the participant to place the CROM device on themselves as if it were a pair of glasses. Secure the device on the head with the Velcro strap.
12. The magnetic yokes will only need to be placed around the neck of the participant for cervical rotation.

Familiarisation Trials:

13. Instruct the participant to perform and become familiar with the CROM movements required for testing (Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot), returning to the neutral position per repetition. Allow the participant to become familiar with the CROM device and harness apparatus.

Protocol:

14. Ensure the participant is stood vertically upright, with a straight back, feet shoulder width apart and hands hanging beside their body.
15. Frontal plane: instruct the participant to laterally flex their neck until full L-Lflx is obtained. Ensure their shoulders remain in a fixed position and without head rotation occurring. Instruct the participant to hold L-Lflx for three seconds and record the angle from the CROM device. Instruct the participant to return to the neutral position. Repeat this process for R-Lflx. Take three recordings for each direction.
16. Sagittal plane: instruct the participant to flex their neck until full Flx is obtained. Ensure their shoulders remain in a fixed position and without head rotation occurring. Instruct the participant to hold flexion for three seconds and record the angle from the CROM device. Instruct the participant to return to the neutral position. Repeat this process for Ext. Take three recordings for each direction.
17. Transverse plane: place the magnetic yoke on the shoulders of the participant with the arrow pointing north. The sagittal and frontal plane meters should read zero to ensure Flx/Ext does not occur. Ensure their shoulders remain in a fixed position. Instruct the participant to rotate their head to the left. Hold L-Rot for three seconds and record the angle from the CROM device. Repeat this process for R-Rot. Take three recordings for each direction.

Testing Debriefing:

18. Instruct participants to stretch as per the same procedure in the standardized warm-up.

Appendix-D: ImageJ Testing Protocol

Inform Participant of the Process:

1. Inform participant of the CROM protocol (Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot). Measurements will be taken pre and post rugby season.
2. CROM will be measured using the CROM device (Williams et al., 2010)
3. All data will be kept anonymous through assigned ID codes

Standardized Warm-up:

4. Instruct participants to warm up by rowing on an ergometer for five minutes
5. 3x10 repetitions of shoulder shrugs, shoulder circumduction, shoulder protractions and retractions, neck half circles (each direction)
6. 3x10 prone chin-tuck isometric protractions and retractions
7. Demonstrate movements required for testing. Allow participants to implement movements as a familiarisation warm-up

Protocol Set-up:

8. Place the rugby scrum cap on the head of the participant
9. Three cameras on tripods for video data collection in each plane (frontal, sagittal and transverse)
10. Cameras centred in each plane relative to the participant
11. Cameras positioned 100cm from the participant

Familiarisation Trials:

12. Instruct the participant to perform and become familiar with the CROM movements required for testing (Flx, Ext, L-Lflx, R-Lflx, L-Rot and R-Rot), returning to the neutral position per repetition. Allow the participant to become familiar with the harness apparatus.

Protocol:

13. Ensure the participant is stood vertically upright, with a straight back, feet shoulder width apart and hands hanging beside their body.
14. Take one video recording per movement plane (frontal, sagittal and transverse), with three repetitions per CROM direction.

15. Frontal plane: instruct the participant to laterally flex their neck until full L-Lflx is obtained and hold for three seconds. Instruct the participant to return their head to the neutral position followed by two more repetitions. Ensure their shoulders remain in a fixed position and without head rotation occurring throughout testing. Repeat this process for R-Lflx.
16. Sagittal plane: instruct the participant to flex their neck until full Flx is obtained and hold for three seconds. Instruct the participant to return their head to the neutral position followed by two more repetitions. Ensure their shoulders remain in a fixed position and without head rotation occurring throughout testing. Repeat this process for Ext.
17. Transverse plane: Instruct the participant to rotate their head to the left and hold for three seconds. Instruct the participant to return their head to the neutral position followed by two more repetitions. Ensure their shoulders remain in a fixed position and without head Flx/Ext occurring throughout testing. Repeat this process for R-Rot.

Testing Debriefing:

18. Instruct participants to stretch as per the same procedure in the standardized warm-up.

Appendix-E: Neck Length Validity Testing

Protocol Objectives:

1. Inform the researchers and participants of the neck length measurement protocol, locating anatomical landmarks measuring L1, L2, L3 and L4 in succession.
2. Inform the researchers of repeat testing for intertester reliability
3. Assure researchers and participants that all data will be kept anonymous through assigned ID codes
4. Prior to testing, ask if participants will comply with removing their upper body clothing for researchers to identify anatomical landmarks

Rig Adjustments:

5. Instruct participants to stand upright with a straight back against the wooden board with arms relaxed beside them.
6. Adjust the harness board to the participants height, held in place with clamps against the squat rack bars.
7. Enclose the harness and adjust the straps so shoulders remain in a fixed position throughout testing.

Protocol Set-up:

8. Camera tripods 100cm away relative to the participants head in the sagittal plane
9. Ensure cameras are perpendicular to the measurement plane and line of measurement
10. Ensure measurement scale is vertical to the camera and line of measurement on the participant
11. Ensure participant head orientation is vertically straight and not tilted away from the camera

Anatomical Landmark Location:

12. Researchers locate and mark with a pen the anatomical landmarks for L1 – L4.
13. L1 = Sternal notch to the sternal notch and the temporomandibular joint
14. L2 = Sternal notch and the upper margin of the hyoid bone

15. L3 = Sternal notch to the external acoustic meatus
16. L4 = Mid-point portion of the ipsilateral clavicle to the mandibular angle

Testing Protocol:

17. Following the steps above, camera photos of neck length will be taken
18. Three repetitions of neck length measurement are calculated using ImageJ

Intertester Protocol:

19. Repeat the neck length protocol two days later with the same researchers and participants.

Appendix-F: Statistical Results

All data were screened for normality and appropriate parametric or non-parametric tests were used accordingly.

A-F-1: *Correlational analysis conducted between average neck strength and average CROM in male and female players at two time-points.*

Average Neck Strength (N)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
Pre-season	Average	.048	.033	.174	.148
Mid-season	Average	.072	.178	.418	.056

Note. hypothesis was accepted at a confidence level of p<.05.

A-F-2: *Correlational analysis conducted between average neck strength endurance and average CROM in male and female players at pre-season.*

Average Neck Endurance (s)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
Pre-season	Average	.594	.017	.162	.156

Note. hypothesis was accepted at a confidence level of p<.05.

A-F-3: *Correlational analysis conducted between pre-season directional neck strength and their directional CROM counterpart in male and female players.*

Pre-season Neck Strength (N)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
LtFlx	L-Lflx	.955	.020	.752	.009
RtFlx	R-Lflx	.088	.162	.441	.050
Ext	Ext	.796	.004	.044	.295
Flx	Flx	.151	.118	.086	.227
LtFlx	L-Rot	.453	.033	.501	.038
RtFlx	R-Rot	.641	.013	.806	.005

Note. hypothesis was accepted at a confidence level of p<.05.

A-F-4: *Correlational analysis conducted between mid-season directional neck strength and their directional CROM counterpart in male and female players.*

Mid-season Neck Strength (N)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
LtFlx	L-Lflx	.326	.057	.722	.011
RtFlx	R-Lflx	.171	.035	.459	.056
Ext	Ext	.259	.075	.763	.008
Flx	Flx	.051	.094	.021	.368
LtFlx	L-Rot	.339	.054	.621	.021
RtFlx	R-Rot	.352	.051	.301	.089

Note. hypothesis was accepted at a confidence level of p<.05.

A-F-5: *Correlational analysis conducted between pre-season directional neck strength endurance and their directional CROM counterpart in male and female players.*

Pre-season Neck Strength Endurance (s)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
LtFlx	L-Lflx	.909	<.001	.321	.082
RtFlx	R-Lflx	.061	.191	.172	.150
Ext	Ext	.459	.033	.220	.123
Flx	Flx	.253	.076	.751	.009
LtFlx	L-Rot	.900	.001	.724	.012
RtFlx	R-Rot	.098	.153	.028	.341

Note. hypothesis was accepted at a confidence level of p<.05.

A-F-6: *Cardinal plane neck strength imbalances were correlated with average CROM in male and female players at pre-season.*

Neck Strength (N)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
LtFlx-RtFlx difference	Average	.009	.338	.142	.171
Ext-Flx difference	Average	.553	.023*	.215	.125

Note. hypothesis was accepted at a confidence level of p<.05.

A-F-7: *Cardinal plane neck strength imbalances were correlated with average CROM in male and female players at mid-season.*

Neck Strength (N)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
LtFlx-RtFlx difference	Average	.407	.041	.982	<.001
Ext-Flx difference	Average	.035	.235	.348	.074

Note. hypothesis was accepted at a confidence level of p<.05.

A-F-8: *Cardinal plane neck strength endurance imbalances were correlated with average CROM in male and female players at pre-season.*

Neck Strength Endurance (N)	CROM (⁰)	Male		Female	
		Sig.	r^2	Sig.	r^2
LtFlx-RtFlx difference	Average	.403	.042	.916	.001
Ext-Flx difference	Average	.050	.208	.251	.108

Note. hypothesis was accepted at a confidence level of p<.05

Appendix-G: Phase 1 Neck Strength Training Intervention

Table 14 Phase 1 isometric neck strength training programme

Stage	Repetition	Exercise
1	10*10 sec	50^o supine
	10*10 sec	40^o supine
	10*10 sec	30^o supine
	10*10 sec	20^o supine
2	10*10 sec	0^o supine
3	10*10 sec	Cervical retraction
4	10*10 sec	Stage 2 and 3
5	3*15 sec	Isometric bands (Flx, Ext, LtFlx, RtFlx)
	3*20 sec	Isometric bands (Flx, Ext, LtFlx, RtFlx)
	3*30 sec	Isometric bands (Flx, Ext, LtFlx, RtFlx)

Table 15 Description of the isometric neck strength training programme

Stage	Description
1	Player is sat on the bench in a supine position, adjusted to the specified angle. Player performs a chin-tuck and isometrically holds the contraction for the specified time. This process is repeated for the required amount of repetitions with a 60 second rest between sets.
2	Player is on the floor in a supine position, performing a chin-tuck and isometrically holding contraction for the specified time. This process is repeated for the required amount of repetitions with a 60 second rest between sets.
3	Player is on the floor in a prone position. The head is lifted off the floor whilst performing a chin-tuck position, isometrically holding contraction for the specified time. This process is repeated for the required amount of repetitions with a 60 second rest between sets.
4	Stage 2 and 3 are performed in succession.

5	Knelt shoulder widths apart, the resistance band is placed around the players head, just above the eyebrows. The researcher stretches the band to the point where the head-neck remains in the chin-tuck neutral position. The player isometrically contracts the neck, resisting movement and maintaining position for the required time recorded by the researcher. This process is repeated for the required amount of repetitions with a 60 second rest between sets.

Appendix-H: Phase 2 Neck Strength Training Intervention

Table 16 Phase 2 dynamic neck strength training programme

Stage	Repetition	Exercise
1	3*8 reps	30% MVC (Flx, Ext)
	3*8 reps	30% MVC (LtFlx, RtFlx)
2	3*12 reps	30% MVC (Flx, Ext)
	3*12 reps	30% MVC (LtFlx, RtFlx)
3	3*15 reps	30% MVC (Flx, Ext, LtFlx, RtFlx)

Table 17 Description of the dynamic neck strength training programme

Phase 2	Description
Ext	The head harness is adjusted to the player with weights and cables attached. The player is knelt with one leg flexed at the hip for stability, facing towards the pulley system. Maintaining a chin-tuck position, the player performs an extension movement of the neck and slowly returns to the neutral position. This process is repeated for the required amount of repetitions with a 60 second rest between sets.
Flx	The head harness is adjusted to the player with weights and cables attached. The player is knelt with one leg flexed at the hip for stability, facing away from the pulley system. Maintaining a chin-tuck position, the player performs a flexion movement of the neck and slowly returns to the neutral position. This process is repeated for the required amount of repetitions with a 60 second rest between sets.
Left Flx	The head harness is adjusted to the player with weights and cables attached. The player is knelt with one leg flexed at the hip for stability, with the pulley system situated on their left. Maintaining a chin-tuck position, the player performs a lateral extension movement to the left at a 45^{o} angle. This process is repeated for the required amount of repetitions with a 60 second rest between sets.
Right Flx	The head harness is adjusted to the player with weights and cables

	attached. The player is knelt with one leg flexed at the hip for stability, with the pulley system situated on their right. Maintaining a chin-tuck position, the player performs a lateral extension movement to the right at a 45° angle. This process is repeated for the required amount of repetitions with a 60 second rest between sets.