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Neck Strength Profile Comparison of University and Professional Rugby Union Players

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Abstract

Neck strength plays a crucial role in preventing concussion, cervical spine injury, and neck pain. However, the absence of a standardised methodology to assess neck strength and a lack of reliable normative data within rugby union poses significant challenges.

This cross-sectional study aimed to compare neck strength between playing levels and positions while establishing anthropometric relationships using the innovative Isometric Neck Strength Testing Apparatus (INSTA). Professional (n=47) and university (n=25) male rugby players participated in maximal isometric neck contractions, evaluating flexion, extension, and lateral flexion strength. Results showed that professional players exhibited significantly greater flexion and extension neck strength compared to university players, while lateral flexion strength remained similar between levels. Forwards consistently outperformed backs, likely due to increased involvement in contact events such as scrums, rucks, and mauls. Notably, front-row players displayed the highest neck strength across all directions. Body mass demonstrated a positive correlation with strength in all directions and positions, while extension strength displayed a weak correlation with age across groups. Height did not show any significant correlation with strength.

The INSTA provided a repeatable method to assess neck strength. Comparative analyses unveiled strength trends among playing positions and levels, shedding light on positional requirements and neck strength profiles across different playing levels. Front-row players exhibited specific neck strength adaptations, whereas backs displayed the lowest neck strength measures.

This study marks the initial steps in gathering repeatable neck strength data, which can contribute to neck rehabilitation, targeted neck strengthening programs, and identifying player requirements for advancing through playing levels.

Continued normative data collection using reliable and repeatable methods like the INSTA can help optimise neck conditioning programs and screening processes. While this study revealed neck strength trends within rugby-playing populations, further research is necessary to conclusively determine neck strength requirements in the future.

Declarations 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.

Signed...... [redacted]

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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.

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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.

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List of Abbreviations

CROM - Cervical Range of Motion

CV - Coefficient of Variation

FFD - Fixed Frame Dynamometry

HHD - Handheld Dynamometry

HHDs – Handheld Dynamometers

ICC - Intraclass Correlation Coefficient

INSTA - Isometric Neck Strength Testing Apparatus

IVMC - Isometric Voluntary Maximal Contractions

MVC - Maximum Voluntary Contraction

SEM - Standard Error of the Mean

TBI - Traumatic Brain Injury

1RM - One Repetition Maximum

1. Introduction

1.1 Background and Context

1.1.1 Rugby Union Injury Risks

Rugby union is a high-impact collision sport which has been associated with a high risk of training and in-game injuries compared to many other sports, particularly to the head and neck (Kara, 2013; Tierney & Simms, 2017a). Studies have reported that 40% of catastrophic acute and chronic rugby injuries occur during scrummaging, resulting in the greatest injury severity in terms of time lost due to injury (Hogan et al., 2010; Trewartha et al., 2015). The tackle, however, is reported to be the most injurious rugby event, and the leading cause of concussion in professional and collegiate rugby union in recent years (Kemp et al., 2008; Kemp et al., 2020a; Kemp et al., 2020b; Patton et al., 2013; Tierney & Simms, 2017a). Concussions are a subset of traumatic brain injury (TBI), attributed to acceleration forces experienced by the brain during impacts, such as in high-speed tackles (Daneshvar et al., 2011; McCrory et al., 2017; Tierney & Simms, 2017a, 2017b). Increasing neck strength has been associated with reductions in head acceleration magnitude during impact, thus reducing the severity of sports-related concussions (Chavarro-Nieto et al., 2021; Collins et al. 2014; Eckner et al., 2014; Farley et al., 2022; Streifer et al., 2019; Viano et al., 2007).

Injury mechanisms such as hyperflexion or buckling of the spine have been observed during scrum collapse leading to compressive loading of the spine (Kuster et al., 2012; Quarrie et al., 2002; Silver, 1984; Trewartha et al., 2015). Increasing neck extension strength, particularly in front row players, has been identified as a key factor in preventing the collapse of the scrum in rugby union (Hamilton & Gatherer, 2014; Olivier & du Toit, 2008). Ensuring the adequate development of neck musculature in preparation for the high forces experienced during scrummaging could reduce the occurrence of scrum collapse, and thus occurrence of associated injury (Hogan et al., 2010; Trewartha et al., 2015).

1.1.2 Neck Strength Assessment

To quantify and compare the neck strength of within human populations, neck strength must be accurately, reliably, and repeatably assessed. Neck strength within human populations has been measured using a wide variety of methods such as handheld dynamometry, isokinetic dynamometry and fixed frame dynamometry (Caccese et al., 2018; du Toit et al., 2004; Dvir & Prushansky, 2008; Mihalik et al., 2011; Peek & Gatherer, 2005; Porfido et al., 2021; Salmon, 2014; Salmon et al., 2015; Streifer et al., 2019). However, the methodologies used in these studies have varying degrees of accuracy, repeatability, and ecological validity Therefore, a comparison of normative neck strength values in the currently available neck strength literature may be of limited value.

The collection of reliable normative neck strength values will enable comparisons between different athletes, playing levels, playing positions, and within the same individual over time. More specifically, comparisons with normative neck strength values may provide insight into concussion and neck injury risk in rugby union players. Identification of neck strength deficiencies can allow practitioners and coaches to implement appropriate training strategies to potentially reduce injury risk (Streifer et al., 2019). Which could be applied to the safe graduation of age-grade or lower-level players to higher levels of competition (Davies et al., 2016; Dezman, Ledet and Kerr, 2013; Hamilton et al., 2014). Such data may also facilitate rehabilitation monitoring and pre-participation screening to prevent future injury (Davies et al., 2016; Hamilton & Gatherer, 2014; Hrysomallis, 2016; Peek & Gatherer, 2005; Streifer et al., 2019). To date, however, there is no consensus on a neck strength measurement method therefore comparisons of neck strength and informed recommendations cannot be achieved (Honda et al., 2018). A method that provides a reliable, repeatable and fast measure of neck strength would be required to collect comparable data sets within human populations, and more specifically rugby union players.

1.1.3 Ecological Validity and Test Practicality

INSTA (Isometric Neck Strength Testing Apparatus) provides a testing apparatus that allows for the fast, reliable and repeatable assessment of neck strength (Williams et al., 2021). Specifically in rugby union, INSTA simulates body positions employed within contact events that can be quickly adjusted using an adjustable bench and load sensors. Even though INSTA provides a viable method of neck strength assessment in professional rugby union, there is a distinct lack of data or normative values. A preliminary data set of neck strength measurements could allow for key comparisons between populations that could highlight deficiencies and inform neck strength training interventions. Therefore, this study aims to assess and compare neck strength within professional and university rugby-playing populations.

1.2 Aims

1. The primary aim of this thesis was to compare neck strength measures between playing levels, and positions and assess anthropometric correlations in professional and university rugby union players.
2. As an additional aim, this thesis aimed to provide normative neck strength values using repeatable and ecologically valid methods in rugby union players.

2. Literature Review

2.1 Rugby Union Overview

2.1.1 Game Characteristics and Positions

Rugby union (rugby) is a team contact sport played by over 6.1 million people worldwide, with over 2.5 million players across England, Scotland and Wales in 2019 (World Rugby, 2019). The men's game turned professional in 1995 (Viviers et al., 2018; World Rugby, 2019). Rugby is played by two teams of 15 players each, over an 80-minute period split into two 40-minute halves (Duthie et al., 2003). An intermittent sport like rugby union has a wide range of physiological requirements such as strength, speed, acceleration, agility, flexibility and endurance, (Kara, 2013). There are 15 positions in rugby, which are generally grouped into two major groups, forwards and backs (Duthie et al., 2003). Forwards have been shown to have higher contact and collision demands whereas backs have greater acceleration, deceleration and high-speed running demands indicating different physiological requirements between position groups (Brooks et al., 2005; Kara, 2013). Men's rugby union became professional in 1995, which led to the increases in speed, force and physical size of players playing within the elite game (Green et al., 2019; Viviers et al., 2018).

2.1.2 Rugby Injuries

As a high-impact collision sport, rugby is associated with a high risk of musculoskeletal and concussion injuries in both training and competition, compared with other sports (Kara, 2013: pg. 17; Tierney & Simms, 2017a). Rugby consists of many sport-specific events that have been shown to cause injury. These include scrums, tackles, lineouts, rucks and mauls, of which tackles have been shown to contribute to the most frequent injury events (Brooks et al., 2005). Tackles accounted for the most frequent injurious events in both British collegiate and English professional men's rugby in the 2019-2020 season (Kemp et al., 2020a; Kemp et al., 2020b). Tackles were the leading cause of concussion as a result of rotational acceleration and inertial loading experienced by the brain during tackles, resulting in shear forces and consequently brain tissue damage (Kemp et al., 2008; Patton et al., 2013; Tierney & Simms, 2017a). Scrums are the formation of eight players from each team, engaging players from three front row players of each team to initiate a competition for possession of the ball, (Hendricks et al., 2020). Scrums have been associated with buckling and hyperflexion of the neck and lower body injuries, accounting for 40% of catastrophic injuries, and the greatest severity of injury within rugby union (Fuller, Brooks and Kemp, 2007). This is likely associated with the repetitive high forces front row forwards experience through scrummaging (Trewartha et al., 2015). Both rucks and mauls are competitive events for the possession of the ball between at least two players from opposing teams. Rucks form when a player has possession of the ball on the ground, however, mauls form when a player has possession in a standing position (Hendricks et al., 2020). Ruck and maul injuries, more frequently lower limb injuries than concussions, are more prevalent in forwards, likely due to their increased involvement in these events (Bathgate et al., 2002; Brooks et al., 2005). Lineouts consist of at least two players from each team in parallel lines and the ball is thrown in from the touchline as a competition for possession. Injury prevalence is low in lineouts, due to non-contact rules, but has been shown to cause lower body injuries (Bathgate et al., 2002; Brooks et al., 2005; Hendricks et al., 2020).

2.2 Neck Strength and Traumatic Brain Injury

2.2.1 Neck Strength vs Inertial Loading in Sports

The cervical spine column provides support to the head whilst allowing its motion in three axes (Heller et al., 2004). Cervical., or neck musculature function is to provide stability, head movement and control the acceleration of the head under impulsive loading (Eckner et al., 2014; Heller et al., 2004). Head acceleration and neck strength have been assessed in head impact events such as soccer heading, providing valuable information about the relationship between the two (Caccese et al., 2018; Collins et al., 2014; Gutierrez et al., 2014). Caccese et al. (2018) suggests that the higher neck stiffness results in a greater effective mass, and lowers head acceleration in soccer heading in children. This is supported in an adult study by Gutierrez et al., (2014) who stipulate that head acceleration during soccer heading cannot be mitigated by weaker necks. Accordingly, laboratory-based studies have also reported lower neck strength to be associated with higher head acceleration from an impulsive load (Eckner et al (2014); Streifer et al., 2019; Tierney et al. (2005). Streifer et al., 2019; Tierney et al. (2005).

2.2.2 Sex Differences in Neck Strength and Inertial Loading

Females were not included in this study due to logical reasons. However, the geometry of the female cervical spine exhibits a more slender and less stable structure compared to males, with females being significantly more likely to experience whiplash in vehicle accidents (Stemper, 2009). Females have lower vertebral cross-sectional area, (Vasavada et al., 2008), lower overall neck girth and significantly lower neck strength (Eckner et al., 2014; Tierney et al., 2005; Vasavada et al., 2008) than their male counterparts. Indeed, under the same impulsive loading conditions, significantly greater head acceleration (both linear and angular) has been reported in females than in males (Eckner et al., 2014; Tierney et al., 2005). Tierney et al. (2008) found that females experienced significantly higher head accelerations in soccer heading trials compared to males. Which further highlights the trend between higher head accelerations during impacts in humans with lower neck strength measures.

In rugby union, Williams et al. (2021)found significantly lower neck strength and smaller neck geometry in female university rugby union players compared with a comparable male cohort. Using in-game head impact telemetry, these authors observed no differences in the overall magnitudes of linear or rotational head accelerations between cohorts despite significant differences in body size. There were, however, different impact kinematics and higher incidence of whiplash in females compared to males. Williams et al. (2021) suggest that lower cervical spine stability and strength may be a key contributing factor in differences in impact kinematics and whiplash observed.

2.2.3 Pre-Activation in Neck Musculature

A confounding factor in the relationship between neck strength and head inertial loading is neck musculature activation. During unanticipated contact, there is little time to brace and engage these muscles (Honda et al., 2018). Several researchers have found pre-activated neck musculature to significantly reduce the linear and angular velocity of the head compared to the unanticipated impacts in male participants (Eckner et al., 2014; Tierney et al., 2005). These authors used an impulsive loading apparatus and suggest that bracing for impact may reduce the magnitude of head acceleration and thus concussion. It follows that unanticipated collisions such as blindside body checks in ice hockey have been associated with higher head acceleration from severe head impacts

(Eckner et al., 2014; Honda et al., 2018; Mihalik et al., 2020: pg. 109). These unanticipated events do not allow for the recruitment of neck musculature and highlight the key role played by neck musculature in mitigating head accelerations during impact.

2.3 Rationale for Neck Strength Measurement

2.3.1 Neck Strength Imbalances and Injury

In soccer heading, Dezman, Ledet and Kerr (2013) assessed the association between flexion and extension strength symmetry and head acceleration variables. During low-velocity soccer heading it has been found that the greater the asymmetry between flexion and extension neck strength the higher the risk of brain injury (Dezman, Ledet and Kerr, 2013). In a systematic review of neck strength assessment studies in rugby union players, Chavarro-Nieto et al. (2021) found that previous studies noted that forward participants displayed a significantly lower ratio between flexion and extension, likely attributed to high extension forces experienced during scrummaging. Reducing asymmetry between flexion and extension neck strength may play a role in the limitation of head accelerations and stabilization of the neck, (Chavarro-Nieto et al., 2021; Dezman, Ledet and Kerr., 2013).

2.3.2 Neck Strength and Concussion Risk

Linear and rotational head acceleration are considered the primary cause of concussive injuries (Meaney & Smith, 2011). Indeed, a growing number of studies using head impact telemetry systems have improved understanding regarding head impact biomechanics (Tierney et al. 2008; Williams et al., 2021). Increases in neck strength have been associated with reduced head acceleration in simulated rugby union scenarios (Collins et al., 2014; Dempsey et al., 2015; Farley et al., 2022; Streifer et al., 2019). Farley et al. (2022) suggested that a 10% increase in isometric neck extension strength can result in a 13% reduction in concussion incidence in rugby union players. Tierney et al. (2005) conducted trials to identify the association between neck stiffness and head accelerations under external force application comparing isometric neck strength values using handheld dynamometers. Using laboratory-based anthropometric testing devices (or crash test dummies), Viano et al., (2007) demonstrated that increasing neck stiffness reduced head acceleration by up to 14% within helmet-to-helmet tackle collisions because of greater coupling between the head and torso. These studies provide an initial indication of the relationship between increased neck strength and reduced head acceleration in rugby union but requires further research to make assertive conclusions.

Associations between concussion risk and neck strength values have been analysed across a high-school athletic population across non-collision sports such as soccer, basketball, and lacrosse, (Collins et al., 2014). These authors compared differences in mean overall neck strength between male and female athletes as well as differences in neck strength within different sports. Similarly, Hildenbrand and Vasavada (2013) produced neck strength profiling within high school athletes, comparing them to collegiate athletes, but included both non-collision and collision-based sports. A total of 90 collegiate athletes and 59 high school athletes from football, soccer, basketball, and wrestling sporting backgrounds were analysed under multiple pre-rotated head positions, (Hildenbrand & Vasavada, 2013).

Some studies suggest that neck strength does not correlate with reductions in head accelerations, showing ice hockey and American football athletes with higher neck strength displayed similar head acceleration in contact events to their peers (Mihalik et al., 2011; Schmidt et al., 2014). These studies utilised helmet-embedded accelerometers known as HIT systems (Ridell, IL, USA). Yet, measuring head acceleration with helmet-embedded sensors has been associated with vast overestimations of head acceleration due to the unpredictable and inconsistent nature of the movement of helmets around the skull (Jadischke et al., 2013; Wu et al., 2016). Jadischke and co-authors (2013) compared the HIT system to 'gold standard' systems finding inaccuracies consistently exceeding 15% during impacts to the instrumented helmets. Indeed, these inaccuracies prevent the accurate prediction of head biomechanics in helmeted sports (Jadischke et al., 2013). Therefore, the absence of association between neck strength and head acceleration suggested by these studies should be handled with caution due to the inaccuracies associated with head acceleration measurement methods employed. Therefore, the absence of association between neck strength and head acceleration suggested by these studies should be handled with caution due to the inaccuracies associated with head acceleration measurement methods employed.

2.3.3 Using Neck Strength Assessment to Reduce Injury Risk in Younger Athletes

In soccer heading, Caccese and co-authors (2018) found that players between the ages of 12 and 24 years old, with smaller head mass, neck girth and neck strength sustained greater head accelerations during soccer heading. Likely attributed to lower maturation levels of neck musculature and potentially a lack of training exposure, compared to their older peers (Chavarro-Nieto et al., 2021; Davies et al., 2016; Hamilton et al., 2012; Hildenbrand & Vasavada, 2013). Caccese et al. (2018) suggest that greater head accelerations experienced by younger athletes should be considered when "determining readiness to begin soccer heading" (pg. 10).

In previous studies, younger rugby union players have been shown to have lower neck strength measurements compared to more senior players, (Chavarro-Nieto et al., 2021; Davies et al., 2016; Hamilton et al., 2012, 2014). Furthermore, Hamilton et al. (2014) found that the number of years of rugby experience was strong a predictor of cervical strength in front-row rugby union players. Placing younger rugby union athletes at a significant disadvantage that is associated with higher injury risk, (Hamilton et al., 2014). Furthermore, Hamilton et al. (2012) suggests that the lack of cervical neck strength in younger athletes may be related to an emphasis on limb training as opposed to neck musculature.

Higher levels of rugby union have demonstrated greater forces experienced in scrums and contact events, (Davies et al., 2016; Green et al., 2019; Streifer et al., 2019). Therefore, to be appropriately prepared to endure the forces associated with scrums and contact events, Hamilton et al. (2014) suggests that age-grade front-row players must satisfy specific neck strength criteria to compete at older age grades and playing levels, (Davies et al., 2016; Hamilton & Gatherer, 2014). In conjunction, coaches should be advised to provide age-grade players with neck conditioning programs to bridge the gap with senior players to reduce injury risk (Davies et al., 2016; Hamilton & Gatherer, 2014).

2.4 Neck Strength as a Modifiable Risk Factor

2.4.1 Neck Strength Training Studies

Training programs have been implemented in non-athletic populations and have shown increases in neck strength variables (Hrysomallis, 2016). For example, Li et al., (2017) demonstrated that both progressive and fixed resistance loading of neck musculature increased isometric neck strength in an office working population over a six-week intervention. In a review of neck strength training studies, Hrysomallis (2016) noted that neck strength training has been shown to elicit significant neck strength improvements from as little as one to two training sessions per week. Also seen in American football studies displaying significant increases in neck strength within a five to eight-week intervention (Hrysomallis, 2016). Furthermore, Chavarro-Nieto (2021) found that neck strength training studies in rugby union have shown significant neck strength increases. A trend demonstrated in studies by Geary et al., (2014) and Naish et al., (2013), where rugby union players showed non-significant increases in all neck strength variables after short neck strengthening program periods, such as five weeks (Daly et al., 2021). Geary and co-authors (2014) presented a five-week training program that is "safe and easy to implement … in rugby union players" and has shown to produce significant increases in neck strength variables (pg. 507).

On the other hand, Becker et al., (2019) implemented a six-week neck strengthening program, exposing soccer-playing participants to weekly neck strengthening exercises to, hypothetically, improve flexion and extension neck strength. Post-intervention, both control and intervention groups displayed non-significant increases of on average 41.2 newtons in isometric flexion neck strength, likely attributed to a learning effect in testing protocols, (Becker et al., 2019). Furthermore, no increases were observed in extension neck strength in intervention participant groups, (Becker et al., 2019). Banded exercises that were implemented in the exercise produced a stimulus of between 2.3 kg and 4.4 kg, depending on the band utilized, (Becker et al., 2019). Hyrsomallis (2016) concedes that studies that do not accurately quantify the forces applied during training cannot provide consistent maintenance of physical exertion when training the neck musculature. Becker et al. (2019) used elastic bands (otherwise known as TheraBands) to apply resistance to neck musculature without quantifying the force applied during interventions whilst stating training resistance applied from the manufacturer's reference values. Uchida et al. (2016) have shown that TheraBands provide varying degrees of resistance depending on the deformation from its initial length and produce "difficulties in controlling the intensity of the exerted strength", (pg. 1269). Therefore, Becker et al. (2019) cannot claim that sufficient stimulus or consistent training forces were achieved in order to provide a sufficient neck strength training intervention.

Similarly, in rugby union participants, Barrett and co-authors (2015) did not find any significant increase in neck strength. Participants were exposed to neck strength training at a fixed resistance of 50% of 1RM, over a six-week period. (Barrett et al., 2019). Chavarro-Nieto (2021) concedes that studies implementing stimuli below the recommended (American College of Sports Medicine) guidelines, above an intermediate level of 60% of 1RM, may lack the required stimulus in order to achieve improvements in neck strength.

Therefore, a lack of quantification, required resistance or training load may have resulted in inconsistent training stimuli potentially leading to ineffective training protocols for neck strength training in these studies. In order for neck strength studies to become more reliable, a repeatable and reliable method for quantifying neck strength must be utilised.

2.5 An Evaluation of Neck Strength Testing Methods

2.5.1 Lack of Standardisation

The lack of standardised protocols and consensus in the field of neck strength assessment in rugby codes can lead to variations in reported findings, making it challenging to establish consistent and comparable outcomes. Without a uniform approach, it becomes challenging to pool data from the few existing studies in rugby union or draw definitive conclusions (Hamilton et al., 2014). Methodological differences including measurement protocols, equipment, and testing procedures add another layer of complexity. To assess neck strength among contact sport athletes, existing studies have used isokinetic or dynamic strength methods, fixed-frame or handheld dynamometry and variations in testing positions and protocols (Peek, 2022). The various methods may lack accuracy, repeatability and ecological validity associated with the position and devices used to assess the neck strength of rugby union players (Dvir & Prushansky, 2008; Salmon et al., 2015). Previous studies have used isokinetic dynamometry, Peek and Gatherers' (2005) 'break test' method, handheld dynamometry (HHD) and fixed frame dynamometry methods to assess and compare neck strength within athletic populations.

2.5.2 Isokinetic Dynamometry

Du Toit et al., (2004) and Schmidt et al., (2014) used an isokinetic dynamometer (ID) to measure torque produced by the neck muscles. IDs are devices used to measure muscle strength using a predetermined counterbalance whilst participants apply maximal force (Baltzopolous and Brodie, 1989). IDs measure muscle strength in torque as they measure moments around a joint of the body (Baltzopolous and Brodie, 1989). Schmidt et al (2014) used an ID known as the HUMAC NORM Testing and Rehabilitation system (CSMi Medical Solutions Inc.) to test isometric neck strength, in prone, supine and side-lying positions. Du Toit et al (2004) used a similar isokinetic device with a specifically designed head "halo" attached, (pg. 4). Restrained at the torso, participants would exert maximal force against the ID or 'halo' attachment of the system and peak torque measured determined max neck strength measures, (Schmidt et al., 2014: pg 2058).

Figure 2-1: Isokinetic Dynamometry used to assess neck strength (Olivier & Du Toit, 2008).

Isokinetic torque measuring systems used by Du Toit et al (2008) and Schmidt et al (2014) to measure isometric neck strength, provide a method that does not allow for any inter-tester variability as the torque is applied and measured by computer software. However, isokinetic devices were designed to measure a segment of the body that has one joint axis (Dvir and Prushanksy, 2008). Due to multiple vertebrae being involved in cervical spine movement, "no fixed axis exists" within the neck thus it is suggested that isokinetic devices are not commonly used in cervical spine strength assessment (Dvir and Prushanksy, 2008: pg. 523; Salmon, 2014).

2.5.3 'Break-Test' Method

Gatherer Systems (Gatherer Systems Ltd, Aylesbury, UK) developed a method to test peak voluntary isometric cervical neck strength in rugby union players through incremental loading (Hamilton and Gatherer, 2014). A dynamometer or load cell was used to measure peak isometric force whilst researchers applied incremental loading via a pulley system or manual resistance (Davies et al., 2016; Hamilton et al., 2012; Hamilton et al., 2014; Hamilton and Gatherer, 2014; Peek and Gatherer, 2005). Participants were tested in a seated position with torso against a treatment bed that was opposite to the direction of isometric contraction with an attached head harness which connected the dynamometer to the participant (Geary, Green and Delahunt, 2014; Peek and Gatherer, 2005). Participants were instructed to maintain a neutral head position whilst incremental loading was applied and neck pain, neurological symptoms or failure to maintain a neutral head position determined the termination of testing (Geary, Green and Delahunt, 2014; Hamilton et al., 2012; Hamilton et al., 2014; Hamilton and Gatherer, 2014; Peek and Gatherer, 2005). Peak forces measured by a load cell or hand dynamometer during testing quantified the maximal voluntary cervical muscle strength, (Hamilton et al., 2012; Hamilton and Gatherer, 2014). Also, Hamilton et al. (2014) utilized the 'break-test' method to assess cervical spine muscular fatigue. Participants were asked to maintain 50% of their peak voluntary isometric extension force until failure, thus, quantifying cervical spine muscle endurance, (Hamilton et al., 2014).

Figure 2-2: 'Break-test' method (Davies et al., 2016).

2.5.4 Handheld Dynamometry

Honda, Chang and Kim (2018) suggest that handheld dynamometers (HHDs) provide the gold standard method to measure muscle strength. Previous research has utilised HHDs to quantify isometric neck strength, with varying methods of application. HHDs are portable handheld devices that are used to measure force and are generally used to quantify muscle strength (Saygin et al., 2021). Furthermore, HHD offers a more affordable and compact alternative to isokinetic dynamometry, which has been considered the gold standard in muscle strength quantification (Saygin et al., 2021).

Caccese et al. (2018), Porfido et al. (2021) and Mihalik et al. (2011) tested cervical spine muscle strength using a HHD placed on the head of participants. Participants were instructed to flex their necks maximally in anterior and anterolateral directions to quantify anterior neck strength in a supine position (Caccese et al. 2018; Porfido et al. 2021; Mihalik et al., 2011). Posterior neck strength was assessed in seated and prone positions by instructing participants to extend their necks maximally in posterior and posterolateral directions (Mihalik et al., 2011; Porfido et al., 2021).

Using handheld dynamometers, Gutierrez, Conte and Lightbourne (2014), Li et al (2017), Tierney et al (2005), Versteegh et al (2015) and Versteegh et al (2020) tested neck strength in general and athletic populations, employing similar methods to Collins et al (2014). Collins et al (2014) measured cervical spine muscle strength using handheld dynamometers and hand tension scales attached to a head harness, comparing the reliability between the two measurement methods. Testers in these studies would place a harness, connected to a tension scale, or dynamometer on the head of the participants, in a seated position with "hips and knees at 90-degree angles" (Li et al., 2017: pg 675). Researchers applied manual resistance to a tension scale and harness or dynamometer when measuring participants' neck strength. Conversely, in studies by Versteegh et al (2015) and Versteegh et al (2020), participants applied their own manual resistance when applying force to the dynamometer to measure neck strength.

Streifer et al. (2019) support the use of a handheld dynamometer as it offers "clear quantification of muscle strength and strength imbalances" (pg. 203). However, the use of manual resistance with handheld dynamometers may result in inconsistencies in the resistance applied by researchers or participants, resulting in inter-tester variability (Streifer et al., 2019). Streifer and co-authors' (2019) suggests that HHD measuring devices should be used with fixed attachments in order "to minimize inconsistencies in clinician force" (pg. 203). To be able to accurately determine the force which is applied to HHDs when quantifying neck strength, the force applied by clinicians or participants should be measured and not considered in the force data. Furthermore, if performed incorrectly, researchers applying manual resistance may overload participants' neck musculature or clinicians may continue to apply resistance at the onset of participant pain or failure, increasing the chance of participant injury.. Attaching devices to fixed frames or structures allows for isometric neck contraction without external manual resistance. Therefore, participants can only exert their voluntary maximal force on the measuring device, so if pain or injury were to occur, participants may stop instantaneously without risk of the continued loading of the neck. In conclusion, inconsistencies associated with researcher or participant resistance application and higher risk of injury associated with previous HHD methodologies may suggest that these devices may not offer the 'gold-standard' method of neck strength assessment (Streifer et al., 2019).

Figure 2-3: Handheld Dynamometry to assess neck and shoulder strength (Mihalik et al., 2011).

2.5.5 Fixed Frame Dynamometry

Fixed frame dynamometry (FFD) is a method of muscle strength assessment that has been derived as an alternative to the HHD to quantify muscle strength (Ransom et al. 2020). FFD utilises dynamometers or similar devices attached to a fixed frame removing the need for a researcher (Ransom et al. 2020). FFD has been identified as the gold-standard for neck strength assessment in previous studies (McBride et al. 2022).

Previous studies have used a "spring-type clinical dynamometer" and load cells attached to a fixed position to measure flexion and extension neck strength (Becker et al., 2019; Dezman, Ledet and Kerr, 2013: pg 322). Participants' neck strength was assessed through maximal contractions through a head harness against a fixed dynamometer or load cell. Similarly, Naish et al (2013) and Eckner et al (2014) employed a similar methodology but also assessed neck strength in lateral flexion directions. Studies such as Porfido et al. (2021) and Becker et al. (2019) utilised handheld dynamometers and force sensors attached to a sling and fixed to a massage bed. This provides an example method that employs fixed attachment to negate variable clinician force when using handheld dynamometers. These methods known as fixed frame dynamometry (FFD) remove any requirement of manual resistance from researchers or participants seen in HHD studies, which may result in variable force application (Streifer et al. 2019). Salmon (2014), Salmon et al. (2015), Ylinen et al. (1999) and Ylinen et al. (2003) used load cells or strain gauge sensors, fixed to a metal headpiece, surrounding the head, removing any need for manual resistance thus removing any risk of inter-tester variability and reducing the likelihood of injury.

In rugby union, Salmon (2014) developed an FFD method using load cells attached to a frame that has been used in other studies such as Salmon et al. (2015), Salmon et al. (2018) and Williams et al. (2021). Four load cells were positioned around the head in the sagittal and transverse planes of a fixed metal headpiece, enabling the measurement of flexion, extension and left and right lateral flexion neck strength, (Salmon, 2014). "The headpiece was aligned … above the eyebrows" and in line with a padded bench, for the torso, to allow for a neutral head position and provide a 90° angle position at the hips, (Salmon, 2014; pg. 126-127). To maintain ecological validity, participants were unrestrained to allow for the recruitment of muscles in body regions like the legs and torso as well as cervical neck musculature, (Salmon et al., 2015). Williams et al. (2021) based their methodology on Salmon's 2014 study but added a knee rest and restraints to remove any effect of extraneous musculature. This apparatus was used to measure the maximal isometric cervical neck strength and endurance in human populations.

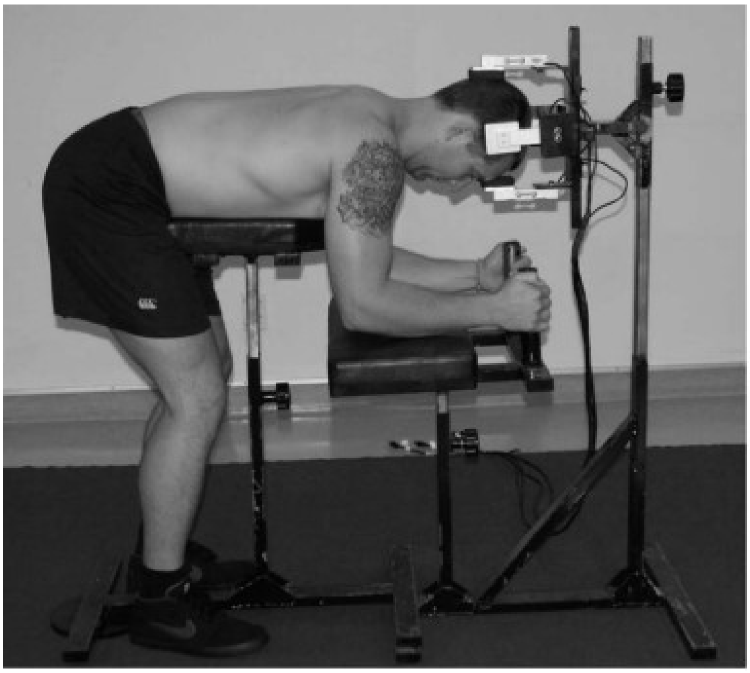


Figure 2-4: Fixed frame dynamometry to assess neck strength in a 'simulated contact posture' (Salmon et al., 2015).

McBride et al. (2022) utilized the VALD ForceFrame (Newstead, Australia) to quantify neck strength in an active human cohort. The VALD system positions adjustable load cells on a fixed frame allowing participant to apply maximal force against and has been used to assess groin adductor strength in the past (McBride et al. 2022). McBride and co-authors (2022) instructed participants to adopt a quadruped position and apply maximal force on the load cells in neck extension, flexion and lateral flexion trials. Loads cells were positioned accordingly, in superior, inferior and lateral positions to the head depending on the contraction direction trial (McBride et al., 2022). McBride et al. (2022) did not restrain participants and allowed for the recruitment of the whole body in order to maintain maximal ecological validity.

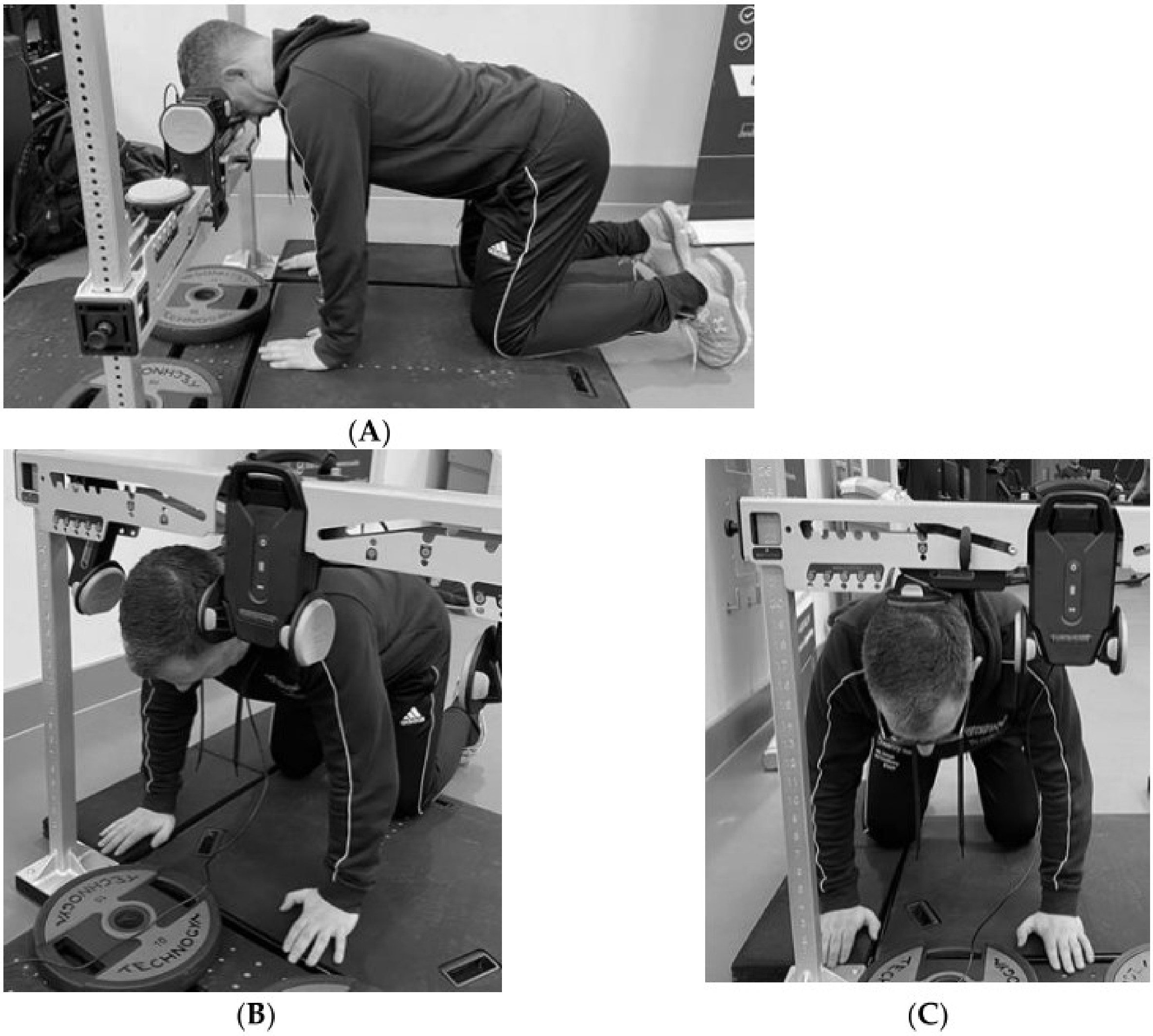


Figure 2-5: VALD instrument used to assess neck strength (McBride et al., 2022).

FFD has generally demonstrated good to excellent reliability between testing sessions in the previous studies mentioned above (McBride, 2022 & Salmon et al., 2015). However, methodologies of neck strength assessment still pose some inconsistencies in application associated with the posture of participants and restraint of participants during assessments (McBride et al., 2022; Salmon, 2014; Williams et al. 2021). Indeed, no consensus methodology of FFD has yet been determined, consequently, leading to a lack of meaningful comparisons between FFD neck strength assessment studies.

2.5.6 Previous Methods Critique

Li et al. (2017), did not assess isometric neck strength by randomizing the direction of contraction throughout testing but used an 'order' when testing participants. These methods may be liable to fatigue or a learning effect, resulting in potentially skewed data sets. For example, flexion was assessed first and left lateral flexion was tested last in Li et al.'s (2017) testing cohort. Hypothetically, results may exhibit increased neck strength measures in variables assessed at the latter end of the order due to technique acquisition. Neck strength testing methods become less novel to the participant and may be liable to a learning effect. Conversely, fatigue may negatively affect neck strength variables in contraction directions that are assessed later in the testing order. In most studies assessing neck strength, randomized trials are used to negate any risk of learning effect or fatigue when assessing human participants. Therefore, randomization of contraction directions during neck strength assessment should be implemented within neck strength assessment.

2.5.7 Measuring Neck Strength in Multiple Planes

Previous research has considered different measures as a representative of cervical neck strength. Some studies have considered neck strength measures in the sagittal plane which only considered flexion and extension (Dezman, Ledet and Kerr 2013; Tierney et al., 2005). Tierney and co-authors' (2005) objective was to assess the effect of neck strength in anticipated and unanticipated flexion and extension loading so only required these measurements. However, Dezman, Ledet and Kerr (2013) investigated the effect of neck strength on head kinematics in soccer heading. Even though the dominant movement of the head and neck may be in the sagittal plane in football, exclusively investigating flexion and extension may lack ecological validity. The force of an impact from a football may not solely act in the sagittal plane therefore lateral flexion and rotation neck strength may influence head kinematics. This highlights the need for lateral flexion and rotational neck strength assessment in athletic populations.

Gutierrez et al (2014) further investigated the effect of neck strength on head kinematics in soccer heading measuring flexion, extension and lateral flexion. Which considers neck strength in the sagittal and transverse planes, leading to a more ecologically valid representation of neck strength in soccer heading. In studies by Collins et al. (2014), Li et al. (2017), Naish et al. (2013) and Schmidt et al. (2014) the same four neck strength measures were considered. However, Streifer et al. (2019) suggest that “cervical spine strength should be considered in 3 planes … flexion/extension, lateral flexion and rotation” (pg. 203).

Caccese et al. (2018), Porfido et al. (2021) and Mihalik et al. (2011) considered cervical spine flexion, extension, lateral flexion and rotational neck strength, providing a more holistic profile of participants’ neck strength. However, Ylinen and co-authors (2003) suggest that rotational neck strength should be measured from multiple starting positions of the head, which was not the case in these studies. Neck rotation strength varies depending on the pre-testing position of participants as there is a “change in lever arm of the muscles involved” (Ylinen et al., 2003: pg. 471). For example, neck rotation strength measures in Ylinen and co-authors’ (2003) study suggested that a pre-rotation position opposite to the direction of contraction resulted in greater rotation force measures. Ylinen and co-authors (2003) concluded that the most accurate rotational neck strength should include measurements from multiple pre-testing positions which places previous neck strength studies’ assessment of rotational neck strength into question. Indeed, multiple measures to quantify rotational neck strength create logistical obstacles, especially in elite sports environments where there are many time restraints. Therefore, assessing rotational neck strength may not be viable in studies assessing professional athletes.

2.5.8 Body Restraint in Neck Strength Testing

Many previous studies did not restrain participants throughout maximal neck strength assessments, (Caccese et al., 2018; Collins et al., 2014; Davies et al., 2016; Hamilton et al., 2012; Hamilton et al., 2014; Hamilton and Gatherer, 2014; Li et al., 2017; McBride et al. 2022; Mihalik et al., 2011; Peek and Gatherer, 2005; Salmon, 2014; Salmon et al 2015). However, Dezman, Kerr and Ledet (2013) utilized restraints at the torso to “isolate the neck muscles and reduce accessory movement”, (pg. 322). The rationale behind reducing the recruitment of accessory muscles through body restraints is founded to produce a repeatable and isolated measurement of neck musculature strength, which, has been attempted in seated, side-lying, prone and supine positions (Becker et al., 2019; Eckner et al., 2014; Du toit et al., 2004; Naish et al., 2013; Porfido et al., 2021 and Schmidt et al., 2014). Even though previous studies have employed methodologies to limit accessory muscle involvement, further research into the effect of accessory muscles on neck strength assessment must be further investigated to empirically suggest the importance of body restraint use in neck strength assessment.

Salmon (2014) argues that to maintain ecological validity, participants from collision sports, such as rugby union, should not be restrained as neck strength assessed in this test would be "functionally relevant for the sporting environment", (Salmon et al., 2015). Furthermore, Salmon's 2014 study implements forearm benches and hand grips allowing participants to push against and anchor themselves against these structures. Similarly, McBride et al. (2022) implemented no restraints to maintain ecological validity and similar positions when considering tackle and scrum techniques in rugby union. These methods are not designed to isolate neck musculature contrary to some previous neck strength studies. Consequently, it could be suggested that these methodologies measure the ability of the participant to apply force to the measuring device using their whole body. Variability in the force applied by the rest of the body could be affected by scenarios such as limb injuries and could result in neck strength measure variability in these studies. The use of body restraints in neck strength assessment needs to be investigated in the future to further understand the effect on neck strength variables.

2.5.9 Position of Participants for Neck Strength Testing

Caccesse et al (2018), Porfido et al (2021) and Becker et al (2019) measured isometric neck strength of athletic populations using similar methods in prone and supine positions. These studies explored relationships between cervical neck muscle strength, head kinematics and neck strengthening methods in soccer heading. Even though these studies employed methodologies to accurately measure neck strength, these methods lack ecological validity with respect to the study's associated sport. Measuring neck strength in prone and supine positions does not directly simulate upright standing postures used during soccer heading. Alternatively, Gutierrez, Conte and Lightbourne (2014) assessed neck strength in a seated position when analyzing relationships between neurocognitive changes and neck strength in soccer heading. A method that provides an example of positioning where the neck musculature is utilized in the same posture at which it is tested.

Davies et al (2016), Geary, Green and Delahunt (2014), Hamilton et al (2012), Hamilton et al (2014), Hamilton and Gatherer (2014) and Peek and Gatherer (2005) utilized the Gatherer system

(Gatherer Systems Ltd, Aylesbury, UK) to assess neck strength in rugby union players in seated positions. Participants of these studies were recruited deliberately as they participate in sports that are considered collision sports. However, Salmon et al (2015) suggest that measures of neck strength in seated and supine positions "have questionable relevance for collision sports" as the majority of collisions occur in a "horizontal position", (pg. 638). Indeed, this led Salmon (2014) to develop neck strength assessment methods in a "simulated contact posture", positioning participants in a standing horizontal trunk position, (Salmon et al., 2015: pg. 639).

Most studies allowed participants to position their feet, knees and hands on the floor in seated and in some cases standing positions. Salmon et al. (2015) suggest that allowing participants to produce force through the feet increases the ecological validity of neck strength assessment within rugby union. However, some studies have implemented strategies to limit the use of the legs during testing in an attempt to isolate cervical neck strength (Naish et al., 2013). For example, Almosnino, Pelland and Stevenson (2010) placed a cardboard box under participants' feet, as an audible and visual indicator, so that the box would collapse if it were to succumb to any force. Similarly, Naish et al. (2013) utilized "air-inflated balance discs" to minimize the risk of force application from the feet. Even though this may limit the amount of force from the lower body it may still allow for some recruitment of the lower body.

Studies that employed prone or supine positions, intentionally or otherwise, such as Caccese et al. (2018), Mihalik et al. (2011) and Porfido et al. (2021) would remove any risk of force application from the lower body as the feet were not in contact with the floor or any other surface. Indeed, Williams and co-authors (2021) adapted Salmon's (2014) method into a prone-lying position and removing armrests, whilst replicating the concepts behind the simulated contact posture, in order or remove the use of the feet or extraneous musculature. Removing the use of the feet and other body parts further isolates the neck musculature and provides a more reliable assessment of neck strength (Dezman, Kerr and Ledet, 2013).

2.6 Benefits of Improved Cervical Strength

2.6.1 Reduction in Cervical Spine Injuries

Daly, Pearce and Ryan (2021) suggest that research on neck strength training reducing cervical spine injury risk is currently very limited and would require further research in both sexes and larger cohorts. However, Naish et al. (2013) found that a 26-week neck strength intervention significantly reduced the number of cervical spine injuries. Injury surveillance data collected over two seasons, showed a significant decrease from 11 to 2 cervical spine injuries in match play, respectively, (Naish et al., 2013). Naish et al. (2013) suggest that non-significant increases in neck strength may not be solely responsible for the reduction in cervical spine injuries. Associated neurological adaptations such as improved coactivation, proprioception and recruitment of deep cervical flexors may have attributed (Naish et al., 2013). In conclusion, Naish and co-authors' 2013 study provides a pilot study assessing the role of neck strength and training in cervical spine injury mitigation but studies with larger cohort sizes over greater durations would be required to ascertain the relationship between these variables.

Nightingale et al. (1996) suggest that neck musculature plays a role in the stabilization of the neck during trauma but is limited in compression loading events such as hyperflexion or buckling. Injury, as a result of compressive loading, has been shown to occur two to three times quicker than neck musculature can be activated, mitigating the role of neck musculature in compressive impacts (Nightingale et al., 1996).

2.6.2 Cervical Strength and Neck Pain

Deep cervical flexors, such as longus colli and capitis muscles, support to the cervical lordosis and the cervical joints (Falla, 2004; Kim & Kwag, 2016). These structures have been shown to play an active role in the reduction of head accelerations (Streifer et al., 2019). Neck pain sufferers often exhibit impaired neuromuscular control of the deep cervical flexors leading to an increased in the recruitment of superficial cervical muscles (Edmondston et al., 2008; Falla, 2004; Salmon, 2014; Salmon et al., 2011; Worsfold, 2020). Click or tap here to enter text.As a result, neck pain sufferers require greater muscular recruitment to produce equivalent force, potentially increasing the risk of TBI (Falla, 2004). Kim & Kwag (2016) and Worsfold (2020) suggest that neck strengthening has the potential for the active rehabilitation of neck pain. Resistance training and improved neck strength forces have been shown to improve neck pain and neck mobility in intervention studies, (Dvir & Prushansky, 2008; Li et al., 2017; Worsfold, 2020). Indeed, improving the activation and strength of deep cervical flexors could reduce TBI risk in neck pain sufferers (Streifer et al., 2019).

2.6.3 Neck Strength and Scrummaging Performance

Trewartha et al. (2015) state that scrummaging in rugby union places high biomechanical forces on front-row players placing them at a higher risk of injury. Hogan et al. (2010) have shown scrums to produce forces exceeding 7,000N are placed which exceeds the 2,000 N injury threshold of the spine. Ensuring sufficient development of neck strength has been identified as an important factor in injury prevention (Hogan et al. 2010).

Scrum stability is achieved mainly by the front-row forwards and the ability of these players to keep the scrum from collapsing (Olivier & Du Toit, 2008). Olivier and Du Toit (2008) explained that it is important for these players to maintain stability in the scrum in order to win or maintain possession. In previous studies, front-row forwards have displayed greater extension neck strength compared to other playing positions which may be attributed to the key role they play in the scrum (Hendricks et al., 2020; Olivier & du Toit, 2008: pg. 102). Scrum performance is an important aspect of a team's attacking play in which neck extension strength plays a role in the success of the scrum, (Green et al., 2019; Hamilton et al. 2014).

2.7 Neck Strength and Anthropometric Correlations

Garcé et al. (2002) have shown that body mass and height were positively correlated with isometric neck strength in the general male populations but showed a lower correlation in comparison to sportsmen. Furthermore, Geary et al. (2013) found that the isometric neck strength profile of rugby union players exceeds that of the general population. Greater body mass, neck girth and neck length have been associated with stronger necks in rugby forwards compared to backs (Chavarro-Nieto et al., 2021). Hamilton and Gatherer (2014) found strong associations between extension and neck circumference in professional rugby union players. Whilst Salmon et al. (2018) found that peak voluntary flexion, extension, and lateral flexion contraction forces were significantly correlated with neck girth in rugby union player populations. A trend that was not similarly found in adolescent rugby union players (Hamilton et al., 2012). Increased neck circumference and strength have predominantly been found in forwards and have been attributed to the higher demands on the neck in events such as scrums rucks and mauls (Geary et al., 2013; Olivier & Du Toit, 2008; Salmon et al., 2018).

Salmon and co-authors (2018) showed that professional rugby union players' body mass only demonstrated a correlation with peak voluntary flexion and extension neck strength variables. A finding was similarly found by Hamilton and co-authors (2012) in adolescent rugby players, where only isometric extension neck strength significantly associated with increased body mass. Conversely, Hamilton and Gatherer (2014) showed that increased body mass were associated with higher neck strength values in all directions.

No correlation was found between age, height, and maximal voluntary neck contractions (Salmon et al., 2018). Whereas age and height were significantly associated with isometric neck strength in adolescent rugby players (Hamilton et al., 2012). Cervical range of motion (CROM) variables in flexion and rotation have shown a moderate association with isometric extension neck strength variables, alongside poor association in extension and 'side flexion' (commonly referred to as lateral flexion in this study) CROM variables (Hamilton & Gatherer, 2014).

2.8 Neck Strength in Rugby Union

2.8.1 Neck Strength Comparison Studies in Rugby

Whilst analysing the reliability of their novel isokinetic dynamometry neck strength testing apparatus Du Toit et al. (2004) analysed the neck strength and circumference of 81 under-19 first-team rugby players but the specific level of competition of these participants was not specified. Even though the main aim of this study was to assess the reliability of novel methods, this study allowed for the comparison between extension, flexion, and lateral flexion in seated positions (Du Toit et al., 2004). Using similar methods, Olivier and du Toit (2008) assessed isokinetic strength profiles in 189 elite South African rugby union players as well as assessing anthropometric variables such as neck girth, height and weight. Comparing positions' neck strength, imbalance ratios, anthropometrics and CROM within elite rugby union player populations, Olivier and du

Toit (2008) began to produce normative values to inform rehabilitation and neck strengthening programs.

Hamilton et al., (2012) evaluated neck strength in school-aged rugby players, using the 'break test' method employed by Peek and Gatherer (2005). Recruiting 382 participants, Hamilton et al. (2012) quantified neck strength and grip strength within all participants and additional neck circumference and CROM data in 166 participants of the larger cohort. More recently Hamilton and co-authors (2014) profiled and compared 30 elite (under-18) age-grade and 22 senior amateur front-row players, using the break test method, to determine whether age-grade players possessed the isometric neck strength to graduate to senior-level rugby. Furthermore, Hamilton and Gatherer (2014) used the break test to present neck strength profiles of 27 professional male rugby union players and assessed associations between anthropometric characteristics and neck strength profile trends.

In a simulated contact posture, Salmon et al. (2015) compared 41 amateur rugby union players' neck strength to a control group of 17 university students. Profiling flexion, extension, and lateral flexion neck strength before and after a competitive rugby union season, Salmon and co-authors (2015) compared peak force production and anthropometric characteristics between three main populations, rugby forwards and backs and a healthy student control group. Using modified methods, Williams et al. (2021) assessed neck strength in 53 male and female collegiate athletes in order to assess associations with neck strength profiles and altered head kinematics in rugby union. In this study, anthropometric characteristics were also assessed and compared between male and female participants (Williams et al., 2021).

Across neck strength assessment research there are many different methodologies that have been used to assess various human populations. Firstly, neck strength studies have assessed neck strength in various participant positions such as prone, seated, supine, standing and quadruped. Furthermore, previous literature has employed an inconsistent application of participant body restraints from no restraints to torso and leg restraints and measuring devices to assess neck strength. As a result of a wide range of methodologies, it is difficult to directly compare neck strength variables from previous neck strength assessment literature. Future research should look to develop a consensus neck strength assessment methodology to allow for constructive comparison between studies and the formation of normative values.

2.9 Summary and Future Research

Many methodologies have been used to assess neck strength in previous scientific literature, such as HHD, ID, 'break test' method and FFD (Almosnino et al., 2010; Collins et al., 2014; Du Toit et al., 2004; Peek, 2022; Salmon, 2014). Previous studies have assessed a wide range of variables associated with neck musculature such as neck strength endurance, neck strength disparities, neck rotation strength and neck stiffness (Geary et al., 2013; Salmon, 2014; R. T. Tierney et al., 2005; Ylinen et al., 2003). However, the most commonly reported parameters associated with neck strength are maximal flexion, extension and lateral flexion neck strength data (Streifer et al., 2019).

Various apparatus has been implemented to assess neck strength in previous studies. For example, handheld dynamometers, spring-loaded dynamometers and strain gauges have been implemented with varying methodologies, but generally used with researcher force application as a handheld device (Collins et al., 2014; Peek, 2022; Peek & Gatherer, 2005; R. T. Tierney et al., 2005). Some studies have utilised isokinetic dynamometers to measure applied torque during neck movements, such as Schmidt and co-authors' 2014 study which used the HUMAC NORM system (CSMi Medical Solutions Inc.). Fixed frame dynamometry has been applied using various methodologies such as devices fixed to frames or beds to assess neck strength in many different participant postures, but have all used similar measuring devices such as load cells and dynamometers (Almosnino et al., 2010; McBride et al., 2022; Salmon, 2014; Williams et al., 2021).

Research into neck strength assessment does not pose a clear and standardised methodology to assess neck strength with repeatability, reliability and ecologically validity (Dvir & Prushansky, 2008; Salmon, 2014). Furthermore, previous studies display various limitations such as inaccuracies in participant or researcher applied resistance, increased injury risk, limited axis of movement or no limitation of extraneous muscle involvement. These limitations are caused by various aspects of methodologies in previous literature such as resistance application, posture during testing and apparatus limitations. Therefore, a reliable, repeatable, ecologically valid and, most importantly, standardised method for neck strength assessment should sought after (Dvir & Prushansky, 2008).

Previous literature has compared neck strength in various populations, however, there is currently little research into the comparison of rugby union players' neck strength, (Hamilton et al., 2014). Studies such as Collins et al. (2014), Hildenbrand & Vasavada (2013) and Tierney et al. (2005) have outlined neck strength comparisons within athletic populations in both collision and non-collision sports but have not detailed rugby union specifically. Previous studies have used isokinetic dynamometry and Peek and Gatherers' (2005) break test to assess and compare neck strength within rugby union populations, but the methods implemented may lack reliability, repeatability, and ecological validity (Dvir & Prushansky, 2008; Salmon et al., 2015). Salmon et al. (2015) and Williams et al. (2021) have employed FFD methods with higher levels of ecological validity for rugby union. However, these studies analyse neck strength within amateur populations and lack neck strength data from elite rugby union players. Therefore, future research must lead to the development of normative values of neck strength and comparisons in elite and amateur rugby union, which may be used to identify imbalances and inform pre-participation screening and injury rehabilitation (Dezman, Ledet and Kerr, 2013; Olivier & Du Toit, 2008). Future research should be directed to making similar comparisons between playing levels and positions that have been attempted by Hamilton et al. (2014), Hamilton & Gatherer (2014) and Olivier & du Toit (2008) with standardised and repeatable methods for neck strength assessment.

Table 2-1: Summary table of Previous neck strength assessment methodologies

Study	Method	Position	Restraints	Resistance Application	Participants	Aim	Outcomes	Limitations	Reliability
Ylinen et al. (1999)	FFD	Multiple	None	Fixed attachment	33 participants	Reproducibility of isometric neck strength assessment	Reliable assessment of neck strength in human population.		ICC = 0.94-0.98 (Inter-session reliability)
Ylinen et al. (2003)	FFD	Multiple	None	Fixed attachment	20 Healthy men	Assess axial neck rotation strength in neutral and rotated head positions	Rotational neck strength varies depending on the starting position of the head.	Positioning of participants not ecologically valid to rugby union.	ICC = 0.94-0.98 (Inter-session reliability)
Du Toit et al. (2004)	ID	Prone, supine, side-lying	Torso	Automated resistance	81 schoolboy rugby players	Reliability and assessment of neck strength using isokinetic dynamometry	Good reliability of ID for isometric neck strength assessment.	Multi-jointed neck not suitable for assessment using ID, due to ID's fixed axis of rotation.	ICC >0.89
Peek and Gatherer (2005)	Break test'	Seated	None	Manual by researcher	1 professional rugby union player	Case study of rugby union player neck strength following neck injury	Suggest the value of neck strength assessment in neck injury rehabilitation	Manual resistance application; Not an ecologically valid posture for rugby union, Lack of restraints; Determined by failure which could increase injury risk	Not reported
Tierney et al. (2005)	HHD	Seated	None	Manual by researcher	60 physically active men and women	Assessment of gender difference in head-neck stabilisation during head acceleration	Lower neck stiffness seen in female participants may be associated with higher head accelerations in	Manual resistance application	ICC = 0.96 (Intra-tester reliability)

							response to external force stimulus.		
Almosnino et al. (2010)	FFD	Seated	Torso, Shoulders	Fixed attachment	26 physically active male participants	Assess re-test reliability of novel fixed frame dynamometry method for neck strength assessment.	Novel neck strength assessment method provides an acceptable degree of reliability	Seated posture not ecologically valid for contact sports such as rugby union.	ICC = 0.9-0.99 (Re-test reliability)
Mihalik et al. (2011)	HHD	Prone, supine, seated	None	Manual by researcher	37 youth ice-hockey players	Investigate head kinematics & neck strength in ice-hockey players	Mean strength values by group/gender.	Manual resistance application; Lack of restraints	ICC >0.821
Hamilton et al. (2012, 2014)	Break test'	Seated	None	Manual by researcher	382 age-grade rugby players & 30 age-grade vs 22 senior rugby union players	Compare neck strength in age groups	Older athletes exhibited greater neck strength	Manual resistance application; Lack of ecologically valid posture for rugby union, Lack of restraints; Determined by failure which could increase injury risk	ICC = 0.9 (Intra-observer)
Naish et al. (2013)	FFD	Seated	Torso	Fixed attachment	27 rugby players	Evaluation of neck strengthening in reducing cervical spine injuries	Significant reduction in match-related injuries.	Positioning of participants not ecologically valid to rugby union.	ICC = 0.94-0.98 (Inter-session reliability)
Dezman, Ledet and Kerr (2013)	FFD	Seated	Torso	Fixed attachment	16 College soccer players	Relationship between neck strength symmetry and head kinematics in soccer heading	Neck strength asymmetries linked to higher acceleration.	Only assessed flexion and extension. Lacks ecological validity in sports due to	Not reported

								forces acting in multiple planes.	
Geary et al. (2013, 2014)	Break Test'	Seated	None	Manual by researcher	25 rugby union players, 15 professional & 10 semi-professional rugby union players	Assess intra-rater reliability of 'break test' method, Assess effect of neck strength training on isometric neck strength	Found excellent intra-rater reliability in a rugby union player population, found a 5-week neck strength training program increased isometric neck strength in semi-professional and professional rugby union players	Manual resistance application; Not an ecologically valid posture for rugby union, Lack of restraints; Determined by failure which could increase injury risk	Intra-rater reliability ICC<0.8
Collins et al. (2014)	HHD	Seated	None	Manual by researcher	6662 high-school athletes	Analyse effectiveness of neck strength assessment in high-school populations and compare neck strength assessment apparatus	Tension scale dynamometer show good correlation with HHDs.	Manual resistance application; Lack of restraints	ICC = 0.83-0.94
Eckner et al. (2014)	FFD	Seated	Torso, Shoulders	Fixed attachment	46 contact sport athletes	Assess effect of neck strength on anticipated and unanticipated impulsive impact loading of the head.	Increased neck strength attenuates head impact kinematics in anticipated impulsive loading. However, the effect of neck strength in reducing head accelerations during unanticipated impacts was not seen.	Seated position during assessment is not ecologically valid for contact sports such as rugby union.	Re-test reliability was excellent (ICC = 0.956)
Hamilton and Gatherer (2014)	Break test'	Seated	None	Manual by researcher	27 professional rugby union players	Profile neck strength in professionals	Normative data by position.	Manual resistance application; Not an ecologically	Not reported

								valid posture for rugby union, Lack of restraints; Determined by failure which could increase injury risk	
Gutierrez et al. (2014)	HHD	Seated	None	Manual by researcher	17 female high-school soccer players	Relationship between neck strength & cognition in soccer heading	Negative correlations between neck strength and head accelerations were discovered in soccer heading.	Manual resistance application.	ICC = 0.93-0.96
Salmon (2014)	FFD	Standing	None	Fixed attachment	Varied sample sizes	Develop FFD method to assess neck strength in different populations	Reliable assessment of neck strength using FFD.	Lack of restraints and allowed recruitment of arms and legs may not isolate neck musculature	ICC = 0.91-0.97 (Intra-class reliability)
Schmidt et al. (2014)	ID	Prone, supine, side-lying	Torso	Automated resistance	49 collegiate American football players	Assess cervical muscle capacity in elite athletes	Greater neck stiffness attenuated angular head accelerations in American football players	Multi-jointed neck not suitable for assessment using ID due to ID's fixed axis of rotation.	ICC = 0.93-0.99 (Intra-class reliability)
Versteegh et al. (2015, 2020)	HHD	Seated	None	Manual by participant	30 & 21 healthy participants	Assessing reliability of HHD in adult populations & Assessing effectiveness of neck strength training in healthy population	HHD is a reliable method of neck strength assessment & neck strengthening programs may reduce concussion risk in sports.	Manual resistance application.	ICC = 0.87-0.95 (Inter-session reliability)
Salmon et al. (2015)	FFD	Standing	None	Fixed attachment	20 participants	Assessment of reliability of neck strength and	Good reliability of FFD for isometric neck strength	Lack of restraints and allowed	ICC = 0.8-0.91

						endurance assessment using FFD in a simulated posture	assessment in a simulated 'contact posture'.	recruitment of arms and legs may not isolate neck musculature	
Davies et al. (2016)	Break Test'	Seated	None	Manual by researcher	21 Age-grade & 19 Senior international rugby union players	Assess neck strength in age-grade and senior international rugby union players	Identified greater neck strength in senior players compared to age-grade players	Manual resistance application; Not an ecologically valid posture for rugby union, Lack of restraints; Determined by failure which could increase injury risk	Not reported
Li et al. (2017)	HHD	Seated	None	Manual by researcher	102 office workers	Effect of neck strength training on chronic neck pain	Neck strength increases following neck strength training program which were associated with reduced neck pain and improved neck strength and mobility.	Manual resistance application; Did not randomise neck strength trials; Lack of restraints	Not reported
Caccese et al. (2018)	HHD	Prone, supine	None	Manual by researcher	100 soccer players	Investigate head kinematics & neck strength in soccer heading	Flexion/extension values. Correlations between variables.	Manual resistance application; Lack of restraints	ICC >0.90 (Intra-rater reliability)
Becker et al. (2019)	FFD	Prone, supine	Torso	Fixed attachment	33 soccer players	Investigate effects of training on neck strength and head accelerations in soccer heading.	Non-significant increases in neck strength following neck strength training program.	Only assessed flexion and extension. Lacks ecological validity in sports due to	Not reported

								forces acting in multiple planes.	
Porfido et al. (2021)	HHD	Prone, supine	Torso	Manual by researcher	99 soccer players and non-athletes	Assess relationship between neck strength/symmetry in soccer players and non-athletes	Strength values in prone/supine. Correlations between groups.	Manual resistance application	Not reported
Williams et al. (2021)	FFD	Prone	Torso, Legs	Fixed attachment	25 female & 28 male	Assess neck strength and head impact kinematics in female and male rugby union players	Increased head acceleration during impact findings in female participants, likely attributed to lower neck strength, lack of coaching and playing opportunities in female rugby union	Assessed amateur university rugby union players, lack of neck strength data in professional rugby union athletes	Not reported
McBride et al. (2022)	FFD	Quadruped	None	Fixed attachment	40 physically active participants	Assess reliability of VALD in assessing neck strength between testers; Assess sex differences in neck strength	Good reliability of VALD apparatus for isometric neck strength assessment.	Lack of restraints and allowed recruitment of arms and legs which may not isolate neck musculature	ICC >0.87, ICC <14%

3 Methods

3.1 Participants

3.1.1 Participant Recruitment and Ethical Approval

Trained male rugby union players, who were actively participating in competitive rugby union activities and were recruited from local professional and university teams. Players from the professional level were determined as contracted players with the respective local professional team. University players were determined by their participation in the local university fixtures and training with the university 1st team. In total, 75 players volunteered for the study and provided written informed consent. Participants were excluded from this study if they had suffered a recent injury to relevant structures such as the head, shoulder, or neck. Participants who had suffered a recent injury (within 3 months of assessment) were assessed and passed by a medical professional, or otherwise excluded. Any participants who were unable to complete familiarisation and/or maximal isometric neck strength testing, for any reason, were also excluded from this study.

Institutional ethical approval was obtained from the Swansea University Sports Science Ethics Committee, prior to the commencement of this study (Swansea University ref: 2016-059, amendment 7). Written consent was obtained before the onset of testing, please see Appendix A and B for the information and consent form provided.

3.1.2 Participant Demographics and Anthropometric Measurements

Of the 72 study participants, 47 played rugby at professional level (age 25.9 ± 4.4 years, body mass 104.2 ± 12.8 kg, height 185.7 ± 7.6 cm) and 25 played rugby at the university level (age 20.2 ± 1.6 years, body mass 98.1 ± 14.2 kg, height 184.8 ± 6.5 cm). Prior to any neck strength measurements, participants' body mass (kg) and height (cm) were measured using weighing scales and a stadiometer (SECA, Kettering, UK).

3.2 Experimental Design and Study Protocols

A cross-sectional study design was used in this thesis.

3.2.1 Testing Apparatus

A isometric neck strength testing apparatus (INSTA) was used to assess isometric neck strength, (Williams et al., 2021). Derived from Salmon's 2014 testing apparatus using fixed frame dynamometry, the INSTA apparatus (Figure 3-1) was designed based on the limitations of Salmon's apparatus (Salmon, 2014; Salmon et al., 2015). Similar to Salmon (2014), a horizontal bench was used to simulate a 'contact posture' of the head, neck and torso, similar to a posture that is employed in rugby union. Contrary to Salmon's 2014 method, a knee pad attached to the bench to prevent contact of the feet with the floor throughout testing. The knee pad was designed to restrict the recruitment of the lower body and extraneous muscle involvement which was allowed in Salmon's (2014) methodology. Whilst, seat belts attached to the bench and knee pad prevented the movement of the torso and legs to further reduce the recruitment of accessory muscles from acting upon the load cells. Additionally, forearm pads included in Salmon's 2014 methodology were not included in this study to prevent the utilisation of the arm muscles during maximal neck strength assessments.

From Williams and co-authors' 2021 study, the INSTA was adapted due to the time constraints associated with a professional rugby union environment. Williams' and co-authors' (2021) iteration of the INSTA required tools to adjust the position of load cells, horizontal bench and knee pad prior to participant assessment, a time-consuming process. The INSTA iteration used in this study was designed to accommodate more user-friendly, fast and efficient alterations using fast-release handles and body restraints. The same load cells used in Williams and co-authors' 2021 study were used in this study and iteration of the INSTA. The iteration of the INSTA frame used in this study allowed for faster participant set-up when assessing neck strength in professional rugby union environments.

Figure 3-1: A volunteer demonstrating the correct testing position on the INSTA.

A vertically adjustable headpiece ensured participants were in an anatomically neutral neck and head position and provided a fixed attachment point for four load cells surrounding the head. Four load cells (Tedea-Huntleigh, Vishay Measurements Group, Hampshire, U.K.) fixed to the headpiece of the INSTA apparatus measured force (1000 Hz) exerted by participants onto foam pads attached to the load cells. Two of the load cells measured neck flexion and extension forces in the sagittal plane. With participants' torsos parallel to the floor, one load cell placed anterior to the head aligned with the occipital bone of the skull measured flexion force and one load cell placed posterior to the head aligned with the forehead measured extension force. Two load cells measured neck left and right lateral flexion strength forces and were positioned lateral to the head and superior to the ears, ensuring no contact with the temples of the skull to avoid injury or discomfort. Load cells capable of measuring up to 200 kg were used in the sagittal plane compared to load cells capable of measuring up to 150 kg used in the transverse plane, due to greater anticipated forces in the sagittal plane. Load cells used in this study were adjustable using sliders attached to the headpiece. Additional calibration of these load cells was carried out at least once per month using known weights of 10 kg and 20 kg.

3.2.2 Apparatus Reliability

The INSTA device was developed to ensure consistent and dependable measurement of isometric neck strength in flexion, extension, and lateral flexion. In a non-elite human cohort tested on three occasions over a one-week period, intraclass correlation coefficient (ICC) with 95% confidence intervals (CI) and coefficient of variance (CV) was calculated to determine the intra-rater reliability for all four contraction directions. ICCs were calculated to quantify the agreement of data collected on different occasions and CV was calculated to assess the measurement of error (McBride et al., 2022). McBride and co-authors (2022) suggest that ICC >0.70 and CV <15% demonstrate acceptable thresholds in previous studies of isometric mid-thigh pull, as this has not yet been determined in isometric neck strength assessment.

The ICC (3,1) model was used, corresponding to a 2-way mixed model, single measure reliability and absolute agreement were calculated using SPSS 25 (IBM, New York, USA). ICC values ranged from 0.879 (95% CI, 0.762-0.947) in left lateral flexion to 0.916 (95% CI, 0.83-0.964) seen demonstrating excellent reliability between testing sessions.

Table 3-1: Intra-tester reliability values in all four directions. ICC - Intraclass correlation coefficient, CV – Coefficient of Variation, CI – Confidence Interval.

Contraction Direction	**ICC**		**Coefficient of Variance**
	ICC (3,1)	95% CI	CV (%)
Extension	0.916	0.830-0.964	9.72
Flexion	0.901	0.803-0.957	9.44
Left Lateral Flexion	0.879	0.762-0.947	15.55
Right Lateral Flexion	0.891	0.784-0.952	14.76

Calibration of the INSTA rig was conducted prior to testing sessions, where known calibrated weights were applied to each load cell while in an upward-facing position, data is provided in Appendix C. For the two INSTA devices used in this thesis, a regression analysis found excellent correspondence between applied and recorded weight ($r^2 = .999, p < 0.0001$), with an intraclass correlation of 1.000 (95 % CI, 0.987-0.994). Detailed tables presenting the CV, intraclass correlation coefficient (ICC), and standard error of the mean (SEM) can be found in Appendix C.

3.2.3 Apparatus Software

Hauch and Bach DOP4 software (Lynge, Denmark) version 2.3.0.0 (Hauch & Bauch, City, Country) was used to record all data (Figure 3-2). A real-time force-time curve was shown on the screen to ensure successful data recording and an example of force-time graphs of maximal voluntary contractions is shown in Figure 3-3.

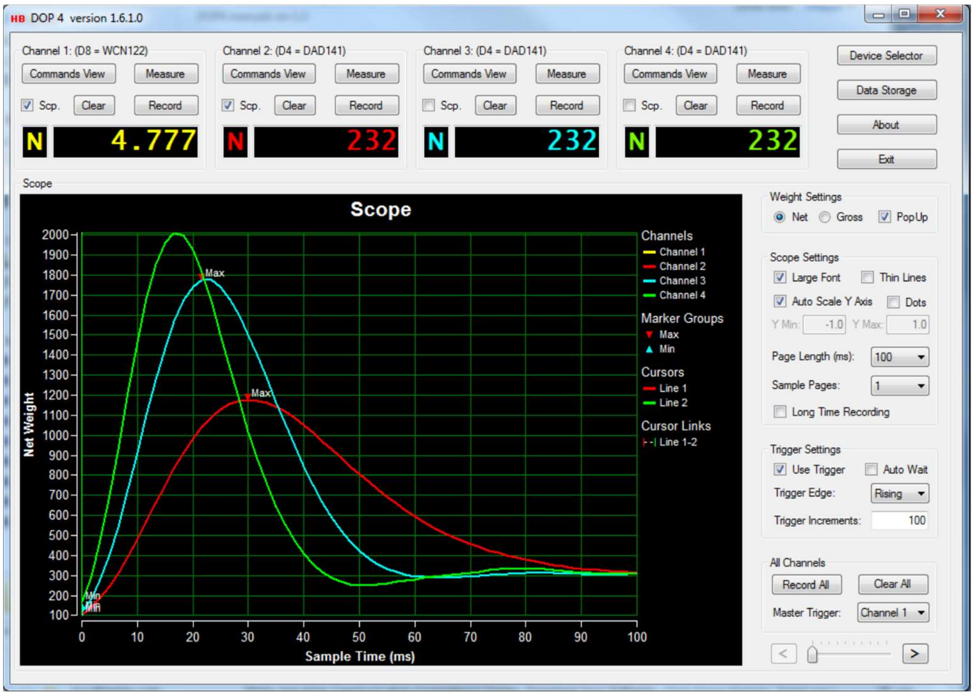


Figure 3-2: The user interface of the DOP4 software system showing a rea-time force-time graph.

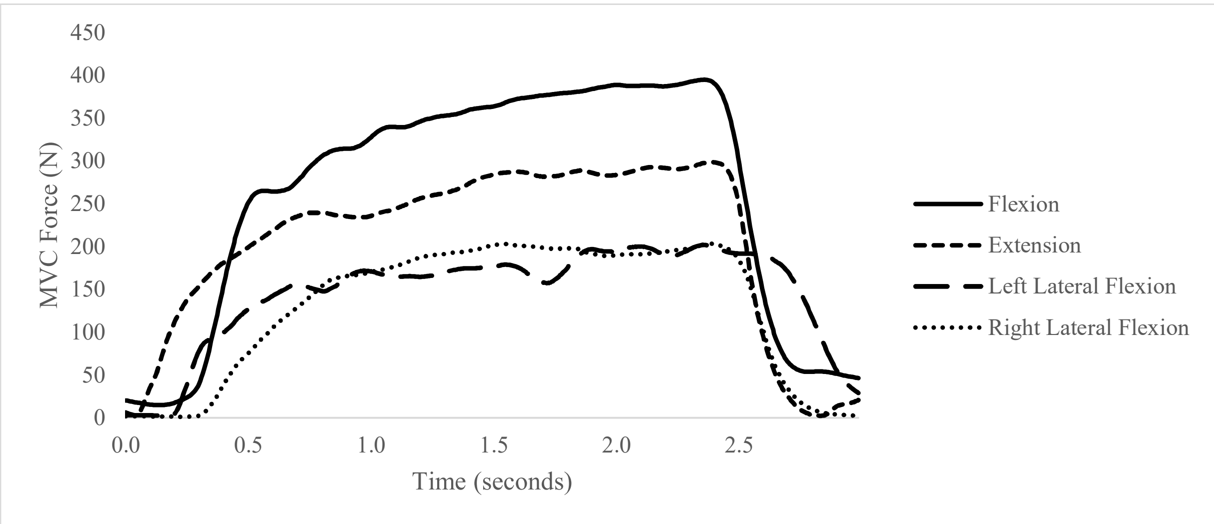


Figure 3-3: Example of force-time graph of neck maximal voluntary contractions (MVC) in flexion, extension, left lateral flexions and right lateral flexion directions.

3.2.4 Testing Protocols

Participants completed two separate testing sessions, one familiarisation session and one maximal testing session. Prior to both testing sessions, participants completed a standardised warm-up, consisting of cardiovascular, shoulder, upper back and neck exercises. Isometric neck contractions were selected due to the low injury risk associated with isometric loading. The cardiovascular warm-up consisted of two minutes rowing split into three sections, 30 seconds of rowing with only arms, 30 seconds of rowing hinging at the hips which allows for the recruitment of the back and arms, and finally one minute of full body rowing. After the cardiovascular warm-up, participants were instructed to complete 10 shoulder shrugs and shoulder circumductions. Finally, participants completed three sets of three-second neck isolation holds, in supine, prone and both side-lying positions, simulating the movements tested on the INSTA. Participants were instructed to tuck their chin towards their chest and raise their head upwards, leading to contractions and priming of the cervical spine musculature.

After the warm-up, participants were positioned in the INSTA in a neutral head position, within the vertically sliding headpiece, with the eyebrows of the participant positioned immediately inferior to the bottom sensor of the headpiece. Participants' hips and knees were positioned at a 90° angle, achieved by the horizontally sliding bench for the torso and vertically sliding knee pad. Sensors were adjusted around the skull of the participant in the sagittal and transverse planes with minimal space between the head and sensor, this allowed for minimal required adjustment to apply force to the sensor. Participants were instructed to place their hands behind their backs or on their hips before the onset of warm-up or testing neck isometric contractions.

For the familiarisation sessions, participants were instructed to perform a perceived 50% three-second neck isometric hold followed by a perceived 70% effort three-second contraction in all four directions, flexion, extension, and left and right lateral flexion. A 15-second rest period between sub-maximal repetitions ensured participants were able to provide feedback as to their position and neck pain, ensuring that they were comfortable, and no neck pain was present during or prior to testing. Familiarisation sessions were completed to familiarise participants with the novel methods used to assess neck strength such as the INSTA and warm-up protocols. This also provided an opportunity to ensure that neck isolation holds, conducted in the warm-up, was performed correctly with sufficient stimulus for a suitable warm-up. Additionally, familiarisation sessions allowed researchers to document the position of the adjustable bench, knee rest and load cells to replicate the same positioning in maximal trials. Positions of the sensors and benches were measured and recorded using adhesive measuring tape attached to the INSTA, so that the same position of the sensors and benches could be replicated in maximal testing sessions. Data was recorded during these submaximal trials but was not included in this study.

Maximal testing sessions took place at least two days post-familiarisation session and at least two days after any game-related activity, to ensure recovery of the cervical musculature and to reduce likelihood of injury. Following completion of the previously mentioned warm up, maximal testing sessions included three-second, 50% perceived effort warm up neck isometric contraction holds in all four directions, separated by 15 seconds of rest. Participants were instructed to contract maximally in the nominated contraction direction. Participants were instructed to slowly increase peak force to reduce likelihood of injury caused by a collision or jerking motion between the head and sensor. Participants were informed that they had one attempt and approximately 3 seconds to graduate up to their maximum voluntary contraction (MVC) force. Researchers provided verbal encouragement to ensure participants reached their MVC. Sensors were set to measure for six seconds to ensure peak force was recorded. Maximal neck strength contractions were recorded in four directions, extension, flexion, left lateral flexion and right lateral flexion. The peak force achieved during maximal contraction trials was recorded as the MVC and was measured in Newtons (N).

3.3 Statistical Analysis

Descriptive statistics (Mean ± SD) were calculated for trials in each of the four directions as well as the respective cohorts, as shown in results section. Multicollinearity was conducted to assess the effect of variables on correlation analysis. Multivariate linear regression was used to assess the effect of anthropometric variables on neck strength measures. Pearson's and Spearman's correlation coefficient analysis was conducted to examine the relationship between anthropometric variables and MVC values of participants. A one-way ANOVA was used to examine main effects for trials between cohorts, significance level was tested at 95%. ANOVA analysis was used to compare the variance between groups within this study. Shapiro-Wilk test was conducted to ensure normality of data, Greenhouse Geisser correction factor was used if any violation of Sphericity was found and Bonferroni pairwise comparisons were used to explore differences between cohorts. All Statistical analysis was conducted in SPSS 25 (IBM, New York, USA).

4 Results

4.1 Player Anthropometric and Neck Strength Values

For all players, age (years) body mass (kg) and body height (cm) (average ± standard deviation) data are given in Table 4-1. Separate values are also given for professional and university players and for forwards and backs for each group. The overall average neck maximum voluntary contraction (MVC) values, in all directions, for all players, positional and level groups are presented in Table 4-2.

Table 4-1: Age (years), body mass(kg) and height (cm) (average ± standard deviation) for all participants combined, and all participant groups.

Mean ± SD	**Population**	**Age (years)**	**Body Mass (kg)**	**Height (cm)**
All Players	All (n=72)	23.9 ± 4.6	102.1 ± 13.5	185.4 ± 7.2
	Front Row (n=26)	24.5 ± 5.1	112.7 ± 7.8◊	182.9 ± 4.1
	Second Row (n=10)	23.6 ± 4.1	109.8 ± 8.3	196.8 ± 3.7†
	Back Row (n=10)	25.2 ± 5.7	103.8 ± 7.4	188.2 ± 5.2**
	Backs (n=26)	23.1 ± 3.8	87.8 ± 7.9ⱡ	182.4 ± 6.7
Professional	All (n=47)	25.9 ± 4.4*	104.2 ± 12.8	185.7 ± 7.6
	Front Row (n=17)	26.8 ± 4.7	113.8 ± 7.3	183 ± 4.4
	Second Row (n=6)	25.8 ± 3.8	113.8 ± 2.3	198.8 ± 1.8†
	Back Row (n=7)	27.1 ± 5.6	110.5 ± 8.5	182.8 ± 3.7+
	Backs (n=17)	24.6 ± 3.8	89.9 ± 6.9ⱡ	181.9 ± 6.3
University	All (n=25)	20.2 ± 1.6	98.1 ± 14.2	184.8 ± 6.5
	Front Row (9)	20.1 ± 2.2	110.5 ± 8.5	182.9 ± 3.7
	Second Row (n=4)	20.3 ± 1.3	103.7 ± 10.7	193.8 ± 3.8+
	Back Row (n=3)	20.7 ± 2.3	96.4 ± 1.5	183.7 ± 1.2
	Backs (n=9)	20.2 ± 1.1	83.9 ± 8.4‡	183.3 ± 7.6

(◊ - denotes significantly greater than back row and backs samples (p<0.05), † - denotes significantly greater than front row, back row and backs samples (p<0.01), ⱡ - denotes significantly lower than second row, back row and backs samples (p<0.01), ** - denotes significantly greater than backs samples (p<0.05), ‡ - denotes significantly lower than front row and second row samples (p<0.01) & * - denotes significantly greater than university sample – (*p*<0.05), + - denotes significantly greater than front row and backs samples (p<0.01)).

Table 4-2: Flexion (Flx), extension (Ext), left (LLatFlx) and right lateral flexion (RLatFlx) maximum voluntary contraction scores (average ± standard deviation) for all players, then professional and university players, forwards and backs, with forwards further sub-classified into front row, second row and back row.

Mean ± SD		Flx (N)	Ext (N)	LLatFlx (N)	RLatFlx (N)
All Players	All (n=72)	341 ± 110	304 ± 78.2	241 ± 70	247 ± 69
	Forwards (n=46)	380 ± 112**	334 ± 79**	262 ± 76**	265 ± 77**
	Front Row (n=26)	425 ± 118†	374 ± 75⸸	291 ± 72⸸	294 ± 79⸸
	Second Row (n=10)	343 ± 66	283 ± 50	216 ± 76	233 ± 66
	Back Row (n=10)	301 ± 76	281 ± 47	229 ± 50	219 ± 44
	Backs (n=26)	272 ± 61	252 ± 42	203 ± 35	217 ± 35
Professional	All (n=47)	356 ± 94*	319 ± 80*	251 ± 64	254 ± 63
	Forwards (n=30)	392 ± 94	351 ± 78	276 ± 64	275 ± 66
	Front Row (n=17)	431 ± 91⸸	391 ± 78⸸	310 ± 57⸸	305 ± 66⸸
	Second Row (n=6)	376 ± 58	313 ± 23	230 ± 44	254 ± 36
	Back Row (n=7)	313 ± 76	291 ± 47	233 ± 45	220 ± 37
	Backs (n=17)	293 ± 54	260 ± 39	207 ± 33	216 ± 37
University	All (n=25)	313 ± 131	277 ± 69	220 ± 77	235 ± 78
	Forwards (n=16)	358 ± 141	299 ± 71	234 ± 90	245 ± 94
	Front Row (n=9)	415 ± 163**	341 ± 61**	256 ± 87**	274 ± 100**
	Second Row (n= 4)	294 ± 45	237 ± 44	195 ± 115	203 ± 4
	Back Row (n= 3)	274 ± 84	257 ± 47	218 ± 71	215 ± 67
	Backs (n=9)	233 ± 55	236 ± 45	196 ± 41	217 ± 33

(** - denotes significantly greater than backs sample ($p<0.01$), † - denotes significantly greater than back row and backs samples ($p<0.01$), ⸸ - denotes significantly greater than second row, back row and backs samples ($p<0.05$) & * - denotes significantly greater than university sample – ($p<0.05$)).

4.2 Player Anthropometric Analysis

4.2.1 Relationship Between Independent Variables

Prior to conducting any linear regression analyses, any multi-collinearity between the independent variables of playing level, playing position, age, body mass and body height were explored. This was conducted to justify the multivariate regression model specifications and ascertain that correlation coefficients from multivariate linear regression analyses are not explained by other factors.

Playing Position vs Body Height

For both playing levels combined, a one-way ANOVA showed body height to correlate with playing position (F = 21.12, p <0.001), with Bonferroni post hoc results showing second row player body height to be significantly greater than all other positional groups (front row p<0.001, back row p<0.003, backs p<0.001). Back row body height was also greater than that of backs (p<0.03). No further differences were observed between front row, back row and backs. Due to second row players being taller than the other positions, body height may influence the correlation between playing position and neck strength in a linear regression.

Playing Position vs Body Mass

For both playing levels combined, a one-way ANOVA showing (F = 48.2, p<0.01). A Bonferroni post-hoc showing front row players to have significantly greater body mass than back row (p<0.02) and backs (p<0.001) players but not second row players. Backs also had significantly lower body mass than second row (p<0.001) and back row (p<0.001) players. Body mass could therefore also influence playing position vs neck strength correlations.

Age

An independent cohorts t-test showed a significant difference in age between the two playing levels (t = 7.9, p<0.001), so age could influence playing level corelations in a multivariate linear regression. No further relationships were found between age and any other independent variable (playing position, body height, body mass).

Body Mass vs Body Height

A linear regression showed that only 18% of the variance in body mass can be explained by body height (R^2 = 0.184, adjusted 0.173).

4.3 Neck Strength vs Predictor Variables

4.3.1 Age vs Neck Strength

A Spearman's correlation showed a significantly positive correlation between peak isometric extension neck strength and age ($p<0.05$, r = 0.290), but not for flexion. Pearson's correlations showed no significant correlations between age and left or right lateral flexion. These analyses did not account for the effect of positional differences.

4.3.2 Body Mass vs Neck Strength

Spearman's correlations showed significant, positive correlations between body mass and both flexion ($p<0.01$, r=0.577) and extension ($p<0.01$, r = 0.597) respectively. Similarly, Pearson's correlations showed a significant positive correlation between body mass, and both left ($p<0.01$, r = 0.494) and right lateral flexion ($p<0.01$, r = 0.449) respectively.

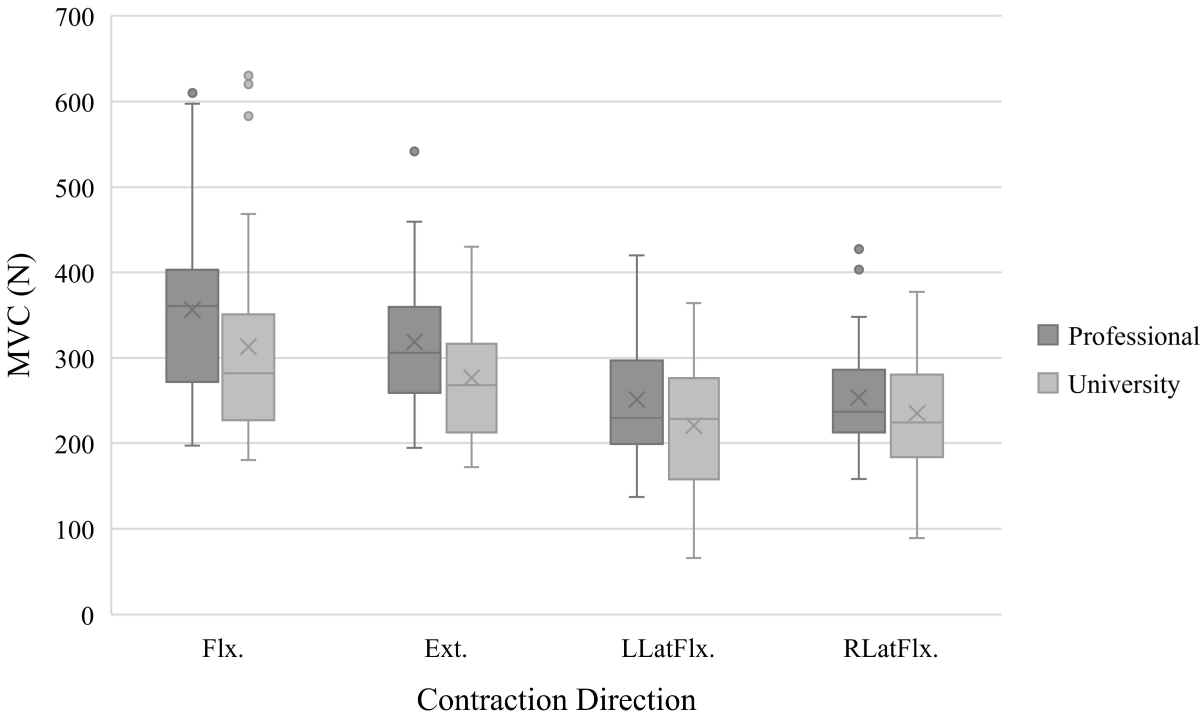
4.3.3 Body Height vs Neck Strength

Spearman's correlations found no significant relationships between body height and either flexion or extension strength. Indeed, Pearson's correlations showed no significant relationships between body height and either left or right lateral flexion strength. All correlation coefficients statistics are displayed in Appendix D.

4.3.4 Playing Level vs Neck Strength

A comparison of the average maximum voluntary contraction (MVC) results for professional and university players can be seen in Figure 4-1. The professional group produced significantly greater MVC forces in flexion and extension compared to university players ($p<0.05$). Peak lateral flexion contraction forces were not significantly different between playing levels.

Figure 4-1: Box and whisker plot showing MVC for professional and university players in flexion (Flx), extension (Ext), left (LLatFlex) and right lateral flexion (RLatFlx).



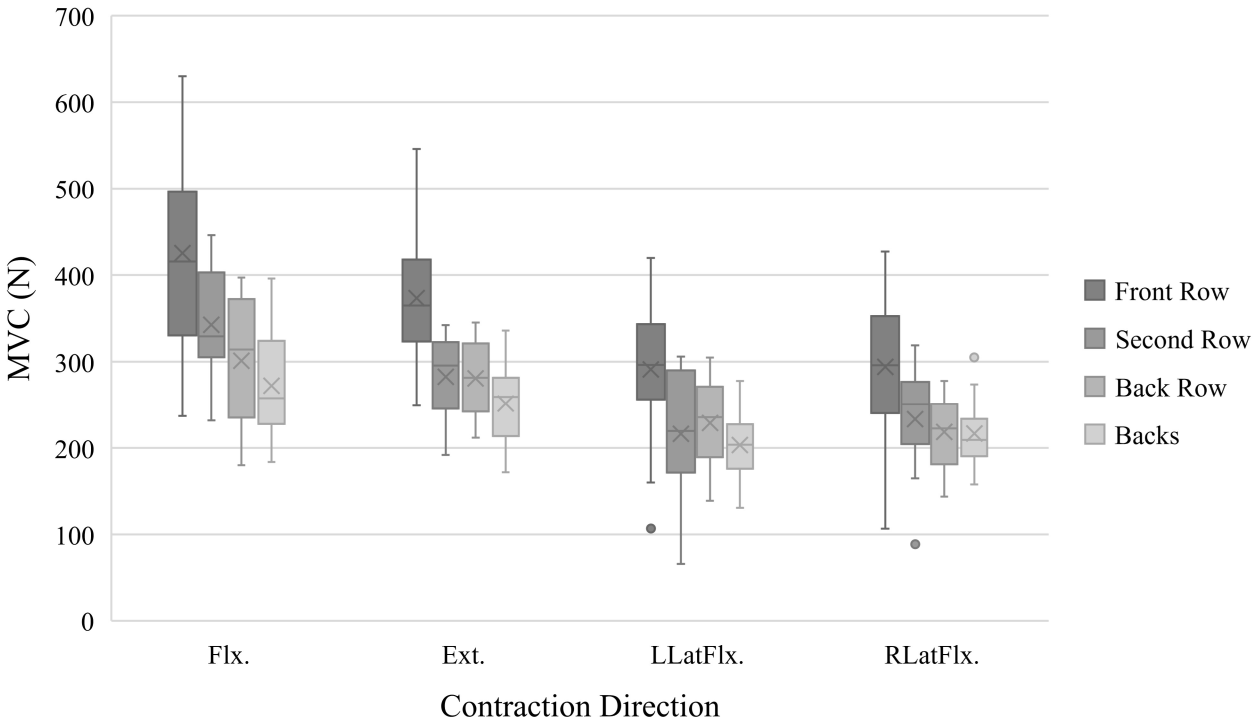
Peak isometric extension neck strength was found to be significantly higher in professional second and back row players compared to collegiate second and back row players, (p<0.01). Mean average age and body mass were also significantly higher in professional players compared to university players, (p<0.01). Flexion, lateral flexion and height showed difference for second and back row players between playing levels.

Statistical analysis showed that peak isometric flexion was significantly greater in professional backs compared to university backs, (p<0.01). The professional back's mean age was significantly higher than the university backs, (p<0.01). Extension, lateral flexion, body mass and height were not significantly different between playing levels in backs players.

4.4 Neck Strength vs Playing Position Groups

For professional and university players combined, playing positions were grouped by each position's in-game contact event requirements. Positional groups were front row (n=26), second row (n=10), back row (n=10) and backs (n=26). A one-way ANOVA showed a significant effect of playing position in all directions (p<0.01). A Bonferroni post-hoc analysis showed front row players to have significantly greater extension (*p*<0.01), left lateral flexion (*p*<0.05) and right lateral flexion (*p*<0.05) compared to second row, back row and backs. Flexion strength was significantly greater in front row players compared to backs and back row players (*p*<0.01), but not second row players. Between second row, back row and backs players, no significant differences were found in any direction (Figure 4-2).

Figure 4-2: Box and whisker plot showing maximum voluntary contraction in flexion (Flx), extension (Ext), left lateral flexion (LLatFlx) and right lateral flexion (RLatFlx) for different positional groups, in professional and university players combined.



4.5 Playing Position Comparison within Playing Level

All neck strength variables were significantly different across playing positions within the professional cohort (*p*<0.01). Front row forwards displayed significantly higher flexion, extension and lateral flexion isometric neck strength compared to backs and second and back row players, (*p*<0.01). No significant difference was found between backs and second and back row players in all neck strength variables. Body mass and height were significantly different between playing position groups within the professional cohort (*p*<0.01). Backs had significantly lower body mass compared to front row and second and back row players (*p*<0.01). Professional second row and back row players had significantly greater mean height compared to the professional front row and backs players *(p*<0.01). Additionally, professional second row players had significantly greater height compared to back row players (*p*<0.05).

Isometric flexion neck strength was significantly different between playing positions at the university level, *(p*<0.01). Front row players exhibited significantly greater isometric flexion neck strength compared to backs (*p*<0.01) and non-significant but higher flexion neck strength compared to second and back row players. Second and back row players had a higher mean isometric flexion neck strength than backs players but showed no statistically significance.

Isometric extension neck strength was shown to be significantly different across playing positions at the university level, *(p*<0.01). Front row players displayed significantly higher peak isometric flexion strength in comparison to both backs and second row players *(p*<0.01). No statistical difference between second and back row players compared to backs players was observed.

Backs had significantly lower mean body mass compared to both front row, second row and back row participants, *(p*<0.01). However, no statistical difference between front row, second row and back row playing position groups was observed. Statistical analysis did not show any significant difference in age, height, left or right lateral isometric neck strength within the university cohort.

5. Discussion and Conclusions

In this thesis, the isometric neck strength tesing apparatus (INSTA) was used to measure neck strength in rugby players of varying characteristics, and explored how neck strength is related to anthropometrics and playing demands. A total of 72 male rugby players aged 18-35 years participated, including 47 professionals and 25 university players. Forward players generally had greater height, mass and neck strength than backs, and professionals were older, heavier and stronger than university players. Front rows showed the highest neck strength overall, followed by second rows then backs and back rows. Strength generally decreased over the season for forwards.

Reliability of the INSTA was established with intra-rater reliability ICC of 0.879-0.916 and CVs of 9.6-15.2% considered significant, and load cell calibration also found excellent accuracy (ICC = 1.00). Reliability analysis, detailed in the methods section, demonstrates that the INSTA methodology has good to excellent reliability when assessing neck strength in participants with the same researcher compared to previous maximal isometric contractions (McBride, 2022).

5.1 Neck Strength Measurement Evaluation

5.1.1 Comparison with Previous Neck Strength Studies

In this thesis, the INSTA method used was based on that of Salmon et al. (2014), with several modifications. These included participants in this thesis being in a kneeling position, with their chest supported, seatbelt restraints used on the legs and torso and with the use of arms eliminated. These modifications were designed to improve the repeatability of the test, by standardising body position and minimising the recruitment of accessory muscles. The method used by McBride and Oxford (2022) was also a prone, quadruped position, utilising the VALD apparatus, with the participant on hands and knees and no restraints. Neck strength trends identified in this study demonstrated lower measures of neck extension and lateral flexion strength, but higher measures of neck flexion strength compared to the findings of Salmon (2014). Previous FFD studies, such as this, that utilised restraints and allowed for accessory muscle involvement, generally identified extension neck strength as the highest neck strength variable (McBride et al. 2022; Salmon, 2014). However, lateral flexion measures were still lower than flexion and extension neck strength in this study and previous FFD studies (McBride et al. 2022; Salmon, 2014). Differences in neck strength profiles seen in this study is likely caused by methodological differences between this study and previous FFD studies. The use of restraints in this study may further stabilise the torso of the participant resulting in a greater ability to contract in flexion directions. On the other hand, allowing participants to stand, like Salmon's 2014 study, during neck strength assessments may allow for the greater recruitment of the lower body resulting in greater extension neck strength scores. Assessment of differing FFD methodologies needs to be assessed further to ascertain whether restraints provide better anchoring for participants, or unrestrained or standing assessment postures allow for greater accessory muscle recruitment.

These discrepancies could be attributed to the various methodological factors, but also individual differences, training backgrounds, and even the specific muscle groups targeted during the assessments. It is also worth considering that while the use of restraints in this study may provide a more controlled and repeatable environment, it would decrease the ecological validity. The use of restraints in this thesis were intentionally designed to limit accessory muscle recruitment and decrease the number of extraneous variables. As a compromise, this did reduce the similarity to real-life forces and movements encountered during rugby. Also, while the reliability testing done for the VALD, Salmon et al. (2015) method and the INSTA used here were acceptable (McBride et al. 2022; Salmon et al., 2015). One of the strengths of the INSTA design is that injuries or weaknesses in other areas of the body, such as broken fingers, will not prevent players from completing the tests.

It is important to note, however, that the methods employed in other studies measuring neck strength in rugby union players may not be directly comparable to each other or to the present study. For instance, Geary et al. (2014) used the break test method, which utilises manual resistance that was not used in this study. Alternatively, Naish et al. (2013) assessed neck strength in seated positions, which was deliberately not used in this study as it may not accurately reflect the dynamic forces experienced during activities such as rugby (Salmon, 2014). Therefore, neck strength data comparisons to this study are limited due various methodological differences.

Discrepancies in the results across studies may be attributed to variations in assessment methods, participant characteristics, and other factors that warrant further investigation.

Future studies should aim to establish standardised protocols for neck strength assessment to facilitate better comparisons and understanding of factors affecting it. A significant strength of the INSTA method used in this thesis, is that has been developed to suit the busy professional rugby training environment. With only four minutes required to complete maximum testing per player (plus the warmup protocol), and repeatable sport-specific methodology. This has proven to be an ideal method for regular neck strength screening in these settings and in this regard, has addressed limitations of other methods.

5.2 Positional Differences in Neck Strength

5.2.1 Forwards vs Backs

In this study, forwards have been shown to possess significantly great neck strength variables compared to backs players. In this unsurprising trend, seen throughout previous rugby union neck strength literature there have been various factors which have been suggested to attribute to this difference in neck strength between playing groups, (Chavarro-Nieto et al., 2021; Geary et al., 2013; Hamilton & Gatherer, 2014; Hrysomallis, 2016; Salmon, 2014). . Salmon (2014) suggested that the increased neck girth exhibited by forwards may attribute to the increased neck strength observed in these studies, (Hrysomallis, 2016; Olivier & du Toit, 2008; Schmidt et al., 2014). Neck girth is a characteristic that has been shown to correlate with neck strength, however, the causation of increased neck strength and girth lies within the exposure to contact events of these forwards players, (Salmon et al., 2018). Quarrie et al. (2013) found that forwards were much more involved in contact events such as scrums, mauls, tackles and rucks, whereas, backs would be more involved in carrying the ball in open space, (Geary et al., 2013). The greater involvement of forwards in contact events means "forwards are more likely to be exposed to activities in training that stress the neck musculature" resulting in strength adaptations, (Salmon et al., 2018: pg. 1085).

Increased neck strength measures identified within the forwards population could reduce the risk of TBIs within this population compared to the backs recruited in this study. As suggested by Streifer et al. (2019), increased neck strength may reduce the risk of sports-related concussions, due to the reduction of energy transfer from sporting impacts to the head (Caccese et al., 2018; Chavarro-Nieto et al., 2021; Eckner et al., 2014; Farley et al., 2022; Gutierrez et al., 2014; Streifer et al., 2019; Tierney et al., 2005). Additionally, Collins et al. (2014) suggested that every 0.45 kg increase in neck strength resulted in a 5% reduction in concussion incidence within high-school athletes. Therefore, the lower neck strength parameters of the backs population identified in this study may suggest that backs are at an increased risk of TBI within rugby union. However, it has been shown that forwards suffered a higher incidence of concussion per 1000 playing hours at the collegiate level recruited in this study, (Kemp et al., 2020b), and may be attributed to the increased involvement in contact events of forwards players compared to backs, (Quarrie et al., 2013). To empirically conclude that neck strength reduces concussion rates within rugby union, injury incidence per contact event should be analysed across a longitudinal study as previous attempts have quantified concussion rates per 1000 playing hours and would not be comparable between forwards and backs populations which have significantly different contact event exposures (Quarrie et al., 2013).

To conclude, an increased exposure to contact events and different positional demands previously shown in forwards may attribute to the increased neck strength variables compared to backs that have been exhibited in this study and previous research. Additionally, increased neck strength measures found in this forward population may suggest a lower risk of TBIs in forwards compared to backs players in individual contact events, but the relationship between concussion incidence and increased neck strength between playing positions must be investigated further.

5.2.2 Position Group Comparison

Comparison between playing position groups in this study demonstrated that, front-row participants showed significantly greater neck strength measures compared to back-row and back players across the whole sample. However, front-row players did not display significantly greater flexion neck strength in comparison to second-row players but showed significantly higher extension and lateral flexion forces.

Increased neck strength measures such as extension neck strength observed in front-row forwards may be attributed to the greater involvement of these players in contact events such as mauls, rucks and more specifically scrums (Quarrie et al., 2013 & Salmon et al., 2018). The forces experienced by these players during these contact events, especially scrums, have been suggested to result in training adaptations leading to increased neck strength (Hamilton et al., 2014; Salmon et al., 2018). Furthermore, the main role of forwards within rugby is to maintain possession of the ball in contact events such as scrums (Quarrie et al., 2013). Scrums are reliant on neck extension strength to maintain stability during a scrum, (Olivier & Du Toit, 2008). Therefore, unsurprisingly, front-row players have displayed significantly greater extension neck strength compared to other playing positions, likely attributed to a greater requirement of neck extension strength during scrummaging.

Conversely, second-row players displayed no statistical difference in flexion neck strength compared to front-row players. Moody (2022) suggests front-row and second-row players experience higher forces compared to back-row players. Similar flexion neck strength measures seen in second-row and front-row players in this study could be attributed to similar strength adaptations caused by scrummaging identified in front-row players as suggested previous studies (Hamilton et al., 2014; Salmon et al., 2018).

Body mass in front-row players was significantly greater compared to back-row and back players in this study. However, body mass between second-row and front-row participants was similar. This finding is unsurprising within rugby union due to the physical demands placed on the forwards who are often physically bigger as a result of their force-dominant demands during the game (Moody, 2022). However, body mass has been correlated with neck girth in previous studies which has been identified as a predictor of neck strength (Eckner et al., 2014; Salmon et al., 2015; Salmon, Handcock, et al., 2018; Streifer et al., 2019; Vasavada et al., 2008). Increased body mass of front-row players compared to back-row and backs players further supports the notion that body mass, as a direct correlation with neck girth, provides a predictor of neck strength within rugby union.

Second-row players within this study exhibit significantly greater height compared to all other playing positions. Hamilton et al. (2012) found that height positively correlated with neck strength in rugby union players. However, this sample has shown that a significantly taller group of second row players do not necessarily exhibit greater neck strength compared to their shorter counterparts. Hamilton et al. (2012) completed their study on a sample of adolescent rugby union players so this trend may be present within developing and maturing adolescent rugby players, but this study suggests that this is not the case in adult rugby union players.

5.3 Playing Level Differences in Neck Strength

Professional rugby union players, in this study, have been shown to possess greater neck strength measures in comparison to the younger university sample. This is a trend that has been commonly identified in neck strength studies in rugby union and has been widely attributed to maturity and training level disparities between playing levels (Chavarro-Nieto et al., 2021). . Similarly, Salmon (2014) found that amateur forwards produced lower neck strength than those observed at the professional level which has been attributed to the greater playing experience and exposure to contact events in professional cohorts compared to lower levels (Chavarro-Nieto et al., 2021; Farley et al., 2022).

An unexpected finding in this thesis was that the professional and university participants showed no significant differences in lateral flexion. This finding contradicts what has been demonstrated between age-grade and adult as well as amateur and professional rugby union players in previous studies, (Hamilton et al., 2014; Salmon, 2014). Considering previous studies suggest that higher levels of competition, playing and training experiences of professional athletes, it would be expected that lateral flexion measures would be higher than those at a lower level (Chavarro-Nieto et al., 2021). Such findings may identify the neglect of neck strength training in the transverse plane of professional rugby players within this cohort. On the other hand, there may be a lack of stimulus from general gameplay and training that improves lateral flexion neck strength. Improvements in lateral neck strength have been demonstrated in extensor muscles within front-row players attributed to forces experienced by the neck during scrummaging (Hamilton et al., 2014; Salmon et al., 2018). Not all positions are exposed to forces experienced by the neck during scrummaging, backs players have no involvement scrums and positions such as second row and back row have different requirements during scrummaging. Lower stimulus of the neck in these positions may attribute to the lower lateral flexion measures seen within the professional cohort, leading to similar measures of lateral flexion neck strength across all positions between playing levels.

5.3.1 Front Row

Front-row players at professional and university levels showed no significant difference in neck strength variables within this study, but professional front-row participants were significantly older than their university counterparts, ($p<0.01$), with no difference in body mass or height. Non-significant differences in neck strength measures between the two playing levels could identify similar forces experienced by both levels of front-row players. However, scrummaging forces would have to be defined and therefore this cannot be conclusively suggested.

In this study university front-row players were significantly younger (20.1 ± 2.2 years old) compared to professional front-row players (26.8 ± 4.7 years old) likely due to the common age of attendance at university. Similarly, Hamilton et al. (2014) found that under-18 front-row players exhibited significantly lower age than adult front-row players, which was unsurprising due to authors purposefully recruiting participants under the age of 18. However, Hamilton et al. (2014) found that neck strength variables, in extension, and lateral flexion contraction directions were significantly lower in, what was considered a trained cohort of age-grade rugby union players compared to amateur senior players. Neck strength in the this study was not significantly different between professional and university participants even though age was significantly higher in the professional cohort. Salmon et al. (2014) suggest that the lower maturation status of the younger age-grade rugby union players may explain previous findings of disparity between the two populations. However, this study may demonstrate that the population of university participants have reached a greater level of maturation resulting in similar neck strength variables to that of senior players. Furthermore, Hamilton et al. (2014) found that age-grade players exhibited significantly lower body mass than adult players and body mass has been shown to significantly correlate with neck strength variables in this study and previous studies (Catenaccio et al., 2018; Garcé S et al., 2002; Hamilton et al., 2012, 2014; Hamilton & Gatherer, 2014; Salmon, 2014; Salmon et al., 2015, 2018; Vasavada et al., 2008). In this study, front-row players from both playing levels demonstrated similar body mass and height, which may suggest that the similar anthropometric characteristics have resulted in the similar neck strength measures observed in this study.

Furthermore, only three of the nine university front-row players displayed neck strength variables that were equal to or exceeded the professional cohorts' mean average neck strength measures. Hamilton and co-authors' 2014 study identified two out of thirty under-18 players showed similar neck strength measures. From this, it could be said that a proportion of university players possessed sufficient neck strength to progress to the professional level, a potential criterion suggested by Hamilton et al. (2014). Informing the graduation of players using such a criteria highlights a potential use for the INSTA technology.

5.3.2 Second Row

An unsurprising finding between playing levels within this study has found that the professional second-row players were significantly older than their university counterparts in this study. Furthermore, professional second-row players have been shown to possess significantly higher isometric extension and flexion neck strength compared to university second-row players It has been previously suggested that age correlates with isometric neck extension strength, a trend that has been displayed in this study between professional and university second-row players (Hamilton et al., 2012).. Differences between the two playing levels have been previously attributed to the increased training exposure, match exposure and higher magnitude and volume of contact events at higher levels, (Chavarro-Nieto et al., 2021; Farley et al., 2022; Hamilton et al., 2014). Green and co-authors (2019) suggest that as you increase the level of competition the forces experienced in the scrum increase due to heavier and stronger players. The increased stress on neck musculature has been suggested to lead to the adaptation of neck musculature resulting in increased neck strength (Salmon et al., 2018). Increased neck strength measures identified in this study between the two playing levels may be explained by the adaptations of the neck muscles in response to greater exposure at higher levels of competition.

Additionally, professional second-row players were significantly heavier than university second and back-row players. Body mass has been previously shown to significantly positive correlations with neck strength in rugby union players, (Hamilton et al., 2014; Hamilton & Gatherer, 2014; Salmon, 2014; Salmon et al., 2018). Furthermore, body mass has been positively correlated with neck girth, which has been identified as a significant predictor of neck strength due to increased muscle cross-sectional area (Schmidt et al., 2014). Even though body mass and neck girth have been previously identified as a predictor for increased neck strength, this trend has not been identified in lateral flexion neck strength measures within this population (Schmidt et al., 2014).

5.3.3 Back Row

Back-row players, regardless of playing level, did not exhibit significant differences in neck strength measures, age, or height. However, professional back-row players were notably heavier compared to their university counterparts. Previous studies have shown a significant correlation between body mass and neck strength in various contexts (Hamilton et al., 2014; Hamilton & Gatherer, 2014; Salmon, 2014; Salmon et al., 2018). Surprisingly, no such difference was observed among back-row players, which may suggest that the heavier front-row rugby players may influence the correlation results within the sport of rugby union.

5.3.4 Backs

University backs displayed significantly lower isometric flexion neck strength compared to professional backs. Typically, backs do not participate in set-piece plays such as scrums and rarely participate in as many contact events as forwards (Quarrie et al., 2013). Therefore, the greater flexion neck strength observed in the professional backs cohort in this study cannot be attributed to greater scrummaging forces that have been suggested at higher levels of competition for the forward-positioned participants in this study. Little research has been conducted concerning the neck strength of backs players at different levels of rugby union. However, the increased flexion neck strength measures exhibited by professional backs participants in this study may be attributed to the greater training and game exposure of these players. Previous studies have identified a correlation between playing experience and increased neck strength in rugby union, (Hamilton et al., 2012, 2014; Williams et al., 2021). Even though it cannot be empirically stated that professional backs players have a greater playing experience compared to university backs, it may be suggested that the significantly older professional backs have experienced a greater exposure to training and gameplay resulting in greater isometric neck flexion measures compared to university backs.

Additionally, the significantly older professional backs sample may suggest a greater degree of maturation disparity within this population. It has been previously found that older players exhibit greater neck strength as a result of more muscle maturation (Salmon et al. 2014). Consequently, this suggests that professional backs players in this study may possess a greater degree of neck muscle maturation resulting in greater flexion neck strength.

5.4 Neck Strength Correlations with Anthropometrics

5.4.1 Age

In this study, extension IVMC measures demonstrated a significantly weak positive correlation with age in this rugby union player sample. All other neck strength variables showed no correlation with age. As previously mentioned, Hamilton et al. (2012) displayed similar correlations in adolescent rugby union players which have been linked to the increased muscular maturity of older players (Salmon, 2014). As previously stated, this sample is not comparable to Hamilton and co-authors study (2012)but links attributed to the maturity of musculature may still hold value. University players in this study displayed a mean average age of 20.2 ± 1.6 years old which is older than the previously mentioned studies and above the age which is considered adolescent, (World Health Organisation, 2022). This may suggest that rugby union players graduating from the University level or similar ages into senior-level rugby union possess lower neck strength. Disparities in neck strength between playing levels suggest an increased importance of neck strength assessment as a tool for readiness to play at elite or senior levels. Furthermore, Davies et al. (2016) suggest that younger rugby union players who displayed lower neck strength were at an increased risk of injury, consequently, considering similar trends demonstrated in this study, the younger university population in this study may have a higher risk of injury.

Conversely, Hamilton et al. (2014) suggest that playing experience provides a strong predictor of cervical strength in elite under-18 and senior rugby union players. Chavarro-Nieto et al. (2021) and Davies et al. (2016) suggest that greater playing experience results in increased neck strength, which has been potentially attributed to the higher volume of contact events, such as tackles, experienced at higher competition levels of rugby union, (Farley et al., 2022). Even though playing experience data was not collected in this study, it would be logical to assume that the professional cohort in this study possessed greater playing experience at higher levels due to their significantly greater age which may explain correlations between extension IVMC and age seen in this study.

In other populations, Garcé et al. (2002) found that age was significantly negatively correlated with neck strength variables and Staudte & Dühr (1994) found that 60-80 year-old participants produced approximately 80% of 20-30 year-old neck strength measures in general populations. Kocur et al. (2019) suggest that "starting from the 3rd decade of life" increasing age results in the atrophy and degeneration of cervical musculature, resulting in reduced cervical strength (Kocur et al., 2019: pg. 2; Schmidt et al., 2014). These studies recruited participants from 18 to 84 years old, which is not comparable to the sample in this study. The oldest recruited participant was 35 years old, so atrophy and degeneration of cervical musculature factors may not necessarily be applicable in this study (Kocur et al., 2019). Therefore, the negative correlation trends found in these studies are not likely to resonate in the sample of professional and university rugby union players seen in this study.

5.4.2 Body Mass

In this study, all neck strength variables showed significantly moderate positive correlations with body mass, a trend that has been similarly demonstrated in previous studies of rugby union players, (Catenaccio et al., 2018; Garcé S et al., 2002; Hamilton et al., 2012, 2014; Hamilton & Gatherer, 2014; Salmon, 2014; Salmon et al., 2015, 2018) . Furthermore, body mass has been shown to positively correlate with neck strength measures in active and non-athletic populations, (Catenaccio et al., 2018; Garcé S et al., 2002; Salmon et al., 2015; Vasavada et al., 2008).

Vasavada and co-authors (2008) found that male participants had strong correlations between body mass and neck circumference which has been identified as a strong predictor of neck strength, (Eckner et al., 2014; Hamilton & Gatherer, 2014; Salmon et al., 2015, 2018). Largely attributed to the notion that cervical "strength increases linearly with increases in physiological cross-sectional area among … cervical musculature", (Schmidt et al., 2014: pg. 2062), it is unsurprising that neck girth and body mass correlate with neck strength variables not only in this study but previous studies of general populations. Similar to findings in the general population, rugby players have previously demonstrated moderate positive correlations between neck girth and body mass which has been attributed to the significantly greater body mass and neck girth of front-row players, (Chavarro-Nieto et al., 2021; Geary et al., 2013; Hrysomallis, 2016; Olivier & du Toit, 2008; Salmon, 2014; Salmon et al., 2018).

. Front-row players have been shown to possess greater isometric neck strength and body mass, similar to findings in this study, largely attributed to the positional demands and physical stress placed on the necks of these individuals in events such as scrummaging, mauls and rucks, (Salmon et al., 2018). Increased isometric neck strength variables and anthropometric characteristics identified in front-row players, in this study and previous studies, may provide an explanation as to why body mass demonstrates significant positive correlations with neck strength in rugby-playing populations.

5.4.3 Height

Height did not correlate with neck strength variables in this study, however, Hamilton et al. (2012) found that height was significantly positively correlated with isometric neck strength within a population of school-aged rugby players (aged 12-18 years old). The sample recruited within this study is not comparable to the sample assessed in this study,. as Hamilton and co-authors' (2012) study participant sample was limited to between 12 and 18 years of age. Due to the sample criteria of this study, this could make this sample liable to an effect of maturation in a population which experiences periods of rapid physical development, (World Health Organisation, 2022). Younger rugby union players have been identified as possessing reduced cervical strength in comparison to their older counterparts attributed to their immature musculature and lesser playing experience, (Chavarro-Nieto et al., 2021; Salmon, 2014).

Catenaccio et al. (2018) found that neck length, which could potentially be linked to the height of an individual, and Garcé et al. (2002) found that height significantly positively correlated with neck strength in general populations. However, no studies with a similar athletic population to this study have associated height or neck length with increased neck strength variables.

5.5 Study Limitations

The fact that this study was conducted in the operational professional rugby environment, and that the methods used were specifically adapted for this, is a significant strength of this study. However, due to the nature of professional sports, time was extremely limited and consequently, the time allowed for data collection from the players was limited. Players were required in training sessions, meetings, and various other responsibilities, so flexibility was key when determining the timings and length of data collection sessions which led to various time-limiting factors.

Data collection was conducted throughout the playing season only, as it was not feasible to access the whole squad in pre-season for various reasons such as player absences and international duties. As a result, it was not possible to ensure that players were completely absent from any game or training fatigue. To limit the effect of fatigue as much as possible, all players were assessed after a 48-hour window from their last competitive game. However, it was not possible to implement such measures to negate any training fatigue without changing the training schedule. Salmon and co-authors (2018) suggest that rugby players are likely susceptible to cumulative microtrauma of the neck and shoulders over a season due to contact events, such as tackling. This microtrauma may lead to pain, dysfunction or a reduction in strength, (Salmon, Sullivan, et al., 2018). Conversely, the same previous study found significant increases in neck strength attributed to loading of the neck during gameplay (Salmon, Sullivan, et al., 2018). Considering both increasing and decreasing neck strength trends were found throughout a season, inconsistencies in neck strength may be present within this study. Even though there is a risk of inconsistent data in this study, the data presented in this study provides normative data on professional and collegiate rugby union athletes which has been lacking in previous studies.

Neck girth has been shown to correlate and identified as a strong predictor of neck strength among human populations, (Eckner et al., 2014; Salmon et al., 2015; Salmon, Handcock, et al., 2018; Streifer et al., 2019; Vasavada et al., 2008). Neck girth was not assessed in this study, due to time restrictions, and therefore correlations or associations between neck strength and neck girth could not be assessed. Furthermore, previous studies have normalised to account for the variance caused by neck girth (Salmon et al., 2015; Salmon, Sullivan, et al., 2018), therefore, the normalisation of neck strength for neck girth and the comparison of normalised neck strength values between this study and previous studies was not possible.

Playing experience in rugby union has been identified as a predictor of neck strength which was not assessed in this study. However, age was found to significantly correlate with extension neck strength and could be logically attributed to playing experience. Even though age was not conclusive playing experience data, it was used to make suggestions regarding neck strength trends within this study.

The accuracy and reliability of neck strength assessment in this study, and likely in previous studies, is reliant on the participant attempting the trials maximally to state these findings as maximal contractions. As is the case with isometric contractions, the participant may terminate a contraction at any time due to fatigue, injury or safety reasons. Even though isometric contraction assessment of neck strength provides a method which reduces the risk of injury, it can be liable to inaccuracies if the participant does not contract maximally during trials. A lack of motivation is a key issue when assessing these types of contractions and may result in submaximal measurements. In this study, participants were observed for any indication of sub-maximal contractions, such as reduced force application compared to familiarisation trials, and verbal encouragement was used throughout data collection to limit the collection of sub-maximal neck strength data. However, the responsibility of maximal contraction lies with the participant and can present inconsistencies when considering the reliability of maximal testing measurements.

Even though intra-rater reliability data for the INSTA was included in this study, a key limitation of this study is the lack of reliability assessment with previous neck strength assessment studies. Previous literature that has employed methods similar to the INSTA can be assessed for reliability with this study which could further inform a standardised methodology and use of data from previous literature in formulating a normative data set for neck strength assessment. There is scope to directly compare reliability of neck strength methods in this study with Williams' and co-authors 2021 and Salmon's 2014 study. Especially considering the INSTA was adapted from Williams' and co-authors 2021 study, neck strength data in this study should be compared to assess for reliability, however this was not conducted in this study. Consequently, this would allow for a stronger comparison of neck strength variables between this study and previous literature.

The positioning of participants in this study was developed upon the principles proposed by Salmon (2014), whereby a 'simulated contact position' was implemented to increase the ecological validity of neck strength assessment. In Salmon's 2014 study participants were stood and allowed to recruit leg musculature to push against load sensors, this was removed in this study to increase repeatability and prevent the use of extraneous muscles. However, it could be argued that removing the use of the legs reduces the ecological validity of the test. In this study and Williams and co-authors' 2021 study, restraints and knee pads were used to limit accessory movement. Even though this has been associated with improving reliability in manual muscle assessment, there is little to no research suggesting this is required to achieve a reliable measure of neck strength (Clarkson, 2020). To ascertain whether these measures are required to improve reliability or repeatability, further research is required to determine the effect of different methodologies on neck strength variables.

Chavarro-Nieto et al (2021) contest that the 'simulated contact position' position employed in this study, and previous studies, favours the forwards as these players have a greater involvement in scrums and more frequently participate in positions like neck strength assessment methods. This could provide an explanation as to why forwards have exhibited significantly greater neck strength compared to backs. However, backs employ neck musculature in these positions when tackling, rucking, and mauling and this 'simulated posture' replicates a position most similar to a position employed within contact events (Salmon 2014 & Salmon et al., 2018). The aim of this study was to compare playing positions and playing levels and correlate anthropometric characteristics in rugby union players with different playing responsibilities utilising an ecologically valid method. Even though this methodology may favour forwards, the INSTA offers an ecologically valid, repeatable, and reliable method to assess neck strength.

Another limitation of the testing methods employed in this study was maintaining consistency in positioning across participants, which has been previously identified by Salmon et al. (2015). Differences in the positioning of the head may lead to alteration of force production when assessing neck strength variables, (Salmon et al., 2015). To reduce the risk of different positioning of participants, familiarisation sessions were conducted to document the settings of the machine for each participant. Replication of these machine settings ensured a similar positioning of participants between familiarisation and maximal trials, which increased the repeatability of the neck strength assessment. Additionally, familiarisation sessions were implemented to reduce the risk of the learning effect within the sample.

Finally, it was not feasible to collect injury history and neck pain prevalence data in this study. Previous injuries may have resulted in reduced neck strength variables, for example, concussions have been linked with reduced neuromuscular control and reduced activation of cervical spine musculature (Bussey et al., 2019). Similarly, neck pain has been shown to reduce neck strength variables in previous studies (Edmondston et al., 2008; Falla, 2004; Salmon et al., 2011; Worsfold, 2020). In order to negate the effect of neck pain and previous injuries, physiotherapists gave permission for each of these participants to participate prior to neck strength assessment trials. The lack of empirical neck pain and injury history data meant exclusion from testing by researchers was not possible, which may make this study liable to reduced neck strength variables. Additionally, researchers were instructed to question players prior to assessments about any current injuries.

5.6 Future Directions

In this study, flexion neck strength measures were shown to be consistently higher than other contraction directions. The causation of this finding is not yet determined and investigations into contributing factors could inform neck strength interventions that may neglect strengthening in other planes of movement. Furthermore, increased flexion neck strength measures may reduce injury risk in the sagittal plane, but lower lateral flexion neck strength measures may predispose players to higher injury risk in the transverse plane. Further investigation into the relationship between head acceleration and neck strength within rugby union players could help determine TBI risk.

Conversely, previous studies using FFD have identified extension as the greater neck strength measure within rugby union players. Different methodologies employing strategies such as restraints and different body positioning may result in different recruitment of musculature. Similar to Williams and co-authors (2021), body restraints were used in this study to, hypothetically, improve isolation of the neck musculature, contrary to previous studies such as Salmon (2014) and McBride et al. (2022). This type of methodology adaptation is common in best clinical practice in assessing muscle strength (Clarkson, 2020). However, specifically in neck strength assessment, no attempts to explore the effects of body restraints on neck strength variables has been conducted. Therefore, future directions should investigate the effect of body restraints to assess whether these methodological changes are required tom improve the standardisation and reliability of neck strength assessment. Further investigation into effect of neck strength assessment methodology on neck strength profile may be required to interpret neck strength profiles more accurately.

Smaller players possessed lower neck strength measures across this cohort and within playing levels and positions, a trend also seen in female players within previous studies. Further research into the effect of weaker neck strength and injury risk in longitudinal studies with detailed and accurate injury prevalence data would provide valuable information for coaches, physiotherapists and sports practitioners alike.

Correlations between neck strength and age within this study highlights the potential effect of maturation on neck strength profiles within senior players. The effect of playing experience was not analysed in this study, however, previous studies identified playing experience as a factor that may affect neck strength due to greater playing exposure (Salmon, 2014). Firstly, research into the effect of playing experience on neck strength profiles with empirical playing experience data may highlight the need for neck strength interventions in players with a distinct lack of experience compared to their counterparts. Secondly, considering this trend was found within a senior cohort, it is important to further analyse this relationship in adolescent players to assess the effect of maturation. Studies such as these may highlight the greater requirement of neck strengthening within younger cohorts when graduating age-grades and playing levels. Additionally, the lack of maturation in younger cohorts may predispose these players to higher risk of injury and future research should analyse the effect of this relationship.

To provide a normative data set of neck strength within professional rugby union players, reliability between assessment methods needs to be established. Future studies should seek to employ a consensus methodology to build a normative set of neck strength data in rugby union players. A normative neck strength data set may allow professionals such as medical and strength and conditioning staff to access normative data to inform rehabilitation and strengthening programs in a clinical setting. Furthermore, this study only assessed male rugby union players which limits the applicability of this data to a growing female rugby union playing population (Williams et al., 2021). Future studies should build upon data collection in female rugby union players as it has previously been identified as an area with largely inadequate resources and knowledge (Williams et al., 2021).

This study only analysed neck strength within two planes, sagittal and transverse. As previously mentioned, rotational neck strength should be included in neck strength assessment to provide a more holistic neck strength profile. Furthermore, neck muscle utilisation and external forces will occur outside of the transverse and sagittal planes so rotational neck strength data in future studies would be useful for coaches, physiotherapists and sports practitioners. However, as previously mentioned, rotational neck strength requires multiple assessments to determine (Ylinen et al., 2003). Future research to determine a repeatable and reliable method for assessing rotational neck strength would be key in providing a more holistic and ecologically valid neck strength profile. INSTA provides a repeatable assessment of neck strength, which could be used to assess the effectiveness of short and long-term neck strength interventions in rugby union cohorts. A comprehensive analysis of neck strength interventions could offer useful information for practitioners implementing neck strengthening programs to rugby union players and other athletes.

5.7 Conclusions

This study has begun to build a dataset of neck strength variables within rugby union using a repeatable method of neck strength assessment using the INSTA. The INSTA allows for the rapid and repeatable assessment of neck strength within the professional rugby union environment that has significant time restraints. A method that could be used to quickly assess neck strength to identify neck strength deficiencies and inform neck strength training programs within professional rugby union.

Identification of neck strength trends, conducted in this study, between differing playing positions provides insight into the different physical requirements of rugby players. Front-row generally possessed greater neck strength measures compared to other playing positions with some similarities to second-row players potentially indicating the effect of scrummaging exposure to increased neck strength variables. Additionally, positive correlations between body mass and neck strength found in this study were similar to findings in previous studies which is likely attributed to the greater body mass of front-row and second-row forwards who exhibit greater neck strength measures.

Professional rugby union players displayed greater neck strength values in flexion and extension compared to university players. However, lateral flexion neck strength was not different between playing levels which may highlight a neglect of neck strength training in the transverse plane considering the greater forces experienced at higher levels of competition.

The INSTA has the potential to be used to assess neck strength in players rehabilitating and graduating to higher levels of competition to highlight lower neck strength values that may increase risk of injury. For this to be achieved, a comprehensive normative neck strength data set would be required to enable comparisons and draw thresholds in order to allow players to return to play or promote them to higher levels of competition. Further research into neck strength across a wide range of rugby union competitions using a reliable and repeatable method such as INSTA would allow for this to be achieved.

In conclusion, this study has provided insight into neck strength trends and values within professional and university rugby players. Secondly, this study has begun the collection of a repeatable data set of neck strength values which can be widely utilised to inform decisions concerning return to play and player graduation. Finally, further research is required to formulate a data set which coaches, physiotherapists and sports scientists can use to reduce injury risk, inform training interventions, and identify neck strength deficiencies within rugby union players.

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Appendices

Appendix A – Participant Information Sheet

PARTICIPANT INFORMATION SHEET
(Version 1.3, Date: 10/09/2019)

Project Title:
Neck Strength Profile Comparison of University and Elite-Level Rugby Union Players

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1. Invitation Paragraph
We are Dan Walker and Josh Moore, MSc students at the Applied Sport, Technology, Exercise and Medicine (A-STEM) Research Centre in the College of Engineering at Swansea University. We are conducting a study to assess the effectiveness of a season-long neck strength intervention in reducing head impact magnitudes in Rugby Union and you are invited to participate.

2. What is the purpose of the study?
Rugby is the sport of choice for more many people in Wales. As with any contact sport, injuries are a common and expected feature within the game. At the senior and professional level of the game, concussion and serious injuries are particularly topical and regularly relayed in the media. All involved in this study take the safety of players at all levels seriously. The aim of this study is to implement an intervention that will improve neck strength, endurance and neck range of motion and assess the effect it has on head impact magnitudes. The hope is that this study will provide data that will contribute to the development of training interventions that will increase player safety.

3. Why have I been chosen?
You have been selected to participate in this research project as you are currently playing rugby union at a first team level for Swansea University. Your participation in this research is voluntary. You are free to withdraw consent and discontinue participation at any time without influencing any present and/or future involvement with Swansea University. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from Swansea University.

4. What will happen to me if I take part?
You may be asked to complete a pre-competition injury and concussion history questionnaire and undertake a measurement of your height and weight, head and neck circumference. You will also be asked to perform some neck strength tests during preseason, several times during the season and at the end of the season. This will be done using a purpose-built isometric neck strength testing device, where you will be instructed to push against padded load cells. Your body and head will be supported in these tests and your head will not actually move. In conjunction with the neck strength testing, you will be invited to have your neck range of motion tested also. This will be done either in The Shed, Swansea School or Medicine or Bay Campus depending on Covid-19 restrictions. For neck range of motion tests, you will be asked to stand on the floor with your back pressing against a solid wooden board. A four-point harness will be used

to ensure your back and shoulders stay pressed against the board while you slowly move your head. A small plastic CROM device will be placed on your head, like a pair of glasses. You will then be asked to slowly move your head in six different directions three times each. A video camera will be used to measure this as a secondary measurement. The footage will only be viewed by the researcher and supervisor to take measurements from.
Rugby athletes may also be asked to wear a custom-fit mouthguard which will contain accelerometer and gyroscope sensors during training and matches.

5. What are the possible disadvantages of taking part?

Only those discomforts and risks that normally occur from participating in rugby union activities. This includes the risk of a sports-related concussion. This risk can be increased if you have had a previous concussion and this will be discussed with you as part of the concussion history assessment. You may be asked to see another health care professional for further assessment and clearance to play as part of this process. The head impact data collected as part of this study is not able to diagnose concussion or any other injury. No data collected in this study can or will be used to detect if you have any other health issues.

6. What are the possible benefits of taking part?

Information gained from this research has potential to help shape training strategies, and develop prognostic indicators of value to athletes, clinicians, physical conditioners and coaches.

7. Will my taking part in the study be kept confidential?

The data from the research project will be coded and held anonymously in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of Swansea University. All reference to participants will be by code number only in terms of any research theses and publications. Identification information will be stored on a separate file and computer from that containing the actual data. Only the lead investigators will have access to computerized data. Should a situation occur where you become injured then your identified next-of-kin / legal guardian / parent that has been recorded and/or signed the consent form will be contacted to advise them of the injury, the care provided and where you have been transferred to. The information obtained will also be passed onto the healthcare service as part of the on-going management of your medical care.

8. What if I have any questions?

If you have any questions please feel free to contact Dan Walker, Josh Moore or Dr Elisabeth Williams. Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor – Dr Williams. Concerns regarding the conduct of the research should be notified to Dan Walker or Dr Williams. Please take the necessary time you need to consider the invitation to participate in this research. It is reiterated that your participation in this research is completely voluntary. If you require further information about the research topic please feel free to contact Dan Walker (details are at the top of this information sheet). You may withdraw from the study at any time without any adverse consequences of any kind. You may ask for a copy of your results at any time and you have the option of requesting a report of the research outcomes at the completion of the study.

Appendix B – Participation Consent Form

PARTICIPANT CONSENT FORM
(Version 1.3, Date: 10/09/2019)

Project Title:
Neck Strength Profile Comparison of University and Elite-Level Rugby Union Players

Contact Details:

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	Please initial
1. I confirm that I have read and understood the information sheet dated …….. (version number 1.2) for the above study and have had the opportunity to ask questions.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.	
3. I understand that sections of any of data obtained may be looked at by responsible individuals from the Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records.	
4. I agree to take part in the above study, to have a photographic image to be taken for educational and research purposes only and that in taking my photo the face image will be made opaque.	

____________________________ ___________________________________
Name of Participant Date Signature

____________________________ ___________________________________
Name of Person Taking Consent Date Signature

____________________________ ___________________________________
Researcher Date Signature

Appendix C – Reliability Data

Table 3: Table showing calibration assessments conducted with known calibration weights

Kg	Observations	Mean Applied Force (N)	Mean Measured Force (N)	Standard Deviation (±)	CV%
2	72	19.62	19.42	0.46	2.40
5	72	49.2	48.45	0.93	2.00
10	72	98.10	97.13	1.84	2.00
15	72	147.15	145.54	2.74	2.10
20	72	196.20	194.17	3.77	2.10
25	72	245.25	242.59	4.77	2.10
30	72	294.30	291.03	5.65	2.10
35	72	343.35	339.35	6.65	2.10
40	72	392.40	387.67	7.64	2.10
All	**648**				**2.10**

Table 4: Table showing statistical results for testing with calibrated weights.

Regression			95% CI for Mean			Intraclass Correlation		
r	r^2	*p*	Mean	LB	UB	IC	Lower Bound	UpperBound
0.999	**0.999**	**<0.0001**	**0.989**	**0.987**	**0.994**	**1.000**	**0.999**	**1.000**

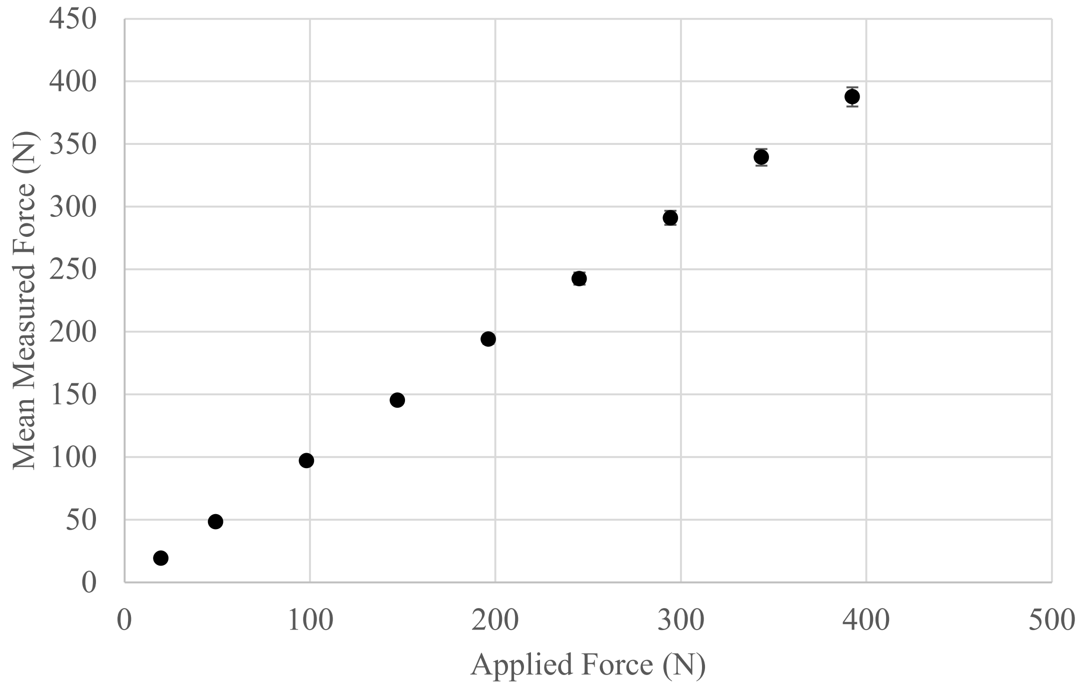

Figure 5: Scatterplot showing applied force against measured force variability.

Appendix D – Anthropometric Correlation Data

Table 6: Table showing Pearson's and Spearman's correlation and associated p-values of anthropometric with maximum voluntary isometric contractions in flexion, extension, left and right lateral flexion contractions.

		MVC Contraction Direction (N)			
		Flexion	Extension	Left Lateral Flexion	Right Lateral Flexion
Age (years)	r	0.188	0.290*	0.206	0.159
	p	0.113	0.14*	0.083	0.181
Body Mass (kg)	r	0.577**	0.597**	0.494**	0.449**
	p	<0.001**	<0.001**	<0.001**	<0.001**
Height (cm)	r	-0.32	-0.139	-0.86	-0.67
	p	0.793	0.243	0.472	0.576