Concussion, neck, and hamstring injury aetiology and injury prevention in Rugby Union

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at The University of Waikato by

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ABSTRACT

Background

Concussion and hamstring injuries are two of the most frequently diagnosed injuries in Rugby Union. Neck and hamstring strength have been identified as a modifiable risk factor to decrease the severity and incidence of these injuries. As such, there is an increasing interest in strengthening the neck and hamstrings in Rugby Union for injury prevention purposes.

Aims

The overarching aims of this thesis were to:

1. better understand the role of neck and hamstring strength and imbalances in the context of concussion, neck, and hamstring injury incidence and prevention;
2. scientifically document the status of neck and hamstring strength and imbalances in Rugby Union players using reliable methods; and
3. evaluate the impact of strengthening exercises and feedback strategies on strength outcomes in Rugby Union players.

Overall, this thesis sought to shed some light on neck and hamstring strength assessment and strengthening practices to inform injury prevention strategies in Rugby Union players.

Methods

This thesis is divided into four sections. The first section comprises a systematic literature review addressing neck strength in Rugby Union, a cohort cross-sectional study that compares the two most common methods to test isometric neck strength (“make” versus “break”), and

a reliability study of isometric neck strength measures in flexion, extension, and bilateral side flexion. The second section includes a systematic literature review on hamstring injury incidence, risk factors, and prevention in Rugby Union. Thereafter, the reliability of measures from a load cell device to assess Nordic hamstring strength and bilateral balance in Rugby Union players is examined. The third section characterises both neck and hamstring strength in Rugby Union players. Specifically, isometric neck and Nordic eccentric hamstring strength values are examined in a large cohort of male and female semi-professional and professional Rugby Union players. Finally, the fourth section involves a randomised-controlled trial with a control group that examined the effect of a six-week progressive Nordic eccentric and isometric hamstring strength training programme performed with or without visual feedback on hamstring strength and bilateral strength balance in Rugby Union players.

Results

The neck strength literature review highlighted no consensus regarding standardised test methods implemented in Rugby Union, and limited evidence regarding direct associations between neck strength and concussion. When experimentally comparing the break to the make test, there were no systematic or proportional differences between methods detected based on the Passing-Bablock procedure. Despite the results suggesting these two methods could be used interchangeably to assess isometric neck strength, the make test showed some procedural advantages (e.g., lower potential for test-related injuries, enhanced participant comfort and confidence, and reduced influence of the examiner). Hence, the make test was chosen as the primary neck strength assessment method in the subsequent studies of this thesis. The reliability study on isometric neck strength measures from the make test revealed good-to-excellent intrasession reliability (ICC=0.85–0.95) and fair intersession reliability (ICC=0.51–0.69) for mean and maximal values.

The hamstring literature review concluded that it is likely worthwhile to combine strategies to prevent hamstring injuries and their recurrences in Rugby Union, and should include Nordic strength assessments and Nordic strengthening exercises. On this basis, Nordic assessment methods were chosen to assess hamstring strength in this thesis. The reliability study on Nordic eccentric strength assessment measures showed good intrasession reliability (ICC=0.79–0.90) and fair intersession reliability (ICC=0.52–0.64) for mean and maximal values.

A total of 342 Rugby Union players (87% male) participated in the characterisation study. Regarding isometric neck strength, male professional players were significantly stronger in all directions than semi-professional players except in extension; and overall, forwards (range: 22–39 kg) were significantly stronger than backs (range: 22–31 kg) in all directions. Flexion-to-extension ratio was 0.76 and side flexion ratio was 1.0 in males. There were no significant differences between forwards (range: 14–23 kg) and backs (range: 14–22 kg) in semi-professional females, except in extension (backs > forwards). Flexion-to-extension ratio was 0.83 and side flexion ratio of 1.0 in females. Considering Nordic eccentric strength, there male professionals were stronger than semi-professional players in terms of absolute strength (422.1 vs 398.7 N), relative to body mass was greater in professionals than semi-professionals (4.57 vs 3.87 $N \cdot kg^{-1}$). Absolute strength was significantly greater in forwards than backs (426.8 vs 387.2 N); but relative to body mass, strength was lower (3.78 vs 4.67 $N \cdot kg^{-1}$). In females, the strength values ranged from 226 ± 41N and 2.8 ± 0.5$N \cdot kg^{-1}$ to 320 ± 1.0N and 3.8 ± 0.6$N \cdot kg^{-}$

[1], forwards ranged from 255 ± 107N to 320 ± 1.0N whilst backs ranged from 226 ± 41N to 295 ± 65N.

Regarding the four section a randomised-controlled trial that analysed the effectiveness of a six-week isometric hamstring and Nordic eccentric training performed with or without visual feedback on hamstring strength and bilateral strength balance in Rugby Union players. The time x group interaction from the repeated measures ANOVA was not significant for both peak strength and bilateral strength balance measures, indicating similar changes between groups from *Pre* to *Post* timepoints. Additionally, there was no main effect of time on outcomes, indicating no significant difference in strength or balance measures from *Pre* to *Post* timepoints. There was a significant main effect of group on peak strength, with controls identified as being significantly weaker than the other two groups during post-hoc pairwise comparisons (94.0 N weaker vs *non-feedback* and 89.3 N weaker vs *feedback*). There was no significant main effect of group on balance.

Conclusion

This thesis presents a compilation of studies focusing on neck and hamstring strength as modifiable risk factors for concussion, neck, and hamstring injuries in Rugby Union. This thesis provides data on isometric neck and Nordic hamstring eccentric strength values using two feasible and reliable test methods that use load cell devices. The data collected from semi-professional male, professional male, and semi-professional female Rugby Union players can be used to inform practice and establish baseline values for practitioners interested in rehabilitation, return to play, and strengthening of neck and hamstring in Rugby Union. The six-week progressive Nordic eccentric and isometric hamstring strength training programme was not superior to usual training (control group) for improving eccentric bilateral strength or decreasing bilateral strength imbalances, warranting exploration of alternative strength training programmes and strategies.

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LIST OF ABREVIATIONS

ANOVA: Analysis of variance
BW: Bodyweight
CI: Confidence intervals
CV: Coefficient of variation
DCR: Isokinetic dynamic control ratio
GPS: Global positioning system
H:Q: Isokinetic hamstring quadriceps ratio
ICC: Intraclass correlation coefficient
N: Newton
Nm: Newton-meter
NOS: Newcastle-Ottawa Scale
NR: Not reported
PTE: Peak torque extension
PTF: Peak torque flexion
PRISMA: Preferred Reporting Items for Systematic Review and Meta-Analysis
RM: Repetition maximal
SD: Standard deviation
Δ: Difference

RESEARCH OUTPUTS ARISING FROM THIS DOCTORAL THESIS

PUBLISHED OR SUBMITTED MANUSCRIPTS TO PEER-REWIEWED JOURNALS

1. Chapter 2
   Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Neck strength in Rugby Union players: A systematic review of the literature. The Physician and Sportsmedicine. 2021;49(4):392-409. doi: 10.1080/00913847.2021 (Appendix A1)

2. Chapter 5
   Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review. The Physician and Sportsmedicine. 2021. doi: 10.1080/00913847.2021.1992601. (Appendix A2)

3. Chapter 4
   Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Reliability of repeated isometric neck strength in Rugby Union players using a load cell device. Sensors. 2022;22(8):2872. doi: 10.3390/s22082872. (Appendix A3)

4. Chapter 3
   Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. To make or to break in isometric neck strength testing? (*under review*) 2022.

5. Chapter 7
   Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Isometric neck strength and eccentric hamstring strength in male and female Rugby Union players. (*under review*) 2022.

6. Chapter 8
   Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Effect of 6-week Nordic eccentric training with or without feedback on hamstring strength and bilateral strength balance in Rugby Union players - A randomised control trial. (*under review*) 2022.

PEER-REVIEWED CONFERENCE ABSTRACTS AND PRESENTATIONS

7. Chapter 2
   Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Neck strength in Rugby Union players: A systematic review of the literature. The Journal of Sport & Exercise Science. 2019;3(1):34-35. doi:10.36905/jses.2019.01.01. (Abstract, Appendix B1).

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8. Chapter 5

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

1.1.1 The sport of Rugby Union

Rugby Union is one of the fastest growing sports with more than 123 Rugby Union playing countries and with nearly ten million players worldwide (Rugby, 2020). It is estimated that there are more than 877 million Rugby Union followers on social media channels and at least 405 million fans, with a rapidly increasing number of players from emerging nations (e.g., Brazil and India) and female participants in the last few years (Rugby, 2020). Rugby Union is a field game and contact sport typically played in the 15s format, consisting of 15 players divided in forward (8 players) and back (7 players) positions. Teams take to the field to play two 40-minute halves in regulatory time. Variations exist in the format as well as in the levels of competition; however, this thesis will focus on the 15-a-side game.

The game of Rugby Union has evolved over time and is currently a competitive sport with high physical demands. The ball in play time has increased from 30% in 1995 to nearly 50% in 2021, resulting in more frequent collisions and greater running demands (Murray, Murray, & Robson, 2014; WorldRugby, 2019b). The number of collisions has been reported to consist of approximately 11,000 contact actions per season and 200 tackles per match (Colin W Fuller, Brooks, Cancea, Hall, & Kemp, 2007; WorldRugby, 2019b). Data from the 2012 to 2020 seasons indicate that tackles, being tackled, and collisions are the game actions most likely to result in injury in professional Rugby Union players (S. Williams et al., 2021), previously, for example scrummaging actions were the leading cause of neck and spinal injuries (K. L. Quarrie, Cantu, & Chalmers, 2002). Previous research involving professional Rugby Union players has also identified tackling as the most common contact action to produce injury [5]. Collisions are the game action with the greatest susceptibility for head and neck injuries when impacted with shoulders or arms [6]. Running actions have also been linked with injury susceptibility, especially with the occurrence of hamstring strains (Kenneally-Dabrowski, Serpell, et al., 2019a; Brooks & Kemp, 2011; Roberts et al., 2013).

1.1.2 Injuries in Rugby Union

Rugby Union is the sport with one the highest match injury rates among all team sports (Sean Williams, Trewartha, Kemp, & Stokes, 2013). Concussion is the number one ranked match injury in Rugby Union (S. Williams et al., 2021) and is of global concern. Hamstring strain injuries are also of concern in Rugby Union. Hamstring injuries are the number on ranked training injury in the English Premiership (Kemp et al., 2021), represent up to 15% of all injuries sustained (2006b), and are a marked contributor to playing and training days lost (RugbyFootballUnion & Surveillance, 2019). Given that player availability correlates with team success (S. Williams et al., 2016a), researching injury also has performance implications. This Thesis hence seeks to address two of the most common match and training-related injuries in Rugby Union.

1.1.3 Concussions and neck strength

Concussion is the number one ranked match injury in Rugby Union in terms of injury rate, with a rate of 12 injuries per 1,000 player match hours (S. Williams et al., 2021). In a single season from 2016 to 2017, Ireland Rugby Union reported 60 concussions in 160 professional players evaluated, with an incidence rate of 18.4 per 1,000 player match hours and a mean severity of 12 days (Cosgrave & Williams, 2019). In England Football Rugby Union (RFU) the injury surveillance project (PRISP) reported in the Premiership from 2019 to 2020 a total of 19.8 concussions per 1000 player match hour, with an increased trend in injury incidence since 2000 (Kemp et al., 2021). A systematic review and metanalysis of 11,620 match and training injuries from 2012 to 2020 showed a total of 1323 concussion injuries amongst elite senior male Rugby Union players, the incidence rate was not significantly different between forwards and backs (S. Williams et al., 2022). Concussion is therefore of concern to all Rugby Union players irrespective of position.

Several factors that accounted for this increased in concussion incidence, such as an increase in identification of concussed cases (G. Fuller et al., 2020), diagnosis of concussion (Matthew Cross et al., 2017), and awareness and education surrounding concussion (Matthew Cross et al., 2017). In professional male Rugby Union players, body mass of players has increased from 2011 to 2018; however, in 2019, body mass of the heavier players plateaued, whilst lighter players have continued to become heavier (Tucker et al., 2021). In female Rugby Union players, there has been fluctuations in body mass since the instigation of professionalism where the trend is less clear (Tucker et al., 2021). These anthropometric changes have occurred alongside an increased injury risk from actions games. For example, in tackle actions, a difference in mass when running at high speed between tackled players and tackler has been linked with an increase in concussions. Specifically, when a tackler with greater body mass tackles a lighter player, the magnitude of the linear and angular velocities of the head, forces acting on the neck, and momentum are increased (G. J. Tierney & Tucker, 2021). To prevent such injuries, it is important to identify how individual characteristics (i.e., neck strength) and game dynamics relate to contact and non-contact injury incidence

For several years, neck strength has been proposed to be a modifiable risk factor for concussion in contact sports, with the potential for decreased injury risk in athletes with stronger necks (Viano, Casson, & Pellman, 2007a; Caccese et al., 2018; Peek, Elliott, & Orr, 2020). A recent study has identified neck strength as a modifiable risk factors to decreasing concussion in Rugby Union, whereby a 10% increase in neck extension strength was associated with a 13% decrease in concussion rate (Farley, Barry, Sylvester, De Medici, & Wilson, 2022). Given this association, several studies have quantified peak isometric strength using customised load cell devices (D. F. Hamilton & Gatherer, 2014b; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014b; Naish, Burnett, Burrows, Andrews, & Appleby, 2013a). The break test appears to be the most common method used to test neck strength isometrically (Davies, Moore, Moran, Mathema, & Ranson, 2016; Geary, B. S. Green, & E. Delahunt, 2013; Geary, B. S. Green, & E. Delahunt, 2014; D. F. Hamilton & Gatherer, 2014a; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a). In the break test, the head is typically held in the neutral anatomical position and external resistance is applied to evoke a maximal muscle eccentric contraction in the desired direction using a cable attached to a handheld dynamometer or load cell until the initiation of the movement (i.e., positional failure). Additional studies performed a concentric isometric strength test with the force measured using a head harness or strap attached to a load cell device to a fixed frame in a seated or lying position in a ‘make test’ manner (Barrett et al., 2015; Konrath & Appleby, 2012; Naish et al., 2013a). Furthermore, a number of studies have implemented neck flexion, extension, and bilateral flexion exercises to improve neck strength and range of motion in Rugby Union players, as well as to decrease fatigue and reduce neck soreness (Barrett et al., 2015; Maconi et al., 2016; Naish et al., 2013a). The results from following a five to 12-week neck strengthening training programme are mixed in Rugby Union. Some studies have reported significant improvements in strength (Geary et al., 2014; Maconi et al., 2016); whereas others report no significant improvements in strength in any direction (Barrett et al., 2015; Naish et al., 2013a). These results suggest that either the assessment methods or training programmes are not well standardised to provide consistent outcomes, warranting further exploration of alternative testing and strength training strategies in Rugby Union players to address neck strength and injury prevention.

In the past, players have expressed their concerns about the potential long-term physiological and cognitive impacts of concussions on players (Walton et al., 2021). There are reports of cerebrovascular and cognitive consequences of concussion in Rugby Union players, including a decline in cerebral flow and cognitive functions after contact events in a single season (Owens et al., 2021). Comparably, when former Rugby Union players were analysed with neuropsychological tests and contrasted with non-contact sport players, the results showed a small to moderate cognitive deficit in the Rugby Union players (Hume et al., 2017). These concerns are important considerations in Rugby Union, and reducing the incidence and/or severity of concussions should be a priority in the sport.

To reduce the incidence and severity of concussion injuries, different strategies have been implemented in Rugby Union. Rule changes is one example, whereby reducing the number of high tackles has been shown effective in reducing neck and catastrophic head injuries in Rugby Union (RugbySmart, 2001; WorldRugby, 2011). World Rugby introduced new tackling rules, and subsequently reported a 12% reduction in concussions at the 2019 Rugby World Cup, with a decrease in incidence from 12.5 to 10.5 concussions per 1,000 player match hour compared to the 2015 Rugby World Cup tournament (WorldRugby, 2019b). Regarding modifiable risk factors, strengthening and activation of the neck muscles before a head impact might be protective and prevent the occurrence of concussion in athletes. Necks with greater cross-sectional areas and stiffness can protect the head from linear and angular accelerations, displacements, and reduce peak velocities due to impacts (J. T. Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014; Farley et al., 2022). Hence, implementing neck strengthening exercises in Rugby Union athletes may prove beneficial for addressing concussion injuries.

1.1.4 Hamstring injuries and hamstring strength

Similar to concussion, hamstring strain injuries are of concern in Rugby Union. Hamstring strain injuries represent 6 to 15% of all injuries sustained in Rugby Union, and are one of the most common match injuries (Brooks et al. (2006b). Hamstring injuries were ranked amongst the top three injuries in terms of recorded days lost (> 84 days) in the England Rugby Football Union Premiership in 2017 (RugbyFootballUnion & Surveillance, 2019). With respect to the epidemiology of hamstring injuries, acute hamstring strains have the highest recurrence rate of any muscle injury with 32% of hamstring injuries reoccurring in the National Football League (Brukner & Khan, 2016; Heiser, Weber, Sullivan, Clare, & Jacobs, 1984). A previous hamstring injury has been identified as a paramount risk factor to sustaining another hamstring injury (Freckleton & Pizzari, 2013a).

Another mechanism linked to hamstring strain injury is hamstring strength deficits and bilateral strength imbalances. In Australian Football Rules, an eccentric hamstring strength threshold value of 256 Newtons (N) was established in the context of injury risk, below which there was a significant increase in injury risk. However, this threshold could differ with different body mass (heavier and/or taller players can reach 256 N with greater ease than smaller players (D. A. Opar et al., 2015), as well as sports. In Rugby Union, data from Nordic hamstring eccentric strength testing performed with a load cell device have indicated that weaker players (bilateral average < 267.9 N) were at a similar risk of sustaining a hamstring injury than stronger players; and hence, did not appear predictive of injury. On the other hand, injured players demonstrated a significantly greater imbalance between limbs (average 17.4%) than players that remained injury-free (imbalance ≤10%) (M. N. Bourne, Opar, Williams, & Shield, 2015b). To measure hamstring strength and bilateral strength balance, different methods have been employed in Rugby Union, with isokinetic testing considered the "gold standard" and most common method to assess hamstring and quadriceps strength (Abdelfettah, Ngandzali, Ouazzani, Erouam, & El Hassan, 2019; Anastasi & Hamzeh, 2011; Beyer et al., 2016; Brown, Brughelli, & Bridgeman, 2016; Deighan, Serpell, Bitcon, & Croix, 2012; Dobbs, Watkins, Barillas, Wong, & Brown, 2017; Severo-Silveira et al., 2018). However, isokinetic testing is not accessible to most Rugby Union players. The Nordic hamstring eccentric test performed with a load cell device is more feasible and implementable in practice (M. N. Bourne et al., 2015b).

1.1.5 Evolution of player characteristics

With the increasingly popularity and commercial investment of stakeholders in Rugby Union, the game has transformed from an amateur to a professional sport with an impact on anthropometric characteristics of players, such as greater body mass and stature, and a reduction in age (C. W. Fuller, Taylor, Brooks, & Kemp, 2013; Hill et al., 2018). Thus, the physical characteristics of male professional Rugby Union players have changed, with bigger, stronger, faster, an fitter professional players than their amateur counterparts (Kenneth L Quarrie & Hopkins, 2007). Likewise, in regards of neck characteristics, compared to players with weaker neck muscles, male players with stronger necks are heavier, taller, older, possess higher bilateral grip strength, and larger neck cross sectional areas (Nutt, McKay et al. 2022). Rugby Union players with a previous history of concussion exhibited greater neck strength imbalances with lower flexion/extension ratios (Nutt, McKay et al. 2022). Therefore, when assessing concussion injury risks, normative isometric neck strength and flexion to extension and bilateral ratios are important for practitioners and coaches in Rugby Union to inform training strategies and injury prevention models (Nutt, McKay et al. 2022).

Regarding hamstring strain injuries and physical characteristics of the players, when assessing hamstring eccentric strength with a load cell device, a significant difference in eccentric strength between injured and uninjured legs has been reported, with the injured leg weaker than the uninjured leg (M. N. Bourne et al., 2015b). In the literature, the incidence of hamstring strain injuries in back players was three times greater than forwards (Brooks, Fuller, Kemp, & Reddin, 2005a), and caused the greatest number of days lost (17 days) in backs (2005b). The difference in incidence of injuries between players positions justify the need for position-specific injury profiling to better target physical preparation and injury prevention strategies (Brooks & Kemp, 2011). Given the increasing incidence and severity of concussion and hamstring injuries (West et al., 2020a), the limited data regarding isometric neck strength or eccentric hamstring strength values in Rugby Union, and the lack of information regarding bilateral strength balances in female Rugby Union players (C. Chavarro-Nieto, M. Beaven, N. Gill, & K. Hébert-Losier, 2021b; C. D. Chavarro-Nieto, C. M. Beaven, N. D. Gill, & K. Hébert-Losier, 2021), further characterising neck and hamstring strength in both male and female Rugby Union players is warranting.

1.1.6 Strengthening hamstring strategies to prevent hamstring injuries

Nordic eccentric exercise training programmes have been implemented in both male and female Rugby Union players to improve hamstring strength, decrease bilateral strength imbalances, and decrease hamstring strain injury incidence (Anastasi & Hamzeh, 2011; Brooks et al., 2006b). In female Rugby Union players, following a 10-week Nordic eccentric hamstring training intervention improved strength by 11 to 13% and reduced bilateral strength imbalance from 10.3 % to 4.6% (Anastasi & Hamzeh, 2011). In a study involving male Rugby Union players, three different strategies were, namely strengthening; strengthening and stretching; and strengthening, stretching, and Nordic eccentric exercises (Brooks et al., 2006b). The group performing Nordic exercises had a lower incidence of hamstring injuries compared to the group performing strengthening exercises alone (Brooks et al., 2006b). On this basis, there appears to be strong justification for believing that Nordic eccentric strengthening might be an effective tool in preventing injuries in sports, more so than strengthening alone.

Feedback in sport has a positive impact on performance. Psychologically, motivational states can lead to specific physiological responses that release epinephrine and increase motor unit recruitment and response to exercise (Croce, 1986). For instance, visual feedback during isokinetic testing of knee extensor muscles can enhance maximal force, leading to recommending the use of feedback during isokinetic strength testing for valid results (Kellis & Baltzopoulos, 1996b).

In semi-professional Rugby Union players, a six-week intervention training study examined the effect of feedback vs no feedback strategies in two parallel groups on squat jump and sprint performances. Speed increased in the feedback group only, indicating that the use of feedback in Rugby Union players during training is a potential tool useful in optimising athlete responses to exercise (Kellis & Baltzopoulos, 1996b). Therefore, there is strong justification for believing that combining strengthening strategies with feedback might be an effective tool in enhancing strength gains and therefore preventing injuries in sports, more so than strengthening alone.

1.2 THESIS AIMS

The overarching aims of this thesis were to:

1. implement standardised neck and hamstring strength assessment practices in Rugby Union using portable devices;

2. better understand the potential role of neck and hamstring strength in relation to concussion, neck, and hamstring injuries in Rugby Union;

3. scientifically document the status of neck strength, flexion to extension and bilateral side flexion ratios and hamstring strength and imbalances in Rugby Union players using feasible and reliable methods; and

4. evaluate the impact of neck and hamstrings strengthening exercises and feedback strategies on strength outcomes, strength ratios, and bilateral imbalances in Rugby Union players.

Overall, this thesis sought to shed some light on neck and hamstring strength testing methods and to improve neck and hamstring strengthening practices to inform injury prevention strategies with the overarching goal of reducing incidence and severity of injuries in Rugby Union players.

1.3 THESIS STRUCTURE

This thesis comprises of nine chapters divided into four sections (Figure 1). Chapter 1 provides a brief introduction to the topic and thesis. Subsequently, the first section addresses the "Neck" in Rugby Union and consists of three subsections divided into Chapters. Chapter 2 is a systematic literature review that critically appraises the scientific literature, regarding neck strength, neck strengthening strategies, and neck and concussion injuries in Rugby Union. Chapter 3 is an experimental study that compares two methods to assess isometric neck

strength in Rugby Union, namely the break and make tests, using a load cell device. This experimental study identifies the level of association of measures between these two methods and establishes their intrasession reliability in cohort of both semi-professional Rugby Union players and healthy participants. Chapter 4 is the last chapter of Section 1, and examines both the intrasession and intersession reliability of neck strength measures in a make test fashion using a load cell device in semi-professional Rugby Union players.
Section 2 explores “Hamstring” in Rugby Union and is subdivided into two chapters. Chapter 5 is a systematic review that addresses hamstring strength and bilateral strength balance measures, as well as hamstring injury incidence, risk factors, injury prevention, and strengthening strategies in Rugby Union. Subsequently, Chapter 6 examines the intrasession and intersession reliability of Nordic hamstring eccentric strength and bilateral strength balance measures derived using a load cell device in semi-professional Rugby Union players.

Section 3 contains a single chapter focused on characterising neck and hamstring strength in Rugby Union players. Specifically, Chapter 7 characterises isometric neck and hamstring eccentric strength values from male and female semi-professional and professional Rugby Union players. The two testing methods relying on a portable load cell device used in Section 1 and Section 2 are also used in Section 3.

Section 4 involves a single chapter with an intervention programme. More precisely, Chapter 8 is a randomised controlled trial that examines the effect of a six-week progressive Nordic eccentric and isometric hamstring training programme performed with and without visual feedback on hamstring strength and bilateral strength balance in male Rugby Union players, whilst including a control group

The final chapter concludes this thesis. Chapter 9 presents a general discussion that synthesised the key findings of the thesis, addresses the strengths and limitations of the thesis, and outlines practical implications and future research directions.

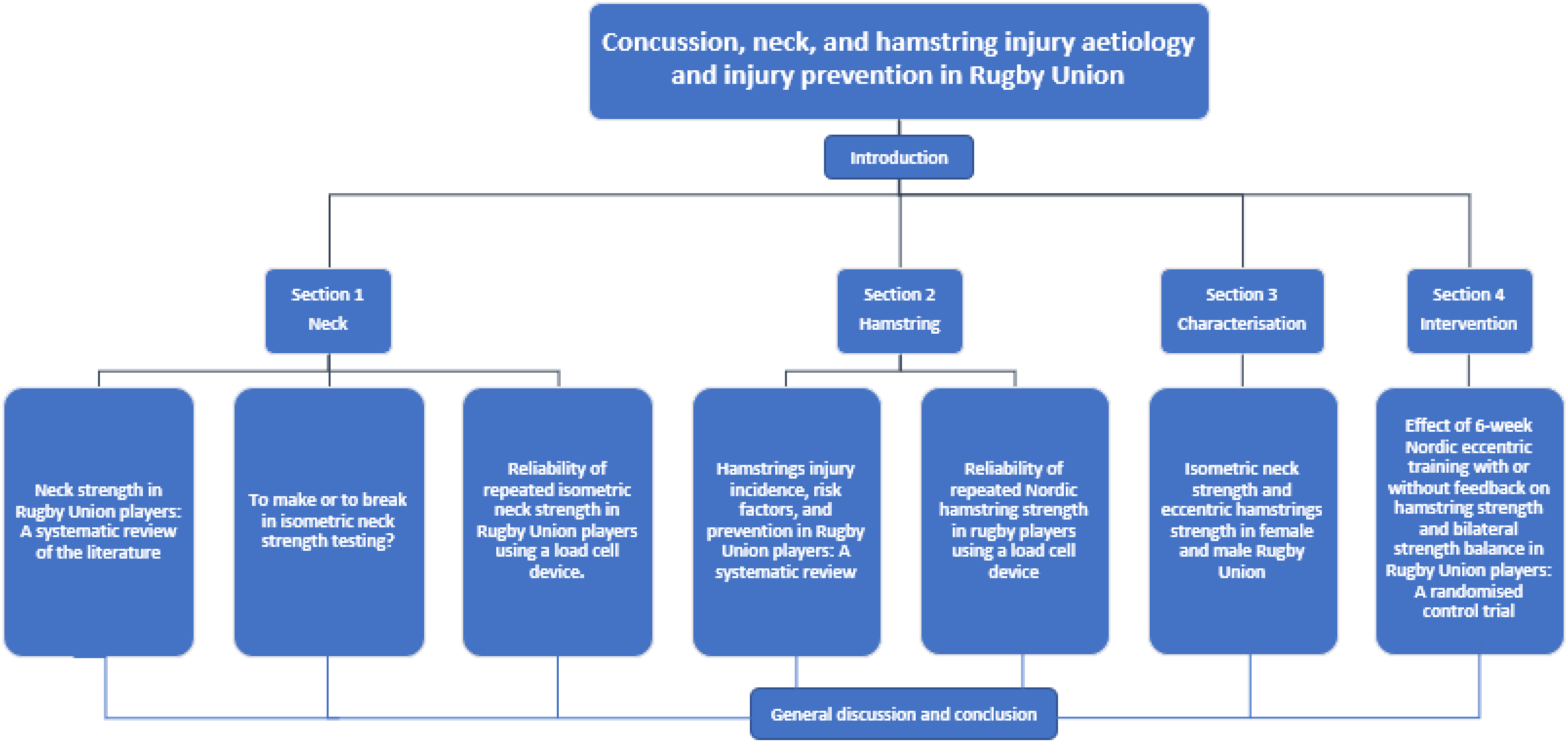

Figure 1. Flow diagram of the thesis structure.

1.4 RESEARCH QUESTIONS

The specific research questions for the individual studies included as part of this PhD thesis are outlined below.

Section 1. Neck

Chapter 2. Neck strength in Rugby Union players: A systematic review of the literature

- What are the current neck strength normative values and assessment protocols in Rugby Union players?
- What is the evidence on the role of neck strength and neck strengthening exercises on injury incidence and prevention in Rugby Union?

Chapter 3. To make or to break in isometric neck strength testing

- Are the make and break isometric test methods to assess neck strength comparable, and which method should be used in future studies?
- What is the association between the make and break test measures and what is the reliability of these two assessment methods?

Chapter 4. Reliability of repeated isometric neck strength in Rugby Union players using a load cell device

- What is the the intrasession and intersession reliability of isometric neck strength in a make test fashion in Rugby Union players using a load cell device?

Section 2. Hamstring

Chapter 5. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review

- What is currently available in the literature regarding hamstring strain injury incidence, risk factors, strength measures, injury prevention, and strengthening strategies in Rugby Union players?

Chapter 6. Reliability of repeated Nordic hamstring strength in rugby players using a load cell device

- What is the the intrasession and intersession reliability of Nordic hamstring strength measures in Rugby Union players using a load cell device?

Section 3. Characterisation

Chapter 7. Isometric neck strength and eccentric hamstrings strength in female and male Rugby Union

- What is the current status of eccentric Nordic hamstring and isometric neck strength of semi-professional and professional female and male Rugby Union players?
- Do these measures differ based on position and level of competition?

Section 4. Intervention

Chapter 8. Effect of 6-week Nordic eccentric training with or without feedback on hamstring strength and bilateral strength balance in Rugby Union players: A randomised control trial

- Is feedback during a six-week Nordic eccentric and hamstring isometric strengthening programme superior to no feedback for improving eccentric hamstring strength and decreasing bilateral strength imbalances in semi-professional male Rugby Union players?
- Are the two aforementioned conditions superior to control for improving eccentric hamstring strength and decreasing bilateral strength imbalances in semi-professional male Rugby Union players?

SECTION 1. Neck

CHAPTER 2

Neck strength in Rugby Union players: A systematic review of the literature

Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Neck strength in Rugby Union players: A systematic review of the literature. The Physician and Sportsmedicine. 2021;49(4):392-409. doi: 10.1080/00913847.2021 (Appendix A1)

Prelude: The main role of this chapter was to summarise the literature on neck muscle strength in Rugby Union. Additionally, this chapter sought to identify the potential role of neck strength and strengthening exercises on concussion and neck injury incidence in Rugby Union. The chapter provides an overview of neck strength and protocols used to assess neck strength in Rugby Union players. The chapter presents neck strength values reported for Rugby Union players in flexion, extension, bilateral side flexion and rotation, as well as flexion to extension and bilateral side flexion ratios with different protocols of testing and levels of competition. The chapter identified gaps in this literature, namely that different methods were used to assess neck strength, there were limited data for female players, and few studies reported the effects of strengthening programmes on incidence of neck and concussion injuries.

2.1 Introduction

Concussions are of major concern given their short- to middle-term impacts on players, and their serious long-term sequelae with links to cognitive decline (Hume et al., 2017) and chronic traumatic encephalopathies later in life (Stewart, McNamara, Lawlor, Hutchinson, & Farrell, 2016). Concussion is the most common injury in professional Rugby Union with the England Rugby Football Union (RFU) reporting that approximately 21% of match-related injuries were concussions (RugbyFootballUnion & Surveillance, 2018), with the incidence increasing for the seventh successive season. In the same period, Ireland Rugby Union reported 60 concussions in 160 professional rugby players (Cosgrave & Williams, 2019). Bitchell, Mathema, and Moore (2020) reported concussions as the most common injury in professional Welsh players, with an increase from 10.6 to 21.4 injuries/1000 hours in the annual incidence of concussion across four seasons from 2012 to 2016. Additionally, a concomitant increase in concussion severity from 86 days lost/1000 hours to 302 days lost/1000 hours was reported (Bitchell et al., 2020)..M. Cross, Kemp, Smith, Trewartha, and Stokes (2016) indicated that players from the RFU with a traumatic brain injury had a 60% increased risk of any subsequent injury over two seasons, hypothesized to be due to impaired neuromuscular control (Howell, Osternig, & Chou, 2015).

The Irish injury surveillance report monitored over 600 male and female amateur players across the country (theIrishRugbyInjurySurveillanceProject(IRIS), 2019). The most frequent match injury in males was concussion, representing 12% of all injuries reported. In females, concussion was also the most common match injury alongside ankle sprains. The loose head prop and hooker were the player positions with the most documented injuries in amateurs.

These data highlight that concussion is not only of concern at the professional level, but also in amateur Rugby Union where the number of participants continues to grow worldwide (WorldRugby, 2016).

In relation to costs, a report from Accident Compensation Corporation (ACC) in New Zealand highlighted that Rugby Union had the largest number of injuries and claims compared to any other sport from 2012 to 2016. This report identified the average cost associated with moderate-to-serious and serious injuries to be the greatest for the head and neck when grouped by anatomical region (King et al., 2019). In the context of injury type, concussion claims were ranked third in terms of mean cost after soft tissue and fracture/dislocation injuries. Considering the socio-economic and medical impact of concussion, various strategies are being implemented and trialled to reduce the incidence and severity of these injuries. These include rule changes introduced by World Rugby in 2017; however, recent data suggest that the overall incidence of concussion has remained unchanged. In fact, the data indicate a significant *increase* in the number of concussions in the tacklers tackling below the line of the shoulders compared to games with players tackling following the previous regulations (Stokes et al., 2019).

In terms of modifiable risk factors for preventing concussion in athletes at an individual level, strengthening the neck musculature and increasing neck girth is one strategy of potential protective value. Necks with greater cross-sectional areas and stiffness can protect the head from linear and angular accelerations and displacements, as well as reduce peak velocities due to impacts (Dempsey, Fairchild, & Appleby, 2015; Viano, Casson, & Pellman, 2007b). In contact sports and healthy individuals, prior activation of neck muscles before a collision has been shown to significantly decrease the peak linear velocity and change in acceleration of the head (J. T. Eckner et al., 2014; Simoneau, Denninger, & Hain, 2008). However, it is not always possible to anticipate a collision in a dynamic on-field environment.

The National Football League's (NFL) Head, Neck, and Spine Committee (Viano, Casson, & Pellman, 2007a) examined the biomechanics of head collisions in 25 NFL male players in a laboratory experiment. Players with stronger necks had lower linear and angular head accelerations, suggestive of a lower risk of concussion due to lesser forces. The Committee highlighted the potential for an increased injury risk in populations with weaker necks, such as females and youth players. In young (17 to 19 years) NFL male players, extension neck strength was shown to be greater than flexion and bilateral flexion (Franco & Herzog, 1987). To reduce neck injuries, the group recommended addressing neck strength and muscle imbalances. Similarly, total neck strength in high school students participating in contact sports was a significant predictor of concussion (Collins et al., 2014). An increased in neck strength equivalent to one pound decreased the probability of concussion by 5 %. Specifically in soccer, stronger necks have also been associated with lower head accelerations when purposely heading the ball, suggesting lower risk of concussion due to the strong association of heading with concussion in this sport (Caccese et al., 2018; Peek, Elliott, & Orr, 2020). However, what type of neck strengthening programme is the most effective for which level of play remains undetermined. Implementing an 8-week isotonic neck-strengthening program in university soccer players increased neck flexion strength by 15% in both males and females, and extension strength by 22.5% in females. However, this study found no significant decrease in head accelerations with force application (Mansell, Tierney, Sitler, Swanik, & Stearne, 2005). In contrast, an 8-week neck training programme involving manual resistance undertaken with high school players competing in contact sports resulted in increased neck flexion, extension, and bilateral side flexion strength, as well as a significant decrease in head acceleration (James T Eckner et al., 2018).

Rugby is a unique field-based team sport as it is dominated by high force and frequency impacts without the use of helmets(Austin, Gabbett, & Jenkins, 2011). Hence, addressing neck strength specifically in Rugby should inform practice in relation to concussion. Given the potential for mitigating risk and harm, it is cogent to critically examine and summarize the existing scientific literature on the topic of neck strength in Rugby Union players. Specifically, we aimed to systematically review and summarize the scientific literature that addressed neck strength in Rugby Union players with a particular focus on the potential role of neck strength on injury incidence, neck assessment protocols, neck strength measures, and neck strengthening exercises.

2.2 Materials and Methods

2.2.1 Information sources and search strategy

We conducted a systematic review of the literature following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (Moher, Liberati, Tetzlaff, Altman, & Group, 2010). The first author (CC) performed a systematic search on 1st of January 2021 to locate published peer-reviewed articles from four electronic databases: PubMed, SciVerse Scopus®, SPORTDiscus™, and Web of Science®. The search strategy consisted of the following keywords and Boolean operators entered in the main search bar of each e-database: "neck

AND strength AND rugby”. The exact resulting search syntax in PubMed was: ("neck"[MeSH Terms] OR "neck"[All Fields]) AND strength [All Fields] AND ("football"[MeSH Terms] OR "football"[All Fields] OR "rugby"[All Fields]).

2.2.2 Inclusion and exclusion criteria

The primary interest of this literature review was to identify original research studies that evaluated neck strength, neck strengthening interventions, and/or included head or neck injury outcomes in Rugby Union. The search included articles published up until January 1st, 2021. Studies were screened for inclusion based on the following criteria: included neck strength assessment measures in Rugby Union players, neck strengthening exercises in Rugby Union players, or neck strength, neck strengthening exercises, and neck injuries in Rugby Union players. Studies were not excluded based on sex, age, or level of competition. Only original peer-reviewed research articles written in English were included.

2.2.3 Screening process

Duplicates from the database search were removed first. Two authors independently screened all titles, abstracts, and full texts for inclusion criteria. The study selection process was replicated for articles that were included through manual searches of other databases and the reference lists of full text screened. The authors met at each screening stage (i.e., titles, abstracts, and full texts) to resolve any disagreement in terms of inclusion, with a third reviewer not needed to resolve outstanding disagreements.

2.2.4 Quality assessment

Two reviewers independently assessed the methodological quality of included studies (n = 14) using the Newcastle – Ottawa Scale (NOS) adapted for cross-sectional studies (Modesti et al., 2016). The reliability for NOS adapted for cross-sectional studies based on intraclass correlation coefficient (ICC) and confidence interval values within (ICC, 0.98; 95% CI, 0.94-0.99) and between (ICC, 0.94; 95% CI, 0.80-0.98) raters is excellent (Hanzlíková & Hébert-Losier, 2020). Prior to assessment, the two reviewers met to discuss and familiarise themselves with the scales. All identifiable information (i.e., authors, affiliations, countries, and sources of publication) were removed from articles by a third party to blind the two reviewers to reduce the assessment bias. Disagreements in the risk of bias assessment scores were resolved by discussion between the reviewers and consensus scores are presented in this article.

The NOS is a methodology assessment tool for observational studies recommended by the Cochrane Collaboration (Hoegberg et al.). The tool uses a "star system", wherein more stars indicates a superior methodological quality and lower risk of bias. The NOS awards a maximum of 10 stars: Five for selection (representativeness of the sample, sample size, non-respondents, and ascertainment of the exposure), two for comparability, and three for outcome (assessment of outcome and statistical test). Reviewers agreed that for the statistical test item, the highest star rating would be allocated for the reporting of confidence intervals, quartiles, or limits of agreement. The methodological quality of studies was divided into three groups based on the number of stars awarded: *weak* (0 to 3 stars), *moderate* (4 to 6 stars), and *strong* (7 to 10 stars) (Peterson, Welch, Losos, & Tugwell, 2011). The design of each study was classified first as experimental or observational, and then as randomised controlled trial, cross-sectional or cohort (McKeon, Medina, & Hertel, 2006; Vandenbroucke et al., 2007; von Elm et al., 2007). No article was excluded from this review based on quality score or study design.

2.2.5 Data extraction and synthesis

The lead researcher extracted data from the selected full-text articles using a standardised form, and the data extracted was verified. For each study, study design, participant information, level of competition, location of the study, study characteristics, strength assessments, and outcome data were extracted. Data were grouped and extracted under three main themes of interest: neck strength measures, neck strengthening exercise programs, and incidence of injuries. Data were managed and analysed using Microsoft® Office Excel 2016 (Redmond, Washington, USA).

2.3 Results

2.3.1 Included studies

The flow diagram from the search strategy and screening process is shown in Figure 2. Fourteen studies met the eligibility criteria.

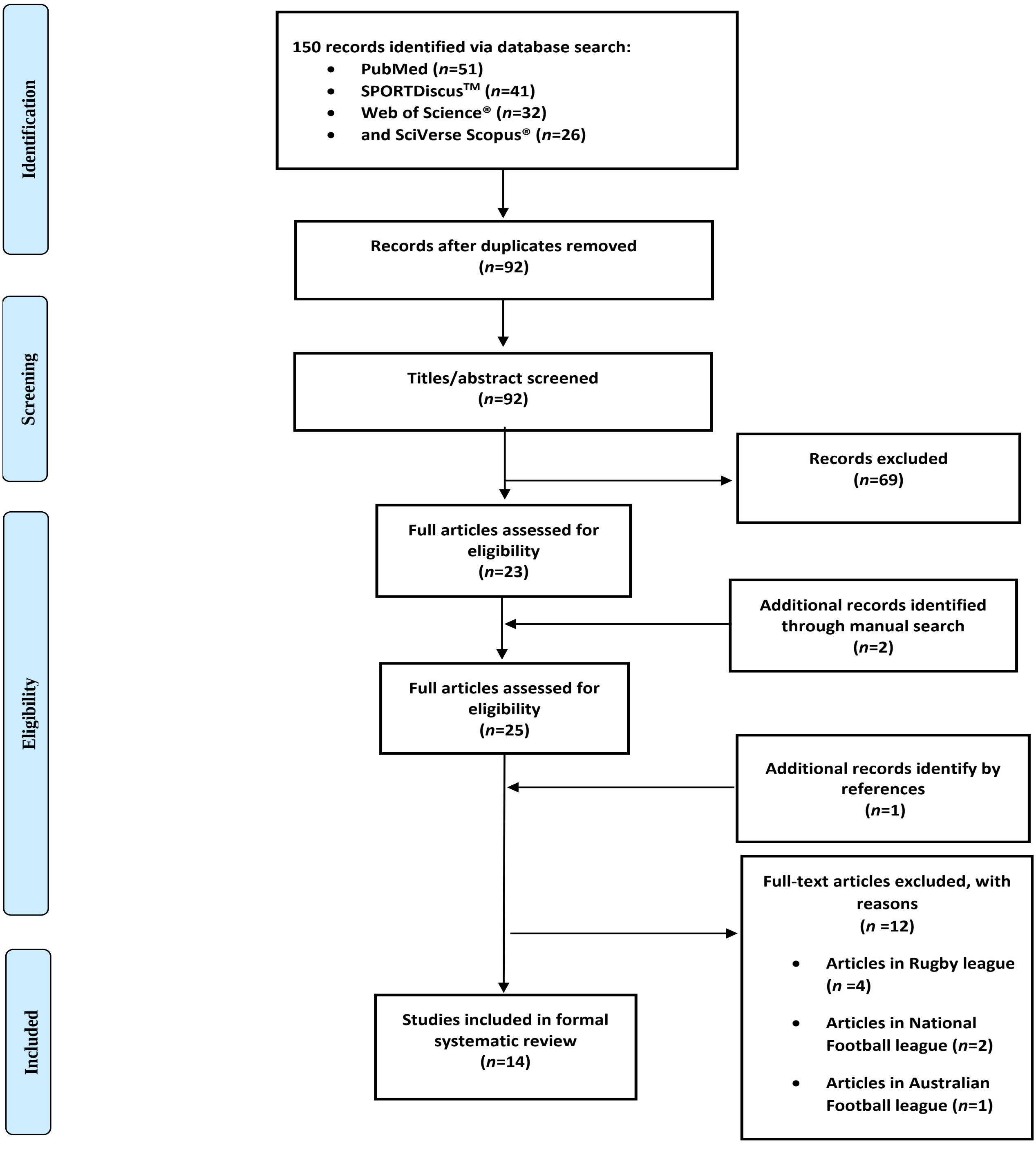

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow chart.

2.3.2 Study characteristics

The main characteristics of the 14 studies that met inclusion are presented in Table 1. Based on the Newcastle – Ottawa Scale (NOS), most studies were of *moderate* quality (n =11, 79%) (Barrett et al., 2015; Davies et al., 2016; Dempsey et al., 2015; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a; Konrath & Appleby, 2012; Maconi et al., 2016; Naish et al., 2013a; Olivier & Du Toit, 2008; Salmon, Sullivan, Handcock, Rehrer, & Niven, 2018; Snodgrass, Osmotherly, Reid, Milburn, & Rivett, 2018). Only two articles were of *strong* methodological quality (Geary et al., 2013; D. F. Hamilton & Gatherer, 2014a), with one study ranked as *weak* (Geary et al., 2014). Item-by-item NOS ratings for each study are presented in Appendix C1.

2.3.3 Participants

The 14 articles that met inclusion involved 1066 male players (mean sample size: 76 participants). Rugby players were professional in seven of these studies (50%) (Davies et al., 2016; Dempsey et al., 2015; Geary et al., 2014; D. F. Hamilton & Gatherer, 2014a; Konrath & Appleby, 2012; Naish et al., 2013a; Olivier & Du Toit, 2008), school-aged in three (21%) (Barrett et al., 2015; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a), amateur (e.g., club) in three (21%) (Geary et al., 2013; Maconi et al., 2016; Salmon et al., 2018), and semi-professional in one (7%)(Snodgrass et al., 2018). Studies were conducted mostly in the United Kingdom (*n* = 5) (Barrett et al., 2015; D. F. Hamilton & Gatherer, 2014a; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a) and Australia (*n* = 4) (Dempsey et al., 2015; Konrath & Appleby, 2012; Naish et al., 2013a; Snodgrass et al., 2018). Ireland (Geary et al., 2013; Geary et al., 2014), Italy (Maconi et al., 2016), New Zealand (Salmon et al., 2018), and South Africa (Olivier & Du Toit, 2008) were also represented in one to two studies each, see Table 1

Table 1. Characteristics of the included studies.

Study	NOS rating*	Level of competition Location	Player characteristics	Study design	Study characteristics
Barrett et al. (2015)	*Moderate* 6 stars	Senior school-aged United Kingdom	32 males Age: 17.3 ± NR y Mass: 87.59 ± NR kg Height: 181.34 ± NR cm	Randomised controlled trial (prospective)	Duration: 1 season Injuries: No Intervention: Strengthening
Davies et al. (2016)	*Moderate* 6 stars	Senior professional and Age-grade professional Wales	40 males **21 seniors** Age: 19 ± 1 y Mass: 109 ± 7 kg Height: 182 ± 5cm **19 age-grade** Age: 27 ± 5 y Mass: 114 ± 6 kg Height: 185 ± 4 cm	Cohort (cross-sectional)	Duration: 1 season Injuries: No Intervention: No

Dempsey et al. (2015)	*Moderate* 4 stars	Elite professional Australia	10 males Age: NR Mass: 98 ± 10.5 kg Height: 189 ± 7 cm	Case series (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Geary et al. (2013)	*Strong* 7 stars	Amateur Ireland	25 males Age: 19.3 ± 1.3 y Mass: 95.2 ± 13.2 kg Height: 185 ± 6cm	Cohort (reliability)	Duration: 1 season Injuries: No Intervention: No
Geary et al. (2014)	*Weak* 3 stars	Professional Ireland	25 males **15 professionals as subjects** Age: 19.3 ± 1.3 y Mass: 95.2 ± 13.2 kg Height: 185 ± 6 cm **10 semi-professionals as controls** Age: 20.7 ± 1.25 y Mass: 101.3 ± 12.3 kg	Case control (retrospective)	Duration: 1 season Injuries: No Intervention: Strengthening

			Height: 185 ± 2.7 cm		
D. F. Hamilton et al. (2012)	*Moderate* 6 stars	School children Scotland	382 males Age: 15 ± 2.1 y Mass: 66.1 ± 11.3 kg Height: 172 ± 7.3 cm	Cohort (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
D. F. Hamilton and Gatherer (2014a)	*Strong* 7 stars	Professional Wales	27 males Age: 22.3 ± 3.9 y Mass: 97.9 ± 10.7 kg Height: 186.2 ± 6.4 cm	Cohort (retrospective)	Duration: 1 season Injuries: No Intervention: No
D. F. Hamilton et al. (2014a)	*Moderate* 6 stars	Senior school-aged and adult senior school-aged Scotland	52 males **30 under18** Age: 16.7 ± NR y Mass: 96.0 ± 13.69 kg Height: 178.7 ± 5.54 cm **22 adults** Age: 27.2 ± NR y	Cohort (cross-sectional)	Duration: 1 season Injuries: No Intervention: No

			Mass: 107.8 ± 13.67 kg Height: 178.7 ± 5.91 cm		
Konrath and Appleby (2012)	*Moderate* 4 stars	Professional Australia	40 males (22 forwards, 18 backs) Age forwards: 24.8 ± 4.1 y Age backs: 24.3 ± 3.9 y Mass forwards:109.8 ± 6.2 kg Mass backs: 92.1 ± 8.2 kg Height forwards: 187 ± 7 cm Height backs: 181 ± 9.9cm	Case series (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Olivier and Du Toit (2008)	*Moderate* 5 stars	Senior elite professional South Africa	189 males Age: 24.31 ± NR y Mass: 99.04 ± NR kg Height: 183.44 ± NR cm	Case series (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Maconi et al. (2016)	*Moderate* 5 stars	Third division amateur Italy	23 males Age: NR Subjects *n* = 12 Mass: 94.3 ± 19.1 kg	Cohort (retrospective)	Duration: 1 season Injuries: No

			Height: 186 ± 6 cm Control *n* = 11 Mass: 92.5 ± 17.2 kg Height: 182 ± 8 cm		Intervention: Strengthening
Naish et al. (2013a)	*Moderate* 6 stars	Professional Australia	27 males Age: 25.2 ± 3.9 y Mass: 102 ± 11.9 kg Height: 187.1 ± 6.3 cm	Cohort (retrospective)	Duration: 2 seasons Injuries: Yes Intervention: Strengthening
Salmon et al. (2018)	*Moderate* 6 stars	Amateur New Zealand	41 males Age forwards: 22.6 ± 2.7 y Age backs: 21.6 ± 2.7y Mass forwards: 103.1 ± 10.8 kg Mass backs: 80.4 ± 22.2 kg Height forwards: 182.9 ± 6.1 cm Height backs: 180.1 ± 5.5 cm	Cohort (prospective)	Duration: 1 season Injuries: No Intervention: No

Snodgrass et al. (2018)	*Moderate* 6 stars	Semi-professional Australia	142 males **Past neck injury group** Age: 22 ± NR y Mass: 99 ± NR kg Height: 184 ± 0.07cm **No past injury group** Age: 20 ± NR y Mass: 104 ± NR kg Height: 183 ± 0.06cm	Cohort (prospective)	Duration: 1 season Injuries: Yes Intervention: No

Notes. Values are means ± standard deviation.

Abbreviations: NOS, Newcastle-Ottawa Scale; NR, not reported.

* *Weak:* 0 to 3 stars. *Moderate*: 4 to 6 stars. *Strong*: 7 to 10 st

2.3.4 Neck strength measures

2.3.4.1. Overview

All studies tested neck flexion and extension. The majority of studies (*n* = 12) also included left and right lateral flexion (Barrett et al., 2015; Davies et al., 2016; Dempsey et al., 2015; Geary et al., 2013; Geary et al., 2014; D. F. Hamilton & Gatherer, 2014a; D. F. Hamilton et al., 2014a; Maconi et al., 2016; Naish et al., 2013a; Olivier & Du Toit, 2008; Salmon et al., 2018; Snodgrass et al., 2018). Six studies also evaluated bilateral rotation (Barrett et al., 2015; Davies et al., 2016; D. F. Hamilton & Gatherer, 2014a; D. F. Hamilton et al., 2014a; Maconi et al., 2016; Snodgrass et al., 2018) Table 2.

2.3.4.2 Protocol

Most of these studies measured peak isometric strength with a customized load cell device (see Strength Assessment, Table 2). Six of the studies undertook a 'break test' with the peak force measured in kilograms or Newtons (Davies et al., 2016; Geary et al., 2013; Geary et al., 2014; D. F. Hamilton & Gatherer, 2014a; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a). The 'break test' measures the peak isometric strength against an incremental load resistance. For this test, the head was held in the neutral anatomical position and resistance was applied to evoke a maximal muscle contraction in the desired direction using a cable attached to a handheld dynamometer (Figure 3) until the initiation of the movement (i.e., positional failure).

Three studies performed an isometric strength test with the force measured using a head harness or strap attached to a load cell device to a fixed frame in a seated or lying position in a 'make test' manner(Barrett et al., 2015; Konrath & Appleby, 2012; Naish et al., 2013a). To measure neck strength, Snodgrass et al. (2018) attached the hand held dynamometer to the forehead of players, and players had to press as hard as possible against the device using the neck muscles. Salmon et al. (2018) and Naish et al. (2013a) used a fixed-frame dynamometer in a rugby-specific contact/collision position, the former assessing neck strength, and the latter performing training exercises in this position and assessing strength in a 'make test' fashion. Maconi et al. (2016) measured neck strength in a seated position with the players attached to a customized ergometer with the neck strength measured against a load cell and electromyography electrodes placed on the neck muscles to determine neuromuscular activation levels. Only one study examined dynamic isokinetic neck strength using an isokinetic dynamometer (Olivier & Du Toit, 2008).

The majority of studies (*n* = 12) evaluated neck strength sitting with the head in a neutral position (Barrett et al., 2015; Davies et al., 2016; Dempsey et al., 2015; Geary et al., 2013; Geary et al., 2014; D. F. Hamilton & Gatherer, 2014a; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a; Maconi et al., 2016; Naish et al., 2013a; Olivier & Du Toit, 2008; Snodgrass et al., 2018); whilst one study assessed contact or scrummaging positions (Salmon et al., 2018), and one study recorded the neck strength lying on a bench in a supine or prone position (Konrath & Appleby, 2012).

Figure 2. Illustration of 'break test' to assess the neck extension muscles.

2.3.4.3. Outcomes

In five studies, neck strength was evaluated by playing position and compared between forwards and backs (Geary et al., 2013; D. F. Hamilton & Gatherer, 2014a; Konrath & Appleby, 2012; Olivier & Du Toit, 2008; Salmon et al., 2018). In all studies, forwards were stronger than backs, but not in all directions across studies. For instance, Geary et al. (2013) showed that amateur forwards were significantly stronger in extension than backs, but not in flexion or bilateral side flexion, whereas Olivier and Du Toit (2008) found significantly stronger necks in forwards compare to backs in flexion, extension, and bilateral side flexion. Konrath and Appleby (2012) reported significantly stronger necks in extension and flexion for forwards than backs, with larger neck girth and longer necks with greater cross-sectional area and muscle mass for forwards in both studies. Of note, Salmon et al. (2018) highlighted that peak force in all directions significantly correlated with neck girth in amateur players, with greater increase in neck strength measures over a season in amateur forwards than backs despite forwards being stronger at baseline.

2.3.4.4. Normative values

In relation to peak isometric strength by level of competition, Davies et al. (2016) showed greater values in extension, flexion, left lateral, and right lateral directions when comparing senior to junior school-aged players. D. F. Hamilton et al. (2012) indicated differences in peak isometric strength in extension from 12 to 18 years. In amateurs players, Geary et al. (2013) indicated greater values in extension, flexion, and bilateral side flexion compared to the results by Salmon et al. (2018) and Maconi et al. (2016)

Flexion-to-extension strength ratios in Rugby Union were, on average, from 0.65 Olivier and Du Toit (2008) to 0.7 D. F. Hamilton and Gatherer (2014a). Forwards exhibited a significantly lower ratio than backs (Konrath & Appleby, 2012; Olivier & Du Toit, 2008), indicating that forwards have greater extension strength relative to flexion strength. Results from Davies et al. (2016) highlighted that age-grade players also had lower flexion-to-extension ratio than senior players, with lesser neck flexor strength (41%) compared to senior players, with no difference between positions.

Three studies evaluated neck strength differences between age groups and indicated that neck strength increases with age from school children to professional players (Davies et al., 2016; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a). In the study by D. F. Hamilton et al. (2014a), adult amateur players demonstrated significantly stronger neck strength in all directions except flexion compared to under-19s level players. In school-aged players, extension neck strength (the only direction assessed) was significantly greater in 18 compared to 12 year old players (D. F. Hamilton et al., 2012). Likewise, Davies et al. (2016) reported that senior players were significantly stronger than younger age-grade players in all directions (flexion, extension, bilateral side flexion, and bilateral side flexion and extension with rotation measures).

Dempsey et al. (2015) measured neck flexion and extension in ten professional players, as well as peak angular and linear accelerations using three-dimensional cameras. The test consisted of a tackle situation, and the attacking player was tracked with body markers and the contact with the defender was analysed. These authors found a significant reduction in medial and lateral angular and linear accelerations of the head in players with stronger flexion and extension neck strength (Duma et al., 2005).

Table 2. Neck strength assessment and outcomes in Rugby Union.

Study	Participants	Strength assessment	Outcomes
Barrett et al. (2015)	34 school-aged players (17 test players and 17 controls)	**Test:** Peak isometric **Equipment:** Load cell and head harness **Type:** Make test **Position:** Seated, neck neutral **Direction:** Extension, flexion, lateral left and right flexion **Protocol:** Mean of 3 RM x each direction and rest period of 30 seconds	**Peak isometric strength pre and post 6-week neck strengthening program (tested group)** **Pre / Post:** Flexion: 24.6 / 27.7 kg Extension: 38.7 / 45.6 kg Lateral left: 33.4 / 39.9 kg Lateral right: 33.1 / 39.1 kg Flexion with left rotation: 21.5 / 24.4 kg Flexion with right rotation: 21.8 / 23.6 kg Extension with left rotation: 31.4 / 35.9 kg Extension with right rotation: 31.6 / 35.8 kg **Key findings:** No significant differences in any direction between groups.
Davies et al. (2016)	19 age-graded professional and 21	**Test:** Peak isometric **Equipment:** Cell load and head harness	**Peak isometric strength** **Baseline (SD) age-grade players:** Flexion: 26 ± 8 kg

	senior front-row forwards players.	**Type:** Break test **Position:** Seated, neck neutral **Direction:** Extension, flexion, lateral left and right flexion and left and right flexion and extension in 45°rotation **Protocol:** Mean of 3 RM x each direction and rest period of 15 seconds	Extension: 52 ± 6 kg Lateral left: 35 ± 8 kg Lateral right: 38 ± 10 kg Flexion in 45° rotation left: 22 ± 4 kg Flexion in 45° rotation right: 20 ± 6 kg Extension in 45°rotation left: 38 ± 9 kg Extension in 45°rotation right: 39 ± 10kg PTF/PTE ratio: 0.5 **Baseline (SD) senior players:** Flexion: 44 ± 12 kg Extension: 71 ± 9 kg Lateral left: 59 ± 11 kg Lateral right: 61 ± 11 kg Flexion in 45° rotation left: 40 ± 8 kg Flexion in 45° rotation right: 41 ± 11 kg Extension in 45°rotation left: 66 ± 9 kg Extension in 45°rotation right: 68 ± 11 kg PTF/PTE ratio: 0.6 **Key findings:** Senior players were significantly stronger than age-grade players in all neck strength measures.

Dempsey et al. (2015)	10 professional players.	**Test:** Peak isometric **Equipment:** Load cell and head harness **Type:** NR **Position:** lying, neck neutral **Direction:** Extension, flexion, lateral left and right flexion **Protocol:** Peak of 3 RM x each direction holds and rest period of 60 seconds	**Peak isometric strength** **Baseline mean (SD)** Flexion: 293.8 ± 65.1 N Extension: 222 ± 49.3 N Lateral left: 221.9 ± 38.8 N Lateral right: 216.6 ± 43.2 N **Key findings:** Positive correlations were found between neck strength flexion, extension, and angular and linear accelerations in a simulated tackling situation.
Geary et al. (2013)	25 amateur players.	**Test:** Peak isometric **Equipment:** Handheld dynamometer, load cell, and head harness **Type:** Break test **Position:** Seated, head neutral	**Peak isometric strength** **Baseline (SD) forwards:** Flexion: 357.1 ± 51.6 N Extension: 637.1 ± 75.1 N Lateral left: 581.1 ± 105.4 N Lateral right: 576.4 ± 79.4 N Total: 2151.9 ± 231.1 N **Baseline (SD) backs:** Flexion: 322.2 ± 53.6 N Extension: 537.8 ± 82.2 N

		Direction: Extension, flexion, lateral left and right flexion **Protocol:** Mean of 3 RM x each direction holds and rest period of 60 seconds	Lateral left: 471.3 ± 73.5 N Lateral right: 482.7 ± 93.7 N Total: 1814.2 ± 211.2 N **Key findings:** Forwards significantly stronger in extension vs backs, as well as in total isometric neck strength.
Geary et al. (2014)	15 professional and 10 semi-professional players.	**Test:** Peak isometric **Equipment:** Handheld dynamometer and head harness **Type:** Break test **Position:** Seated, head neutral **Direction:** Extension, flexion, lateral left and right flexion **Protocol:** Peak of 3 RM x each direction holds and rest period of 60 seconds	**Peak isometric strength pre and post 5-week neck strengthening program** **Pre (SD) / Post (SD**) Flexion: 334.4 ± 39.3 / 396 ± 75.5 N Extension: 606.1 ± 97.3 / 733.8 ± 127.1 N Lateral left: 555.5 ± 88.3 / 657.1 ± 122.9 N Lateral right: 570 ± 106.5/ 668 N ± 142.1 N **Key findings:** A 5-week neck strengthening program significantly increased sagittal (flexion and extension) and frontal (lateral right and left) plane isometric measures.

D. F. Hamilton et al. (2012)	382 schoolchildren players.	**Test:** Peak isometric extension strength **Equipment:** Customised neck device with a load cell **Type:** Break test **Position:** Seated, head neutral **Direction:** Extension **Protocol:** Mean of 3 RM x each direction and rest period of 30 seconds	**Peak isometric extension strength** **Baseline (SD) by age:** 12 y: 18 ± 3.1 kg 13 y: 21 ± 3.9 kg 14 y: 25 ± 5.7 kg 15 y: 28 ± 6.0 kg 16 y: 30 ± 6.0 kg 17 y: 32 ± 6.3 kg 18 y: 34 ± 8.1 kg **Key findings:** Peak isometric neck extension strength increased with age from 18 kg at 12 y to 34 kg at 18 y.
D. F. Hamilton and Gatherer (2014a)	27 professional players.	**Test:** Peak isometric **Equipment:** Customised neck device with a load cell **Type:** Break test **Position:** Seated, head neutral **Direction:** Extension, flexion, lateral left and right flexion, Left and right rotation	**Peak isometric strength** **Baseline (SD) forwards:** Flexion: 32 ± 5.6 kg Extension: 44.9 ± 7.1 kg Left lateral flexion 42.9 ± 7.7 kg Right lateral flexion: 43.1 ± 7.5 kg Rotation left: 37.5 ± 6.9 kg Rotation right: 38.5 ± 5.5 kg

		Protocol: Mean of 3 RM x each direction and rest period of 30 seconds	**Baseline (± SD) backs:** Flexion: 28.5 ± 3.9 kg Extension: 39.5 ± 5.2 kg Lateral left: 35 ± 4.5 kg Lateral right: 35 ± 4.5 kg Flexion with left rotation: 33 ± 3.3 kg Flexion with right rotation: 33.4 ± 3 kg All players PTF/PTE ratio: 0.7 **Key findings:** Forwards were significantly stronger than backs in all directions, except flexion.
D. F. Hamilton et al. (2014a)	30 senior school-aged and 22 male adult senior school-aged front-row players.	**Test:** Peak isometric **Equipment:** Customised neck device with a load cell **Type:** Break test **Position:** Seated, head neutral **Direction:** Extension, flexion, lateral left and right flexion, Left and right rotation **Protocol:** The mean 3 RM x each direction holds and rest period of 60 seconds	**Peak isometric strength** **Baseline [95% CI] under 19 y:** Flexion: 22.5 [20.4 to 24.72] kg Extension: 41.7 [39.36 to 44.18] kg Lateral left: 32.2 [30.04 to 34.45] kg Lateral right: 31.8 [29.66 to 24.01] kg **Baseline [95% CI] adults:** Flexion: 25.4 [22.94 to 27.86] kg Extension: 53.7 [48.42 to 58.99] kg

			Lateral left: 40.5 [36.36 to 44.71] kg Lateral right: 42.4 [39.24 to 45.73] kg **Key findings:** Adults were significantly stronger than the under-19 group in all directions, except in flexion.
Konrath and Appleby (2012)	40 professional players.	**Test:** Peak isometric **Equipment:** Customised neck device with a load cell and velcro head strap **Type:** Make test **Position:** Supine and prone and head horizontal to the floor **Direction:** Extension and flexion **Protocol:** The peak of 3 RM x each direction with 5 sec duration and rest period of 60 seconds	**Peak isometric strength** **Forwards:** Flexion: 295.2 N Extension: 328 N PTF/PTE ratio: 0.92 **Backs:** Flexion: 244 N Extension: 229 N PTF/PTE ratio: 1.28 **Key findings:** Forwards were significantly stronger in flexion and extension vs backs.

			Forwards had significantly lower isometric flexion to extension ratios than backs.
Maconi et al. (2016)	23 amateur players and 11 controls	**Test:** Peak isometric **Equipment:** Customized ergometer load cell **Type:** Flexion of the head against an unmovable support **Position:** Seated, neck neutral **Direction:** Extension, flexion, lateral left and right flexion and left and right rotation **Protocol:** The peak of 3 RM x each direction of 3 sec and rest period of 30 seconds	**Peak isometric strength pre and post 12-week neck strengthening program** **Pre (SD) / Post (SD)** Flexion: 135 ± 47 / 202 ± 44 N Extension: 164 ± 37 / 214 ± 41 N Lateral left: 137.5 ± 29.7 / 141.6 ± 35 N [no significant increase post training] Lateral Right: 144.2 ± 30.5 / 146.1 ± 31.8 N [no significant increase post training] Flexion with left rotation: 130 ± 31 /165 ± 31 N Flexion with right rotation: 129 ± 31 / 154 ± 22 N **Key findings:** Flexion, extension, flexion with left and right rotation neck strength measures increased significantly after a 12-week training program. There were *no significant changes* in right and left flexion with training.

Naish et al. (2013a)	27 professional players	**Test:** Peak isometric **Equipment:** Customized load cell device, head harness, and immovable metal frame **Type:** Make test **Position:** Seated, head neutral **Direction:** Extension, flexion, lateral left and right flexion **Protocol:** The peak of 3 RM x each direction with 5 sec duration and rest period of 30 seconds	**Peak isometric strength pre and post neck strengthening program at week 5** **Pre (SD) / Post (SD)** Flexion: 277.6 ± 63.0 / 288 ± 64.1 N Extension: 367.7 ± 47.9 / 372.4 ± 50.9 N Lateral left: 363.2 ± 53.9 / 372.2 ± 50.6 N Lateral right: 376.4 ± 44.7 / 383.6 ± 51.9 N **Key findings:** An intervention of neck strengthening did not significantly affect strength values at week 5.
Olivier and Du Toit (2008)	189 professional players	**Test:** Peak isokinetic torque **Equipment:** Isokinetic dynamometer **Type:** Isokinetic test **Position:** Seated, head neutral **Direction:** Flexion, extension, lateral left and right flexion	**Peak isokinetic strength** **Baseline [95% CI] front row forwards:** Flexion: 42.6 [39.76, 45.54] Nm Extension: 65.6 [62.12, 69.0] Nm Lateral left: 64.8 [60.65, 67.51] Nm Lateral right: 65.1 [61.08, 69.16] Nm **Baseline [95% CI] backs:** Flexion: 33.5 [32.26, 34.76] Nm Extension: 46.1 [44.38, 47.86] Nm

		Protocol: The peak of 3 RM x each direction and NR rest period	Lateral left: 50.4 [48.25, 52.55] Nm Lateral right: 50 [48.21, 51.81] Nm **Difference of peak torque relative to body weight** **PTF/BW** **PTE/BW** Front row 0.38 [0.36, 0.40] 0.59 [0.56,0.62] Second row 0.4 [0.36 ,0.44] 0.57 [0.52,0.62] Back row 0.41[0.38, 0.44] 0.58 [0.54,0.62] Backline 0.4 [0.38, 0.42] 0.55[0.53,0.57] All players PTF/PTE: 70% [68.40-71.6] **Key findings:** Among positions the difference of peak torque relative to body weight was small. Extension of front row forwards significantly greater than any other player. Front row forwards were significantly stronger than backs in all peak torque measures.

			Peak torque ratio: Front row forwards demonstrated PTF/PTE ratios 65% lower than any other position.
Salmon et al. (2018)	41 amateur players.	**Test:** Peak isometric **Equipment:** Load cell and fixed-frame dynamometer **Type:** Bracing against the bench **Position:** Contact posture (tackle / scrummaging) **Direction:** Extension, flexion, lateral left and right flexion **Protocol:** 1 RM x each direction, held by 5s and rest period of 60 seconds	**Peak isometric strength pre and post 20-week Rugby Union season** **Pre (SD) / Post (SD) forwards:** Flexion: 238.8 ± 149.4/ 245.7 ± 125.80 N Extension: 326.6 ± 116.9 / 367 ± 116.73 N Lateral left: 195 ± 97.9 / 234.5 ± 93.31 N Lateral right: 221.5 ± 128.7 / 233.9 ± 90.05 N **Pre (SD) / Post (SD) backs:** Flexion 161.8 ± 51.3 / 175.9 ± 57.7 N Extension 253.4 ± 74.09 / 276 ± 60.5 N Lateral left: 169.3 ± 64.59 / 196.7 ± 63.46 N Lateral right: 182.2 ± 73.19 / 190.8 ± 48.41 N **Key findings:** Forwards exhibited higher peak values at baseline in all directions vs backs.

			After a 20-week in-season follow-up, neck strength in significantly improved in forwards in extension 16%, flexion 19%, left 35% and right 27% lateral flexion and backs in extension 10%, flexion 21%, and left lateral flexion in 27%. Forwards demonstrated significant improvements (35.3-59.1 N) in all directions post-season compared to controls.
Snodgrass et al. (2018)	142 semi-professional players.	**Test:** Peak isometric **Equipment:** Handheld dynamometer **Type:** Push against a manually applied force **Position:** Seated, neck neutral **Direction:** Extension, flexion, lateral left and right flexion and left and right flexion and extension with rotation	**Peak isometric strength** **Baseline (± SD) no history of neck injury:** Flexion: 17.9 ± 3.5 kg Extension: 23.2 ± 2.7 kg Lateral left: 18 ± 3.6 kg Lateral right: 17.3 ± 3.6 kg Flexion with left rotation: 14.5 ± 2.2 kg Flexion with right rotation: 15.3 ± 2.7 kg **Baseline (± SD) history of neck injury:** Flexion: 18.2 ± 3.7 kg Extension: 22.6± 19.0, kg Lateral left: 18.1 ± 3.8 kg Lateral right: 17.5 ± 4.0 kg

		Protocol: The mean of 3 RM x each direction NR rest period	Flexion with left rotation: 14.7 ± 2.2 kg Flexion with right rotation: 15.8 ± 3.1 kg **Key findings:** No significant difference was observed in strength between players with and without a history of neck injuries.

Notes. Values are means ± standard deviation, means [95% confidence intervals], and minimum – maximum ranges.

Abbreviations: BW, bodyweight; CI, confidence interval; PTF, peak torque flexion.; PTE, peak torque extension; RM repetition maximal ; N, Newton; Nm, Newton-meter; NR, No report; SD, standard deviation

2.3.5 Neck strengthening programs

Four of the included studies implemented a neck strengthening program (Barrett et al., 2015; Geary et al., 2014; Maconi et al., 2016; Naish et al., 2013a) (Table 3). The stated goals of the studies included increasing neck strength (Barrett et al., 2015; Geary et al., 2014; Naish et al., 2013a), resilience to fatigue, and range of motion (Barrett et al., 2015); reducing neck soreness (Maconi et al., 2016) and neck injuries (Naish et al., 2013a); and identifying neck imbalances as a potential risk factor for injuries (Barrett et al., 2015). All four training programs implemented isometric routines, with one study also implementing concentric exercises (Maconi et al., 2016). In the two studies involving professional players, one used rigid cables (Naish et al., 2013a) and the other manual resistance (Geary et al., 2014) for neck strengthening; although the studies were performed at the same level of competition and implemented similar training protocols (two to three sets of 3 or 4 reps of neck holds of 3 to 10 s in four directions twice a week), differences between outcomes are likely due to the difference in timing of the strength test, strength test measures, and training loads. The other two studies performed training exercises using elastic cords with variable resistance loads in school-aged (Barrett et al., 2015) and amateur players (Maconi et al., 2016). All four studies implemented neck flexion, extension, and bilateral flexion exercises; with one study incorporating right and left rotation (Barrett et al., 2015). These exercises were executed two to three times per week, usually three to four sets of four to twelve repetitions per session. The program duration varied from five to twelve weeks.

After implementing a 5-week strengthening training program, Geary et al. (2014) found significant increases in neck strength in flexion (18%), extension (20%), and left (18%) and right (17%) lateral flexion. Maconi et al. (2016) found greater gains in strength in neck flexion (50%), extension (30%), and bilateral rotation (left 27%, right 19%) following 12 weeks of strengthening, but not in lateral flexion. In contrast, Naish et al. (2013a) found no significant improvements in strength after a 26-week strengthening training period when measured at week five of the program, with no further assessment performed thereafter. Similarly, Barrett et al. (2015) reported that a 6-week training program did not significantly increase neck strength in any direction.

Table 3. Neck training protocols and results.

Study	Participants	Training program	Protocol	Outcomes
Barrett et al. (2015)	34 senior school-aged players (17 test players and 17 controls)	6-week duration Isometric holds with a head harness and custom variable resistance elastic cords. The control trained and played as normal.	**Type:** Isometric **Frequency:** 3 x per week **Sets and reps**: 4 sets x 6 reps **Load**: 50% MVC	**Mean change (%) intervention / control:** Flexion: 15.7 / 14.7% Extension: 21.7 / 13.2% **Mean change (raw units) intervention / control:** Flexion: 3.1 / 2.7 kg Extension: 6.9 / 4.4 kg **Key findings:** A 6-week neck strengthening program did not significantly increase neck strength in any direction compared to controls.
Geary et al. (2014)	15 professional and 10 control semi-professional players	5-week duration Isometric holds in flexion, extension, and left and right lateral flexion against a manual resistance.	**Type:** Isometric **Frequency:** 2 x per week. **Sets and reps**: 1 set x 3 reps **Load:** 10 s holds against manual resistance	**Mean increases [95% CI]:** Flexion: 61.6 [33.1, 90.03] N Extension: 127.6 [68.2, 187.0] N Left lateral flexion: 101.5 [46.4, 156.6] N Right lateral flexion: 98 [47.6, 148.3] N **Key findings:**

				A 5-week neck strengthening program significantly increased sagittal and frontal isometric measures.
Maconi et al. (2016)	23 amateur male players and 11 control	12-week duration Isometric and concentric strengthening using elastic bands.	**Type:** Isometric **Frequency:** 3 x per week **Sets and reps**: 3 sets x 10 reps **Load**: 10 s holds at 70% MVC **Type:** Concentric **Frequency:** 3 x per week **Sets and reps:** 3 sets x 8 reps	**Pre (SD) / Post (SD):** Flexion: 135 ± 47 / 202 ± 44 N Extension: 164 ± 37 / 214 ± 41 N Flexion with left rotation: 130 ± 31 / 165 ± 31 N Flexion with right rotation: 129 ± 31 / 154 ± 22 N Right lateral flexion: 144.2 ± 30/ 146.1 ± 31N Left lateral flexion: 137.5 ± 29.7/ 141.6 ± 35.0N **Key findings:** A 12-week neck strengthening program significantly increased all neck strength measures, except for left and right lateral flexion.
Naish et al. (2013a)	27 professional players	26-week duration Isometric cable holds in flexion, extension, and left and right lateral flexion.	**Preseason**: Weeks 1-13 **Type:** Isometric **Frequency:** 2 x per week **Sets and reps**: 2-3 sets x 4-12 reps	**Pre (SD) / Post (SD)** Flexion: 277.6 N ± 63 / 288 N ± 64.1 Extension: 367.7 N ± 47.9 / 372.4 N ± 50.9 Lateral left: 363.2 N ± 53.9 / 372.2 N ± 50.6

			Load: 70%-100% 1RM **Maintenance phase**: Weeks 14-26 **Type:** Isometric **Frequency:** 1-2 x per week. **Sets and reps**: 2- 3 sets of 3-4 reps. **Load:** 3 s holds %MVC NR	Lateral right: 376.4 N ± 44.7 / 383.6 N ± 51.9 **Key findings:** A 26-week neck strengthening program did not significantly improve neck strength measures after 5 weeks.

Notes. Values are means ± standard deviation, means [95% confidence intervals], and minimum – maximum ranges

Abbreviations: CI, confidence interval; MVC, maximal voluntary contraction; N, Newton; NR, not report; RM, maximal repetition; SD, standard deviation

2.3.6 Neck strength measures, training programs, and injuries

Two of the studies reviewed considered the relationship between neck strength measures, neck strength training programs, and injuries in Rugby Union (Naish, Burnett, Burrows, Andrews, & Appleby, 2013b; Snodgrass et al., 2018) (see Table 4). Naish et al. (2013a) performed a 26-week isometric neck-strengthening program in professional players across two competition seasons. In the second season, a neck strengthening program was introduced (13-week strengthening period followed by a 13-week maintenance) and compared injury reports to the previous season. The results indicated that the athletes had a significant reduction in neck injuries during matches played within the neck strengthening program. In their retrospective analysis, there was a significant reduction in match neck injuries from eleven to two after the intervention program.

The other longitudinal study that aimed to understand the association between physical characteristics and incidence of neck pain and injuries by Snodgrass et al. (2018) evaluated 142 semi-professional players. The neck assessment included measurements relating to neck strength, anthropometrics, proprioception, and range of motion. No significant difference was found in neck strength when comparing players with or without a history of neck injury. On the other hand, a greater number of previous neck injuries was observed with increasing age and playing experience. In-season neck injuries were associated with a reduced range of motion in left and right lateral flexion.

Table 4. Neck strength and injuries.

Study	Participants	Duration	Neck strength measure and/or training program	Outcomes
Naish et al. (2013a)	27 professional Super Rugby Union players.	26-week training program	26-week training program Isometric cable holds in flexion, extension, and left and right lateral flexion. Preseason: weeks 1-13 **Type:** Isometric **Frequency:** 2 x per week **Sets and reps**: 2-3 sets x 4-12 reps **Load:** 70%-100% 1RM Maintenance phase: weeks 14-26 **Type:** Isometric **Frequency:** 1-2 x per week. **Sets and reps**: 2- 3 sets of 3-4 reps. **Load:** 3 s holds	**2-season neck injury report:** **First season (no neck training program):** Players injured: 8 Number of injuries: 12 Training injuries: 1 Match injuries: 11 **Second season (with neck training program):** Players injured: 6 Number of injuries: 6 Training injuries: 4 Match injuries: 2 **Key findings:** Significant reduction in match neck injuries, not in peak strength values after a neck strengthening program.

Snodgrass et al. (2018)	142 semi-professional players.	Pre-season	Pre-season assessment of neck strength, anthropometrics, proprioception, and range of motion. Neck injuries monitored during a competitive Rugby Union season.	**Characteristics of the 11 neck injuries:** **Position:** Front row: 5 (45%) Back row: 5 (45%) Wing: 1 (10%) **Phase of play:** Tackle: 7 (64%) Scrum: 1 (9%) Ruck: 2 (18%) Maul: 1 (9%) **Concussion:** Yes: 4(36%) No: 6 (55%) ***missing data** **Previous neck injury:** Yes: 7 (63%) No: 4 (36%) **Key findings:** Older and more experience players had more history of previous neck injuries.

2.4 Discussion

2.4.1 Neck strength measures in Rugby Union

In Rugby Union, neck strength has been measured in a number of studies with the intention of determining differences between age groups, positions, and injury prevalence (Barrett et al., 2015; Davies et al., 2016; Dempsey et al., 2015; Geary et al., 2013; Geary et al., 2014; D. F. Hamilton & Gatherer, 2014a; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a; Konrath & Appleby, 2012; Maconi et al., 2016; Naish et al., 2013a; Olivier & Du Toit, 2008; Salmon et al., 2018; Snodgrass et al., 2018). We examined the scientific literature addressing neck strength in Rugby Union with a focus on neck strength assessment protocols training programmes and relationships with injuries. The studies included in this review were implemented with male players; therefore, we advise against the generalisation of findings to female players due to – amongst other reasons – the previously reported physiological differences between sexes (R. T. Tierney et al., 2005). Furthermore, pooling results across studies to make strong inferences is challenging given the various testing procedures, equipment, and units used.

Isometric neck strength was assessed in nearly all studies, except in one where isokinetic strength was examined (Olivier & Du Toit, 2008). Overall, the 'break test' displayed greater neck strength values compared to the other methods of testing although no direction comparisons between testing methods have been undertaken, and the outcome of these tests showed strength variations based on player characteristics, positions, and level of competition. Adopting a standardized method of assessment of neck strength to compare outcomes across studies is of upmost importance. Indeed, there is a lack of consistency between studies, and no dynamic and eccentric testing procedures. As such, important physical properties (i.e., stiffness) of the neck musculature are not currently being examined with respect to their association to neck, head, or concussion injury risk in Rugby Union (Queen, Weinhold, Kirkendall, & Yu, 2003).

2.4.2 Methodological Discussion

Salmon et al. (2018) assessed amateur players with a fixed-frame dynamometer in a rugby specific position (similar body position to player running into contact or scrum position) and found stronger necks in all directions for forwards compared to backs at baseline. At the conclusion of a playing season, both forwards and backs (except in right lateral flexion) exhibited greater neck strength, with the improvement being somewhat unexpected for the backs given their lesser contact demands and associated neck loading. In contrast, Geary et al. (2013) assessed neck strength in a seated position in a 'break test' fashion and found greater extension strength in forwards than backs, and not in any other direction . This difference in strength outcomes between positions could be attributable to the rugby specific position used by Salmon et al. (2018) with the isolation of the neck muscles and the improved neuromuscular recruitment assumed in the scrummaging posture. Furthermore, it could be that this rugby specific position was more familiar for forwards given their scrummaging on-field role, with the test position being unfamiliar for backs. From these studies, the considerable variation in test methods is clear; therefore comparing studies to build up a picture of neck strength in players and to get a definitive relationship between neck strength and injury is challenging with the current literature.

2.4.2.1 Position Effects in Neck Strength

Variables such as greater body mass (Geary et al., 2013; D. F. Hamilton & Gatherer, 2014a; Konrath & Appleby, 2012; Olivier & Du Toit, 2008; Salmon et al., 2018), larger neck girths (Konrath & Appleby, 2012; Olivier & Du Toit, 2008; Salmon et al., 2018), and longer necks (Konrath & Appleby, 2012; Salmon et al., 2018) were associated with stronger necks in forwards compared to backs. In professional players, greater body mass was associated with larger cross-sectional neck areas and stronger necks (D. F. Hamilton & Gatherer, 2014a). At this level, forwards from Geary et al. (2014) displayed the highest isometric strength values in this review. The test was performed in a 'break test' manner, with forwards being stronger than backs in all four directions. To date, there is no consensus regarding what strength values at this or at any level of competition should be targeted and sufficient to minimize risk of injury. Indeed, levels of neck strength require further investigation to assist coaches and players to understand what is required to prevent injury and/or decrease injury severity. We strongly suggest that recommendations be prescribed regarding neck strength in younger rugby athletes given the "in-game" stressors such as scrum, ruck, maul and collision and the rising numbers of head injuries observed.

2.4.2.2 Neck Strength Ratios

With regards to the ratio between flexion and extension, forwards appear to have a significantly lower ratio compared to backs (Konrath & Appleby, 2012; Olivier & Du Toit, 2008), with greater extension strength measures compared to flexion. These findings are probably due to the neck extension forces exerted by forwards to keep the neck stable during scrummaging. In relation to age, younger players showed lower flexion to extension ratios compare to senior players (Davies et al., 2016). These discrepancies in neck musculature are a potential risk factor for neck injuries, where a flexion to extension ratio imbalance having been associated with higher head angular and linear accelerations in other cohorts (Dezman, Ledet, & Kerr, 2013). Promoting strength symmetry between muscles is a strategy used in practice in attempts to mitigate injury risk in other anatomical parts of the body (e.g., knee) (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008). The neck is not except as symmetry in muscle strength between flexors and extensors is crucial in neck stabilization (Rezasoltani, 2005).

2.4.3 Neck strengthening training programs

In the studies reviewed, four studies implemented neck strengthening programs in Rugby Union players. Two studies reported a significant increase in neck strength of the players post intervention (Geary et al., 2014; Maconi et al., 2016), and two reported no improvements (Barrett et al., 2015; Naish et al., 2013b). In a longer 12-week intervention that added concentric exercises, Maconi et al. (2016) found a significant increase in strength in all directions except in bilateral side flexion. This research group also noted improvements in coactivation of neck muscles, motor recruitment, and muscle firing rate patterns of neck musculature using electromyography.

The American College of Sports Medicine (ACSM) guidelines for exercise prescription (Ratamess, 2013) recommend for resistance strength training the following routine: frequency of 2 to 3 times per week, with 2 to 4 sets of 8 to 12 repetitions at a load of 60 to 70% for intermediate and >80% for experienced participants to improve strength and power.

Based on these parameters, the most comprehensive training strategies were implemented by Geary et al. (2014) and Naish et al. (2013a) using isometrics, and Maconi et al. (2016) using isometrics and concentric exercises. Barrett et al. (2015) performed lower training intensities and repetitions than the ACSM recommendations, using 50% of maximal voluntary isometric contractions and 6 repetitions. This exercise prescription might have not induced enough stimulus to produce improvement in strength.

As mentioned previously, most protocols undertaken in rugby were performed with isometric exercises without dynamic, neuromuscular, or eccentric training routines. Lisman et al. (2012) implemented an 8-week isometric resistance training for the neck muscles in collegiate NFL players. The intervention was effective in increasing left lateral flexion (7%) and extension strength (10%), but did not affect tackling head accelerations or activation of neck stabilizers during tackling. These results hence suggest that isometric neck strength alone may be insufficient to reduce incidence and severity of head injuries and that training stabilizer muscles, and that incorporating neck stabilisation training modalities could be important. This proposition is supported by results from Schmidt et al. (2014) who demonstrated that stronger and larger necks was not protective of head injuries in NFL players, whereas stiffer and more responsive neck musculatures to cervical perturbations were protective. Modelling studies substantiate that strengthening strategies in American football and other contact sports should include eccentric training and preparation for impact exercises to reduce head injury metrics (Mortensen, Vasavada, & Merryweather, 2020). Despite very different rules and regulations regarding mandated protective equipment between American Football and Rugby Union, these studies overall highlight the importance of diverse neck training strategies in decreasing the severity of impacts. Future research in rugby should seek to implement neuromuscular, eccentric, and anticipation for impact training to determine their relevance and effectiveness in the context of concussions in rugby.

2.4.4 Neck strength measures, training programs and injuries

Injury risk factors, including neck asymmetries, previous injuries, as well as deficits in range of motion and proprioception, have not been linked to neck and head injuries in Rugby Union players (Lark & McCarthy, 2007). Despite the introduction of a new tackle rule, the incidence of concussions in professional players continue to increase (C. Fuller, A. Taylor, M. Douglas, & M. Raftery, 2020; Stokes et al., 2019). It would seem that improving neck strength should be a priority in any injury prevention and performance program in Rugby Union. Neck strength values can assist in the preparation and screening of rugby players at every level, i.e., targeting specific preseason training strategies; as well as providing a clinical tool to aid the rehabilitation of cervical injuries or return to play protocols. Few studies have examined the relationship between neck strength values, neck strengthening exercises, and the incidence of neck and head injuries (Naish et al., 2013a; Snodgrass et al., 2018).

Naish et al. (2013a) presented a paradoxical result, wherein the decrease in the number of neck match injuries was not associated with changes in neck strength values after a strengthening program. The researchers attributed this result to neurological changes in neck proprioception, greater stabilization of deep cervical flexors, and improvements in muscle co-activation due to the training program. A limitation could exist in the neck strength evaluation, which was only measured at week five of the 26-week program, with no further assessments undertaken. As such, it is uncertain whether neck strength changes occurred after the initial 5-week period and the extent to which they influenced the prevalence of neck injuries.

None of the studies in the current review evaluated the association between neck strength or strengthening programs and the incidence of concussion injuries. However, Dempsey et al. (2015) found players with stronger necks in flexion and extension had a significant reduction in medial and lateral angular and linear head accelerations. The pre-activation of the neck flexor and extensor muscles before a collision has been shown to significantly decrease the peak linear velocity and deaccelerating of the head (J. T. Eckner et al., 2014; Simoneau et al., 2008). As such, there is the potential for neck strength to reduce concussion risk in Rugby Union. However, the systematic review by Le Flao, Brughelli, Hume, and King (2018) found no clear relationship between neck strength and head/neck accelerations and their influence on concussion injuries, and a review of the literature by Hrysomallis (2016) found inconsistent outcomes that increasing isometric neck strength reduce head accelerations and therefore a better head stabilization with impact anticipation strategies.

2.5 Conclusion

In Rugby Union, neck strength has been measured through different playing positions and levels of competition; however, there is no consensus regarding a standardized method to assess neck strength in Rugby Union. All studies have been completed in a male population, with an obvious gap pertaining to the assessment of neck strength in female athletes. Nonetheless, senior elite male players were stronger than younger-aged players, which could be due to their immature musculature and/or lesser training experience. Forwards were stronger in extension than any other directions assessed, and when compared to backs, were generally stronger and possessed larger necks and greater cross-sectional areas.

Implementation of isometric exercise routines in professional players have been reported to improve neck strength in all directions. Whilst the training programs across levels showed different outcomes, establishing an evidence-based strengthening routine with different exercise modalities (i.e., isometric, eccentric, and concentric) is essential. Moving forward, work should be undertaken to further standardise and develop guidelines regarding strength test protocols and benchmark values, as well as training protocols across age groups and performance levels.

CHAPTER 3

To make or to break in isometric neck strength testing?

Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. To make or to break in isometric neck strength testing? (*under review*) 2022.

Prelude: Making meaningful inferences from the studies review in the previous chapter proved challenging given the different neck strengthening methods across studies. The lack of consensus on the most appropriate method to assess neck strength which is practical for Rugby Union players is a clear gap. The make and the break tests two most common methods used to assess neck strength in the reviewed literature. However, there was a lack of experimental data directly comparing these two test methods for the neck, bringing into question the ability to make cross-study inferences and comparisons. This chapter therefore carried out an original experimental study that compared these two common isometric neck strength testing methods (i.e., make vs break) and determined their relative interchangeability. Furthermore, it is important that testing methods provide reliable outcomes, and that methods used in science and clinically applicable. Hence, this chapter also assessed the intrasession reliability of the two isometric neck strength tests using a portable load cell device connected to a head harness. The outcomes from this study should inform practice and future studies assessing neck strength. In the context of the thesis, this study would inform which method would be most suitable to use in subsequent studies: the make or break.

3.1 Introduction

Concussion is the most prevalent injury in Rugby Union with increasing numbers of diagnoses and days lost every year based on a 16-season review (2002-2019) conducted by the England Rugby Football Union (West et al., 2020b). The report highlighted concussion (21%) as the most common match-related injury in 2019, with this injury being the most frequent for the fifth consecutive year. Activation and strengthening neck muscles before a head impact might confer a degree of protection to prevent concussion in athletes, whereby stiffer necks and necks with a greater cross-sectional area can reduce head angular and linear accelerations (J. T. Eckner et al., 2014).

Isometric neck strength test measures have been used in Rugby Union players (C. Chavarro-Nieto et al., 2021b) and other contact sports (Collins et al., 2014; Viano et al., 2007a) to assess differences in strength between positions and levels of competition, as well as to screen for modifiable risk factors for neck injuries and concussion. Across the literature, however, there is no standard test protocol implemented (C. Chavarro-Nieto et al., 2021b). Numerous studies in Rugby Union have assessed isometric neck strength using a make test performed with the head held in neutral, using a head harness attached to a load cell device fixed to a frame, with the athlete exerting maximal force in either flexion, extension, or right/left lateral flexion from a seated or lying position (Barrett et al., 2015; Konrath & Appleby, 2012; Naish et al., 2013a). This approach to isometric neck strength testing using a load cell device has shown good intratester reliability (Pearson’s correlation from 0.89 to 0.98) (Ylinen, Rezasoltani, Julin, Virtapohja, & Mälkiä, 1999). However, no significant changes in neck strength measures in Rugby Union players assessed in this make test manner were observed across a 26-week strengthening programme, which may indicate low sensitivity of measures, despite a significant decrease in neck match-injuries [6]. Another tool used in clinical settings rather than load cells for isometric testing is a handheld dynamometer (Conable & Rosner, 2011). Typically, this approach requires an individual to push against an examiner's manually-applied force, but this method was unable to identify significant differences between Rugby Union player positions (Ashall, Dobbin, & Thorpe, 2021) or players that experienced neck pain or injury during a Rugby Union season (Snodgrass et al., 2018), indicating it might not be sensitive enough for use in Rugby Union.

An alternative to the make test for isometric testing is the break test. When the break test is used to assess the neck, normally the head is held in neutral and resistance is applied to evoke a maximal muscle contraction in the desired direction using a head harness attached to a cable until the initiation of the movement (i.e., positional failure) with data recorded using a handheld dynamometer or load cell device. In Rugby Union, the break test to assess neck strength is more common than the make test (Davies et al., 2016; K. Geary, B. S. Green, & E. Delahunt, 2013; K. Geary, B. S. Green, & E. Delahunt, 2014; D. F. Hamilton & Gatherer, 2014b; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014b). Similar to the make test, this method has been implemented in seated or laying positions with good to excellent intrarater and interrater reliability [intraclass correlation coefficient (ICC) from 0.80 to 0.92] (K. Geary et al., 2013; D. Hamilton, Simpson, & Gatherer, 2010). Although the isometric neck test performed in a break test fashion is a well-validated test in healthy populations (Chiu & Sing, 2002; Garces, Medina, Milutinovic, Garavote, & Guerado, 2002), anecdotally, there is concern from clinicians in terms of the 'aggressively' of this test and injuring players during testing (Kolber & Cleland, 2005). When contrasting findings available in the literature in Rugby Union, it appears that the break test results in greater absolute neck strength values over other assessment methods (C. Chavarro-Nieto et al., 2021b), which corresponds to experimental findings of superior break than make test values reported for other muscle groups (Bohannon, 1988; Stratford & Balsor, 1994). However, this assumption has not been verified for the neck muscles.

Isometric neck strength testing is not only used in an athletic context, but also in the more general population with normative values being established in this group (Garces et al., 2002). Isometric neck strength values can also be used in the presence of pain, and is able to differentiate between individuals with versus without chronic neck pain (Ylinen et al., 2003). Given the common use of isometric neck strength testing in athletic and non-athletic populations and lack of experimental evidence directly comparing the make and break testing methods for the neck, we aimed to compare the make and break isometric test methods used to assess neck strength in a healthy population and Rugby Union players in four different directions. A secondary aim was to determine the association between methods, as well as to revisit the intra-session reliability.

3.2 Materials and Methods

3.2.1 Participants

To detect a moderate effect size difference between paired make and break comparisons, a sample of 46 individuals was needed to achieve a power of 90% and a two-sided level of significance of 5% (Dhand, (2014)). A cross-sectional study design was used, which included a cohort of 46 individuals comprised of 29 males (mean ± SD, age 20.9 ± 2.1 y, height 181.9 ±

3.2 cm, and mass 96.3 ± 21.0 kg) and 17 females (age 20.2 ± 1.2 y, height 170 ± 6.8 cm, and mass 66.5 ± 7.8 kg). The participants included eleven semi-professional Rugby Union players and 35 healthy active university students. Inclusion criteria required all participants to be free of neck pain, cervical injury, or illness in the last month that could compromise maximal isometric contraction of the neck musculature. All participants were informed of the purpose, benefits, and risks of the study through written and oral description, and gave their written consent to participate prior to engaging in any activity. The study protocol was approved by the University of Waikato Human Research Ethics Committee (HREC(Health) 2019#74) and adhered to the latest Declaration of Helsinki.

3.2.2 Instrumentation

Tests were conducted using a SOUFEI digital portable load cell (SF-912 Soufei Electronic Technology Co., Ltd, China) of 100 g accuracy with the capacity set to 50 kg. The load cell was connected via Bluetooth to an iPad Model A1566 device, and data were recorded at 20 Hz. Participants were seated in a standard fixed gym seat bench.

3.2.3 Procedures

This study assessed the neck strength in a make and break test fashion in the same day, and assessed four different directions: flexion, extension, and right and left lateral flexion. The two data collection sessions were scheduled 1 hour apart. The order of the make versus break test was randomised. The order of each direction tested was also randomised prior to the experimental trials, and kept the same for a given individual between the two conditions. Before the experimental procedure, all participants completed a warm-up protocol of three submaximal isometric repetitions in each direction tested. For the experimental procedure, participants completed three maximal effort repetitions in each of the four directions tested, with 30-second rest between contractions and 60-second rest between directions. The instructions provided before the make test was “pull as hard as you can with 100% strength and hold for 5 seconds” and for the break test was “pull as hard as you can with 100% strength against me and hold for 5 seconds”. The peak force in kilograms was recorded during the maximal isometric hold and used as main outcome measure.

Participants were seated on a standard bench chair with the head and neck in a neutral position, with a seat belt attached to the trunk to minimise trunk movement. A head harness was placed around the forehead for flexion, occiput for extension, and temporal bones for lateral flexion. The head harness was attached to a cell load apparatus via a rigid cable attached to a fixed metal frame in the make test (**Figure 4A**). For the break test, the examiner held the rigid cable and pulled in the opposite direction of the assessed neck strength direction until the initiation of movement (i.e., position failure) (**Figure 4B)**. Two balance air pads were placed under the feet to prevent further movement from the lower limbs, as shown in Figure 4.

A **B**

Figure 3. Illustration of the **(A)** make test for neck extension; and **(B)** break test for neck flexion.

3.2.3 Statistical analysis

The three repetitions completed for the make and break test for each direction were used to examine the intra-session reliability. The reliability of measurements was assessed using typical error, coefficient of variation (CV), and intraclass correlation coefficient (ICC), and were calculated using statistical spreadsheets (Hopkins, 2017). Reliability was qualitatively assessed based on ICC values according to the following thresholds: < 0.4 poor, 0.4 to 0.75 fair, 0.75 to 0.9 good, and > 0.9 excellent (Rosner, 2015).

The mean of the three trials for each test was used to compare between the make and break conditions. Scatterplots with regression confidence and prediction interval of the make versus the break tests were used to assess distribution in flexion, extension, and right and left lateral flexion. The normal distribution of the variables was assessed with Shapiro-Wilks's tests. A two-tailed dependent paired t-test was used to assess the difference in values between methods. The magnitude of the difference was quantified using Cohen's *d* effect size and was considered as trivial when $d < 0.2$, small when $d < 0.5$, moderate when $d < 0.8$, and large when $d \geq 0.8$ (Cohen, 2013). Bland-Altman plots were also constructed to assess bias and variability between make and break tests in each direction tested, with 95% limits of agreement (LOA: mean of difference ± 1.96 standard deviation) (Bland & Altman, 1995).

The Passing-Bablock procedure was used as a statistical method to assess systematic and proportional differences between methods. This regression analysis is a statistical procedure that allows an estimation of analytical methods agreement and possible systematic bias (Bilic-Zulle, 2011). The regression equation **y = bx + a** reveals proportional (b= regression line's slope) and systematic (a = regression line's intercept) differences. The results were interpreted as follows: if 0 is in the 95% CI of "a", and 1 is in the 95% CI of "b", the two methods are comparable. If 0 is not in the 95% CI of "a", there is a systematic difference; and if 1 is not in the 95% CI of "b", then there is a proportional difference between the two methods (Bilic-Zulle, 2011). All data were analysed using Microsoft Excel 2016 (Microsoft Corp., Redmont, WA, USA).

3.3 Results

Summary and reliability statistics for the isometric make and break tests are shown in **Table 1**. The intra-session relaibility for the make and break tests (ICC = 0.95 to 0.97) were excellent in all four directions. The typical error ranged from 1.4 to 2.3 kg (CV = 5.7 to 12.0%) for the make test, and 1.3 to 2.1 kg (CV = 7.1 to 10.2%) for the break test (Table 5).

Overall, the mean of the break test in all directions was greater than the make test. There was a significant difference in flexion and left lateral flexion mean values between make and break tests (Table 6, $p \leq 0.002$), with a *small* effect size. Scatterplots with linear regression confidence model and prediction interval of the make vs break tests showed good precision and linearity in each of the directions tested. These results are presented as Appendix D1.

The Bland-Altman displayed a mean bias ranging from 0.85 kg to 1.9 kg (Figure 5). The Passing-Bablock regression analysis showed a good correlation between the two methods with no outliers across the four directions tested. Slopes ranged from 0.98 to 1.15 and intercepts from -3.6 to -0.5 across directions; with no proportional or systematic difference in any direction tested between the make and break tests (Table 5).

Table 5. Summary and intrasession reliabiliy statistics for the isometric make and break tests. Values include mean, standard deviation, and 95% confidence intervals [upper, lower].

		Make test				Break test			
	n	**Mean ± SD (kg)**	**ICC [95% CI]**	**TE (kg) [95% CI]**	**CV% [95% CI]**	**Mean ± SD (kg)**	**ICC [95% CI]**	**TE (kg) [95% CI]**	**CV% [95% CI]**
Flexion	46	19.1 ± 8.8	0.96 [0.94 – 0.97]	1.42 [1.26 – 1.66]	7.0 [5.9 – 8.7]	21.1 ± 9.1	0.95 [0.93 - 0.97]	2.08 [1.83- 2.42]	7.1 [5.6 - 10.2]
Extension	46	25.8 ± 8.9	0.96 [0.94 – 0.98]	1.52 [1.34 – 1.78]	5.7 [4.8 – 7.1]	26.7 ± 8.4	0.95 [0.92 – 0.97]	1.69 [0.50 -1.98]	7.2 [6.1 – 9.0]
Right Lateral Flexion	46	19.9 ± 8.1	0.96 [0.94 – 0.98]	1.4 [1.24 – 1.64]	7.3 [6.2 – 8.8]	21.0 ± 7.2	0.96 [0.94 – 0.97]	1.38 [1.22 – 1.61]	8.9 [7.5 – 11.1]
Left Lateral Flexion	46	19.7 ± 7.0	0.97 [0.95 – 0.98]	2.34 [2.08 – 2.75]	12.0 [10.2 – 14.7]	21.3 ± 7.0	0.95 [0.92 – 0.97]	1.33 [1.17 – 1.55]	10.2 [8.6 – 12.4]

Notes. CV: coefficient of variation, CI: confidence interval, ICC: intraclass correlation coefficient, SD: standard deviation.

Table 6. Comparison of make vs break tests using Bland-Altman bias plots**,** Passing-Bablock regression procedures, Cohen's d effect sizes, and dependent paired t tests (p value).

	Bland Altman Bias ± SD (Lower LOA , Upper LOA)	**Passing-Bablok regression**				**Cohen *d* effect [95% CI]**	**Paired t test (p value)**
		Slope [95% CI]	**Proportional Bias**	**Intercept [95% CI])**	**Systematic Bias**		
Flexion	1.9 ± 3.9 (-5.7, 9.6)	0.98 [0.86, 1.11]	No	-0.5 [-3.5, 0.79]	No	0.22 [0.09, 0.34]	0.002
Extension	0.85 ± 4.14 (-7.2, 8.9)	1.13 [0.99, 1.28]	No	-3.6 [-7.5, 0.07]	No	0.10 [-0.04, 0.24]	0.094
Right Lateral Flexion	1.01 ± 5.25 (-11.2, 11.2)	1.15 [0.91, 1.43]	No	-2.3 [-6.8, 0.8]	No	0.14 [-0.05, 0.34]	0.337
Left Lateral Flexion	1.68 ± 3.43 (-4.9, 8.3)	1.05 [0.92, 1.19]	No	-1.7 [-6.4, 1.0]	No	0.22 [0.09, 0.36]	0.001

Notes. CI: confidence interval; LOA: limit of agreement; SD: standard deviation.

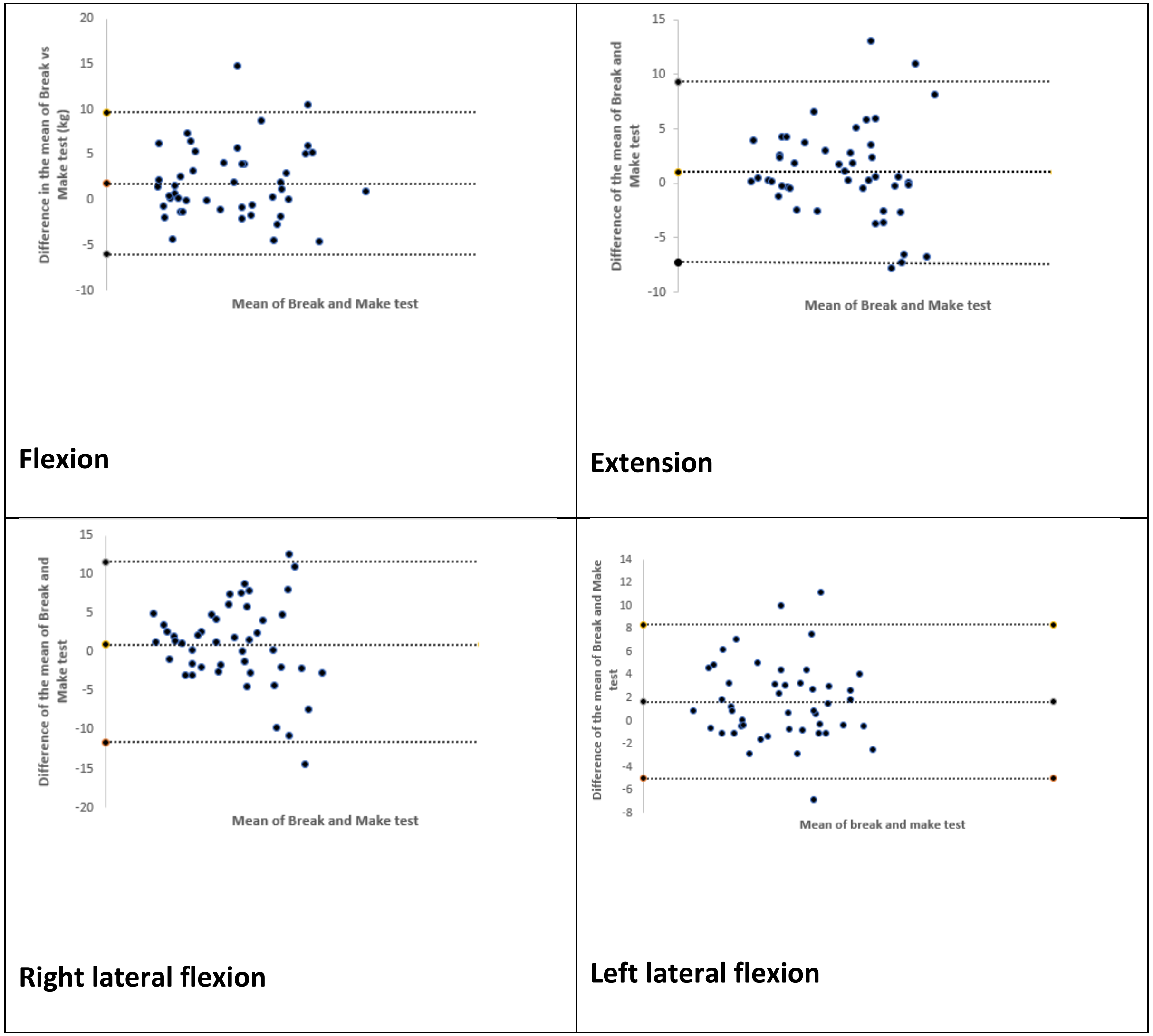

Figure 4. Illustration of the Bland-Altman plots comparing the mean isometric neck strength between the make and break test methods in flexion, extension, and right and left lateral flexion for 46 individuals. Upper and lower lines represent the 95% limits of agreement between the two methods (mean ± 1.96 standard deviation).

3.4 Discussion

We aimed to compare two methods of isometric neck strength test, the make and break tests; and secondly, to determine the association between methods and revisit their intra-session reliability. We found overall greater mean values with the break compared to the make test. Overall, both tests had good precision and linearity, and excellent intra-session reliability, with ICCs ranging from 0.95 to 0.97. In another study with healthy individuals assessed the reliability of make test isometric neck strength measures with a load cell performed in a seated position similarly to ours, demonstrating excellent between-day reliability (ICC 0.94 to 0.98) (Ylinen et al., 1999). When tested using a computerized dynamometer, no significant intra-session or inter-session differences were detected, with strong correlations of measures within (*r* 0.951 to 0.989) and between (*r* 0.731 to 0.969) sessions, and CV < 15% when assessed in a neutral neck position (Garces et al., 2002), suggesting that both within and between session assessments of isometric neck strength are reliable. In semi-professional Rugby Union players, the intra-session reliability of the make test to assess neck strength using a fixed-mounted handheld dynamometer was good for flexion, extension, and bilateral side flexion (ICC 0.77 to 0.92), as well as when tested against manual resistance in these four directions (ICC 0.77 to 0.90) (Ashall et al., 2021). When assessing the reliability of the break test using a handheld dynamometer in academy Rugby Union players, the intra-session reliability displayed ICC values of 0.85 for flexion, extension, and right lateral flexion, and 0.80 for left lateral flexion (K. Geary et al., 2013). It would seem that measuring neck strength in a make or break test fashion with a handheld dynamometry is overall less reliable in a seated position compared to the load cell set-up we used. The relatively lower reliability of handheld dynamometer could be the result of the testing interaction between the participant and examiner, wherein a stronger examiner can increase reliability (Deones, Wiley, & Worrell, 1994). A systematic review and meta-analysis of reliability studies using handheld dynamometer devices found that reliability differed across muscle groups (Chamorro, Armijo-Olivo, De la Fuente, Fuentes, & Chirosa, 2017), highlighting the importance of determining reliability of testing procedures used in clinical practice.

When comparing mean values, the break test (range: 21 to 26.7 kg) generally displayed greater values than the make test (range: 19.1 to 25.8 kg), with significant *small* differences in flexion and left lateral flexion. The range seen in our study are marginally higher than those from isometric neck strength values in a cohort of semi-professional Rugby Union players tested using a mounted handheld dynamometer (range: 17.3 to 23.5 kg) (Ashall et al., 2021). This latter study showed that make test isometric neck strength values assessed with a handheld dynamometer were greater when fixed compared to when held by an examiner. The authors recommended clinicians employ a fixed mounted handheld dynamometer given the manual method systematically underestimated maximal isometric neck strength in all four directions (Ashall et al., 2021). This underestimation was possibly due to failure of the examiner to resist the participants' strength; or the participants' awareness that they can overcome the examiner's strength, therefore not exerting a maximal effort (Ashall et al., 2021). When comparing these two methods in assessing upper limb maximal strength using a hand-held dynamometer, the literature review by Kolber and Cleland (2005), found that testing in a make test fashion was more reliable than the break test. The authors also proposed the make test decreased the potential for injury compared to the break test, although resulted in lower absolute strength values. Across Rugby Union literature, the break test has shown greater strength values compared to all the methods trialled (C. Chavarro-

Nieto et al., 2021b). It has been suggested that the higher values are due to angle variations, with potential influence from interaction between the tester, device, and participants (Stratford & Balsor, 1994).

The make and break regression analyses exhibited good precision and good linearity, with no systematic or proportional differences for all of the directions tested. Bland-Altman representation also showed good agreement between the two methods in all directions tested, although a positive off-set indicated that the break test produced greater strength values than the make test with a *trivial* to *small* effect size across directions. The mean bias detected in our study (0.95 to 1.9 kg) was lower than the mean bias reported elsewhere (1.8 to 3.8 kg) comparing fixed versus manual handheld dynamometer resistance (Ashall et al., 2021). The between-study difference is possibly due to differences in devices used. With a manual dynamometer, the strength of the examiner limits the ability to quantify or resist the strength of the participant (Mulroy, Lassen, Chambers, & Perry, 1997) and participants may perceive the ability to overcome the tester, which inhibits their maximal effort (Ashall et al., 2021). Using a rigid cable with load cell set-up provides a mechanical advantage to the tester, and therefore likely provides a more consistent and valid representation of maximal strength in strong individuals, such as rugby players. In the current study, both make and break tests were conducted in a seated position with a similar method applied in both tests, using a head harness, cable, and load cell device, like previous research (K. Geary et al., 2014; Naish et al., 2013a). Our intra-session reliability was excellent (ICC ≥ 0.95), similar to K. Geary et al. (2013) that used a comparable set-up. This reliability is superior the handheld dynamometer approach (ICC ≥ 0.77) due to challenges in achieving a standard and consistent test position across participants when using a handheld dynamometer (Ashall et al., 2021). When examining three different variations of make test set-up with a handheld dynamometer, significant differences in strength between the lying push test, seated push test, and seated pull test were detected, although the magnitude and directionality of differences were inconsistent between directions assessed (Krause et al., 2019). In contrast, using the cable and load cell approach here, we found a more consistent difference, wherein break tended to be higher than make. Granted, variations in position (e.g., lying vs seated) were not assessed; but nonetheless, the greater consistency potentially reflects the superior reliability and procedural methods of the load cell with harness and cable set-up than the handheld dynamometer.

The current results with isometric make and break neck tests coincide with the systematic literature review of neck strength with Rugby Union players (C. Chavarro-Nieto et al., 2021b), whereby the break test displayed greater absolute values compared to the make test. Studies comparing break vs make test in different joints (i.e., elbow) with a handheld dynamometer found significant differences between the two methods, with 1.06 greater values for break test overall, with individual studies reporting 1.3 times higher break test strength values (Bohannon, 1988; Stratford & Balsor, 1994). In Rugby Union, assessing neck strength has been used to establish differences between age groups, positions, and injury prevalence. For instance, in a study comparing two methods to test neck strength with a handheld dynamometer, no difference was found between neck strength by playing position in Rugby Union players (Ashall et al., 2021). When the neck strength was measured in a make test fashion in Rugby Union players, no changes in neck strength were observed across a 26-week strengthening program when measured at week five of the program (with not further assessment), despite a significant decrease in match neck injuries (Naish et al., 2013a).

Moving forward, comparing additional test methods and positions, adopting a standardised test method, and identifying the relationship between neck strength, concussion, and neck injuries are considered important areas to pursue.

3.5 Conclusion

The make and the break test methods were reliable to test neck strength in all directions tested. There were no systematic or proportional differences between methods. These findings suggest the make and break test performed in a seated position to assess isometric neck strength can be used relatively interchangeably, although a *small* group-level difference exist in flexion and lateral flexion with superior break test values. There are some procedural advantages of using the make test rather than the break test to assess isometric neck strength, including decreasing the potential for test-related injuries, enhancing participant comfort and confidence in testing procedures, and reducing the influence of the tester. Therefore, we recommend testing neck isometric strength in a make test fashion.

CHAPTER 4

Reliability of repeated isometric neck strength in Rugby Union players using a load cell device.

Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Reliability of repeated isometric neck strength in Rugby Union players using a load cell device. Sensors. 2022;22(8):2872. doi: 10.3390/s22082872. (Appendix A3)

Prelude: The previous chapter identified that the make and break test methods were both reliable for assessing isometric neck strength in all directions tested, with no systematic or proportional differences between methods. Ultimately, though, using the make test was recommended over the break test mainly for methodological reasons. Given the latter recommendation, the make test was used to assess isometric neck strength in Rugby Union for the remainder of this thesis.

The current chapter aimed to re-examine the reliability of outcomes specifically in Rugby Union players given that the previous reliability chapter involved both Rugby Union players and healthy active university students. Furthermore, the chapter sought to examine intersession reliability in addition to intrasession reliability. Examining both intrasession and intersession reliability specifically in the population of interest was important to inform future studies, establish minimal detectable change values for practice, and ensure the variables examined in Chapter 7 were reliable in Rugby Union players specifically.

4.1 Introduction

Concussion is consistently ranked as the most common injury in professional male English Rugby Union players (21%), with increasing incidence and severity from 2002 to 2019 (West et al., 2020b). Considering the medical impact of concussion in Rugby Union, various strategies are being implemented and trialled to reduce the incidence and severity of these injuries. Given that the tackler is the player with the largest incidence of concussion, World Rugby introduced a series of evidence-based initiatives to lessen concussion rates and severity, and improve player welfare (WorldRugby, 2021). These initiatives include improving the tackling technique, reducing the height of the tackle, and changing the speed of the tackle, which presumably have contributed to the 12% reduction in concussions at the 2019 Rugby World Cup compared to the 2015 tournament (WorldRugby, 2019a). In Rugby Union, the average momentum when tackling another player is above 320 kg·m/s, and elicits high levels of muscle activation at the neck and shoulder, particularly in previously injured players (Stastny et al., 2016). While rule changes have been identified as one strategy to address concussion in Rugby Union (WorldRugby, 2019a), neck strength has also been identified as a modifiable risk factor (J. T. Eckner et al., 2014; Simoneau et al., 2008). Training and return to sport protocols highlight the clinical and rehabilitative value of neck strength in neck and head injuries (Naish et al., 2013a; Peek & Gatherer, 2005). Furthermore, flexion-to-extension and left-to-right lateral flexion imbalances in neck strength are potential risk factors for neck injuries, wherein flexion-to-extension imbalances have been associated with higher head angular and linear accelerations in other cohorts than Rugby Union (Franco & Herzog, 1987). These ratios are often assessed in Rugby Union, with a review summarising greater strength values in extension compared to flexion (C. Chavarro-Nieto et al., 2021b), with forwards possessing a significantly lower ratio (0.56) compared to backs (0.61) (K. Geary et al., 2013). Considering bilateral lateral flexion ratios, left to right ratio values range from 0.98 in backs and 1.00 in forwards across the literature (K. Geary et al., 2013).

Currently, variations exist in neck strength assessment methods, benchmark values, and exercise prescription in Rugby Union (C. Chavarro-Nieto et al., 2021b). The most common test used to assess neck strength in Rugby Union is the 'break' test, which measures peak isometric neck strength when resisting against an incrementally applied load (C. Chavarro-Nieto et al., 2021b). Although the break test is the most common method used in Rugby Union, clinicians have expressed concerns regarding the 'aggressively' of this method and potential to in-jure players during testing (Kolber & Cleland, 2005). The resistance is applied to evoke a maximal muscle contraction in flexion, extension, and bilateral lateral flexion directions using a head harness attached to a cable and dynamometer or load cell until the initiation of the movement (i.e., positional failure) (Davies et al., 2016; K. Geary et al., 2013; K. Geary et al., 2014; D. F. Hamilton & Gatherer, 2014b; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014b). Previous reliability studies with this neck strength assessment method demonstrate good-to-excellent intrarater and interrater reliability [intraclass correlation coefficient (ICC) 0.80–0.92] when implemented in seated or lying positions (K. Geary et al., 2013; D. Hamilton et al., 2010).

An alternative is to use the 'make' test, which is performed using a head harness attached to a load cell device to a fixed frame or tested against a manual resistance in seated or lying positions with the participant exerting maximal strength against the load cell or handheld dynamometer (Barrett et al., 2015; Konrath & Appleby, 2012; Naish et al., 2013a). Reliability of make test isometric neck strength measures from a load cell in healthy individuals was excellent between-day (ICC 0.94–0.98) performed in sitting (Ylinen et al., 1999). In semi-professional Rugby Union players, the make test intrasession reliability assessed using a fixed-mounted handheld dynamometer was good for flexion, extension, and bilateral lateral flexion (ICC 0.77–0.92), as well as when tested against a manual resistance in these four directions (ICC 0.77–0.90) (Ashall et al., 2021). However, intersession reliability for the neck test in Rugby Union has not been examined. The lack of data on the between-day reliability of the make test in Rugby Union might explain research showing no significant changes in make test neck strength measures during a 26-week neck strengthening programme in Rugby Union despite a significant decrease in neck match-injuries (Naish et al., 2013a).

It is of upmost importance that clinicians use reliable methods when assessing individuals to inform their clinical practice. It is also essential that normative data for neck strength values be available for male Rugby Union players to inform management of this unique cohort, particularly in rehabilitation and return to play. In Rugby Union, there are no studies examining the reliability of an isometric make test using a rigid cable with load cell in a seated position set-up, or information on the between day reliability on the make test. Therefore, we aimed to examine the reliability of make test isometric neck strength measures in Rugby Union players using a load cell device.

4.2 Materials and Methods

4.2.1 Study design

A repeated-measures reliability study was conducted targeting semi-professional male Rugby Union players. Based on methods described to establish minimum sample size requirements for reliability studies (Walter, Eliasziw, & Donner, 1998), a minimum of around 20 participants was needed when setting the acceptable reliability level at $\rho 0=0.40$ (i.e., fair reliability threshold) and desired reliability level at $\rho 1>0.75$ (i.e., good reliability threshold) with an $\alpha=0.05$ and $\beta=0.20$ knowing that players were assessed on three occasions.

4.2.2 Participants

Twenty-three semi-professional male Rugby Union players [mean ± standard deviation (SD), age 22.3 ± 3.2 y, height 184 ± 7.5 cm, and body mass 100 ± 11 kg] agreed to participate in this study that took place during their regular season. Inclusion criteria required participants to be free of neck pain, cervical injury, or illness in the last month as to not compromise maximal isometric neck strength. All participants were informed of the purpose, benefits, and risks of participation through written and oral description, and gave their written informed consent to participate. The study protocol was approved by the University of Waikato Human Research Ethics Committee (HREC(Health) 2019#74) and adhered to the latest Declaration of Helsinki.

4.2.3 Instrumentation

Tests were conducted using a SOUFEI digital portable load cell (SF-912 Soufei Electronic Technology Co., Ltd, China) of 100 g accuracy with the capacity set to 50 kg. The load cell was connected via Bluetooth to an iPad Model A1566 device, and data were recorded at 20 Hz. Participants were seated in a standard fixed gym seat bench for testing.

4.2.4 Procedures

This study assessed the neck strength in a make test fashion in four different directions: flexion, extension, and right and left lateral flexion. Each player completed three testing sessions over three consecutive weeks, one week apart. Before the experimental procedure, all participants completed a warm-up protocol of three submaximal isometric repetitions in each direction tested.

For the experimental procedure, we followed procedures similar to those reported elsewhere (Ylinen et al., 1999) and implemented in professional Rugby Union players (Naish et al., 2013a). Participants were seated on the standard gym bench with the head and neck in a neutral position. A seat belt secured the trunk to minimise movement and two balance air pads were placed under the feet to prevent further movement and contributions from the lower limbs. A head harness was placed around the forehead for flexion, occiput for extension, and temporal bones for lateral flexion. The harness was attached to a load cell apparatus via a rigid cable attached to a fixed metal frame (Figure 6). For data collection, participants completed three maximal effort repetitions in each of the four directions tested, with 30-second rest between contractions, and 60-second rest between directions. The order of testing was randomised between participants and held constant between testing occasions. The instructions provided before the make test was to “pull as hard as you can with 100% strength and hold for 5 seconds”. The peak strength in kilograms was recorded for each isometric contraction and used as the main outcome measure.

Figure 5. Illustration of the isometric make neck strength test experimental setup for extension.

4.2.5 Statistical analysis

Data are described using means ± SD. The normal distribution of variables was assessed with Shapiro-Wilks’s and d'Agostino-Pearson tests. Data were log-transformed for reliability analysis to reduce bias arising from non-uniformity of error when appropriate. The three repetitions completed during the first session were used to examine the intrasession reliability for each direction. For intersession reliability, analysis of both mean and maximal values was undertaken for each direction. The intersession reliability reflects the stability of measures as it defines the day-to-day variability in measures, which typically needs more than one-day between measures in sport measures (Atkinson & Nevill, 1998). The reliability of intrasession and intersession measurements was assessed using intraclass correlation coefficient (ICC), coefficient of variation (CV), typical error (TE), and mean change (Δ), and were calculated with their SD or 95% confidence limits [lower, upper] using a customized statistical Excel spreadsheets (Hopkins, 2017) in Microsoft Excel for Office MSO (Version 2111 Build 16.0.14701.20254). Relative reliability was interpreted as poor, fair, good, and excellent when corresponding ICCs were < 0.40, 0.40 to 0.75, > 0.75 to 0.90, and > 0.90 [24]. Absolute reliability was considered good and acceptable when corresponding CVs were ≤ 10% and ≤ 20% (Hébert-Losier & Beaven, 2014; Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002).

Trials and repetitions were assessed for systematic error (i.e., learning effects) using a one-way repeated measures analysis of variance (RM ANOVA) using STATA (Statics/data analysis version 16.1, StataCorp, College Station, TX). The Duncan method was applied in post-hoc testing. Statistical significance level was set at $p \leq 0.05$ for all analysis. If the assumption of sphericity was violated, the adjusted p-values were reported.

4.3 Results

Descriptive and reliability statistics related to intrasession isometric neck strength values and ratios are shown in Table 7. Those related to intersession mean values are displayed in Table 8, and intersession maximal values are reported in Table 9.

Extension

Isometric neck extension demonstrated good intrasession reliability (ICC = 0.85, TE = 2.5 kg, and CV = 8.8%), fair intersession reliability for mean values (ICC = 0.51, TE = 4.5 kg, and CV = 15.9 %) and fair intersession reliability for maximal values (ICC = 0.54, TE = 4.9 kg, and CV= 15.1%). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.732$).

Flexion

Isometric neck flexion demonstrated excellent intrasession reliability (ICC = 0.91, TE = 1.6 kg, and CV = 6.7%), fair intersession reliability for mean values (ICC = 0.60, TE = 3.3 kg, and CV = 14.5%), and fair intersession reliability for maximal values (ICC = 0.58, TE = 3.3 kg, and CV = 14.5%). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.053$).

Left lateral flexion

Isometric neck left lateral flexion demonstrated excellent intrasession reliability (ICC = 0.95, TE = 1.6 kg, and CV = 6.4%), fair intersession reliability for mean values (ICC = 0.56, TE = 3.9 kg, and CV = 18.1), and fair intersession reliability for maximal values (ICC = 0.63, TE = 4.0 kg, and CV = 18.6%). There was no systematic bias for intrasession and mean intersessiom analyses based on the RM ANOVAs ($p \geq 0.058$). However, bias was detected for max intersession reliability analysis ($p = 0.044$). Post-hoc testing revealed a significant difference between Trial 3 and 1 ($p = 0.031$), and Trial 3 and 2 ($p = 0.033$), with lower values at the third session.

Right lateral flexion

Isometric neck left lateral flexion demonstrated excellent intrasession reliability (ICC = 0.88, TE = 1.9 kg, and CV = 7.9%) fair intersession reliability for mean values (ICC = 0.53, TE = 5.0 kg, and CV = 19.8%), and fair intersession reliability for maximal values (ICC = 0.59, TE = 5.0 kg, and CV = 19.8%). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.431$).

Flexion-to-extension and lateral left-to-right ratios

Intrasession flexion-to-extension ratio values ranged from 0.77 to 0.81 with excellent reliability (ICC = 0.86, TE = 0.13, and CV = 11.5%). Intrasession lateral left-to-right ratio values ranged from 0.97 to 0.99 with fair reliability (ICC = 0.75, TE = 0.08, and CV = 8.2%). Intersession mean flexion-to-extension ratios demonstrated fair reliability (ICC = 0.55, TE = 0.82, and CV = 24%) as did lateral left-to-right ratios (ICC = 0.52, TE = 0.94, and CV= 18.8 %). Intersession relability for max flexion-to-extension (ICC = 0.53, TE = 0.77, and CV= 20.7 %) and lateral left-to-right (ICC = 0.53, TE = 0.89, and CV: 16.8 %) ratios were fair. There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.649$)

Table 7. Descriptive and reliabiliy statistics related to intrasession isometric neck strength values. Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for the four different directions examined.

	Isometric strength (raw units)			Δ isometric strength (raw units)			Reliability statistics			
	T1	T2	T3	T1 - T2	T2 - T3	T1 - T3	ICC [95% CI]	TE (kg) [95% CI]	CV (%) [95% CI]	p-value
Extension (kg)	31.9 (5.6)	32.3 (6.4)	31.4 (7.5)	0.5 (3.4)	-0.9 (3.4)	-0.5 (3.4)	0.85 [0.75 - 0.92]	2.5 [2.0 - 3.0]	8.8 [7.1 -11.7]	0.538
Flexion (kg)	23.9 (4.7)	25.8 (5.9)	25.7 (5.6)	0.2 (2.1)	0.1 (2.5)	-0.3 (2.0)	0.91 [0.84 - 0.95]	1.6 [1.3 – 1.9]	6.7 [5.6 – 8.5]	0.809
Left lateral flexion (kg)	25.4 (5.9)	25.6 (6.4)	25.6 (6.3)	0.2 (2.1)	-0.1 (2.5)	-0.2 (2.1)	0.95 [0.90 - 0.97]	1.6 [1.4 - 1.9]	6.4 [5.6 – 8.5]	0.873
Right lateral flexion (kg)	26.1 (5.3)	25.8 (5.9)	25.7 (5.6)	-0.4 (2.0)	-0.1 (2.7)	0.4 (3.3)	0.88 [0.78 - 0.94]	1.9 [1.7 – 2.3]	7.9 [6.5 -10.7]	0.734
Flexion / extension ratio	0.77 (0.20)	0.77 (0.21)	0.82 (0.31)	0.0 (0.3)	0.1 (0.2)	0.1 (0.3)	0.86 [0.69 - 0.91]	0.13 [0.11–0.15]	11.5 [9.6 -11.5]	0.363
Left / right ratio	0.98 (0.15)	1.00 (0.13)	1.00 (0.16)	0.1 (0.2)	0.0 (0.3)	0.1 (0.2)	0.75 [0.58 – 0.87]	0.08 [0.07 – 0.10]	8.2 [6.9 – 10.7]	0.617

p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

Table 8. Descriptive and reliabiliy statistics related to intersession isometric neck strength (mean of three trials). Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for the four different directions examined.

	Isometric strength (raw units)			Δ isometric strength (raw units)			Reliability statistics			
	T1	T2	T3	T1 - T2	T2 - T3	T1 - T3	ICC [95% CI]	TE (kg) [95% CI]	CV (%) [95% CI]	p-value
Extension (kg)	32.0 (6.0)	31.7 (6.4)	31.2 (6.7)	0.1 (8.2)	-0.4 (3.2)	0.7 (8.4)	0.51 [0.26 - 0.75]	4.5 [3.6 – 6.3]	15.9 [12.6 – 22.6]	0.732
Flexion (kg)	24.0 (4.8)	23.5 (5.7)	22.1 (4.3)	-0.7 (4.3)	-2.5 (4.9)	3.1 (5.1)	0.60 [0.35 -0.77]	3.3 [2.8 - 4.1]	14.5 [12.0 – 19.5]	0.053
Left lateral flexion (kg)	25.5 (6.1)	24.9 (4.1)	22.8 (6.4)	0.1 (5.5)	-2.0 (5.3)	2.1 (6.1)	0.56 [0.32 - 0.75]	3.9 [3.4 – 5.0]	18.1 [14.9 – 24.4]	0.058
Right lateral flexion (kg)	25.7 (5.5)	25.6 (6.6)	24.2 (8.2)	0.6 (8.0)	-1.4 (4.6)	1.1 (8.2)	0.53 [0.27- 0.73]	5.0 [4.3 – 6.3]	19.8 [16.3 – 26.9]	0.431
Flexion / extension ratio	0.78 (0.27)	0.77 (0.28)	0.74 (0.13)	0.0 (0.3)	-0.1 (0.2)	0.1 (0.3)	0.55 [0.29- 0.74]	0.82 [0.70- 1.02]	24.0 [19.7 - 32.7]	0.649
Left / right ratio	1.00 (0.27)	1.01 (0.28)	0.96 (1.37)	0.0 (0.3)	-0.1 (0.2)	-0.1 (0.2)	0.52 [0.23 - 0.76]	0.94 [0.8 – 1.16]	18.8 [0.2 - 0.75]	0.646

p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient,

SD: standard deviation, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

Table 9. Descriptive and reliabiliy statistics related to intersession isometric neck strength (maximal value from three trials). Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for the four different directions examined.

	Isometric strength (raw units)			Δ isometric strength (raw units)			Reliability statistics			
	T1	T2	T3	T1 - T2	T2 - T3	T1 - T3	ICC [95% CI]	TE (kg) [95% CI]	CV (%) [95% CI]	p-value[a]
Extension (kg)	33.6 (6.3)	33.4 (6.2)	33.1 (6.8)	0.4 (8.1)	-0.1 (3.6)	0 (8.4)	0.54 [0.25 - 0.76]	4.9 [4.0 - 6.2]	15.1 [12.0 – 21.5]	0.849
Flexion (kg)	25.3 (5.2)	25.1 (5.9)	23.4 (4.7)	-0.5 (4.6)	-2.8 (5.4)	3.3 (5.4)	0.58 [0.33 - 0.76]	3.6 [3.0 – 4.8]	14.5 [12.0 – 19.5]	0.055
Left lateral flexion (kg)	26.8 (6.3)	26.8 (4.7)	24.2 (6.4)	0.4 (5.6)	-2.4 (5.6)	1.6 (5.9)	0.69 [0.43 - 0.85]	4.0 [3.4 - 4.8]	18.6 [14.9 - 26.0]	0.044*
Right lateral flexion (kg)	27.6 (5.4)	26.0 (4.5)	25.0 (7.1)	-0.9 (5.1)	-0.8 (5.5)	2.4 (4.9)	0.60 [0.35 – 0.77]	3.6 [3.12 – 4.53]	16.9 [13.9 – 22.8]	0.097
Flexion / extension ratio	0.74 (0.21)	0.73 (0.25)	0.70 (0.20)	0.0 (0.3)	-0.1 (0.2)	0.1 (0.2)	0.53 [0.27 – 0.77]	0.77 [0.66 – 0.95]	20.7 [17.0 – 28.1]	0.547
Left / right ratio	0.97 (0.14)	1.04 (0.16)	0.97 (0.11)	0.1 (0.2)	-0.1 (0.2)	0.0 (0.2)	0.53 [0.26 - 0.73]	0.89 [0.76 – 1.08]	16.8 [13.5 – 24.0]	0.162

$p < 0.05$. [a]p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, change, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

4.4 Discussion

We examined the reliability of make test isometric neck strength measures in male Rugby Union players using a load cell device in extension, flexion, and left and right lateral flexion. Reliability of flexion-to-extension and left-to-right lateral flexion ratios were also examined. Intrasession reliability was good to excellent (ICC = 0.85–0.95), whereas intersession reliability – which here reflects the stability in measures – was fair for both mean and max values (ICC = 0.51–0.69). Similar make test isometric methods have been used to assess Rugby Union players, but reliability was not assessed (Naish et al., 2013a), providing new insight, particularly with regards to intersession reliability and stability of measures.

Our intrasession reliability results coincide with previous studies in semi-professional Rugby Union players using different devices, wherein intrasession reliability of make test isometric neck strength measures using a fixed-mounted handheld dynamometer was good to excellent for extension, flexion, and bilateral lateral flexion (ICC= 0.77–0.92), as well as when tested against a manual resistance in these four directions (ICC = 0.77–0.90) (Ashall et al., 2021). When the reliability was assessed in a break test fashion with a handheld dynamometer in a seated position in academy Rugby Union players, intrasession reliability was good, but did not reach excellent across directions (ICC = 0.80–0.85) (K. Geary et al., 2013). Regarding values of absolute reliability, intrasession reliability was good with CV ≤ 10%, and intersession reliability for mean and maximal values were acceptable with CV ≤ 20%. When tested using a computerized dynamometer in a seated position, no significant intrasession or intersession differences were detected in non-Rugby Union cohorts, with strong correlations between measures for intrasession (r 0.951–0.989) and intersession (r 0.731–0.969). The CV were <

15% when assessed in a neutral neck position and reached 26% in 10° of neck extension, suggesting that both intrasession and intersession assessments were reliable (Garces et al., 2002). Our results indicate that the current method to test neck strength in Rugby Union within the same session is good, and we here provide new information regarding intersession reliability and stability of measures. When tested a week apart, reliability can be considered acceptable. The intersession reliability was the weakest for extension, which aligns with findings on flexion and extension intersession isometric neck strength assessed using a scrum device in university school Rugby Union players (Salmon, Handcock, Sullivan, Rehrer, & Niven, 2015). The lower reliability in extension was thought due to variations in technique and body positioning between sessions (Salmon et al., 2015). It would seem that using a head harness and cable with a load cell device in a seated position in Rugby Union players is also subject to variations in position between sessions, which could explain the superior intrasession than intersession reliability outcomes.

To our knowledge this the first study examining the reliability of an isometric neck strength test in a make test manner using a rigid cable, a head harness with load cell device, in a seated position in Rugby Union players. Our study found neck strength values in semi-professional Rugby Union players range from 22 to 33 kg in all directions. These maximal isometric neck strength values are similar to those observed with amateur players assessed in a contact position using a load cell or fixed-frame dynamometer (Salmon et al., 2018). Our ranges were, however, greater than those from isometric neck strength values assessed in a cohort of semi-professional Rugby Union players tested using a mounted handheld dynamometer and a make test approach (range 17.3–23.5 kg) (Ashall et al., 2021). The difference potentially reflects the superior procedural methods of the load cell with harness and cable set-up than the handheld dynamometer set-up due to the testing interaction between the participant and examiner in the latter method (Ashall et al., 2021). When professional players were assessed in a similar fashion to ours, specifically in a seated position with a customized load cell device, a head harness, and an immovable metal frame in a make test fashion, the maximal strength values were greater than reported here (i.e., 29–39 kg) (Naish et al., 2013a). Several studies have attempted to identify normative neck strength values in Rugby Union players with different methods of testing (Barrett et al., 2015; Davies et al., 2016; Dempsey et al., 2015; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014a; Konrath & Appleby, 2012; Maconi et al., 2016; Naish et al., 2013b; Olivier & Du Toit, 2008; Salmon et al., 2018; Snodgrass et al., 2018); however, there is no agreement on the strength testing method to be used or requisite strength levels (C. Chavarro-Nieto et al., 2021b). The results of the present study provide data on isometric neck strength for semi-professional male Rugby Union players in flexion, extension, and left and right lateral flexion, as well as flexion-to-extension and left-to-right lateral flexion ratios using a reproducible set-up. In addition, our study indicates that reliability is good-to-excellent intrasession and fair intersession when players are tested in-season.

Extension-to-flexion ratios ranged from 0.74 and 0.82 with good intrasession reliability, and left-to-right lateral flexion ratios were around 0.97 to 1.01 with fair intrasession reliability. Intersession reliability was fair for both ratios. Our results are similar to those reported elsewhere in semi-professional Rugby Union players with flexion-to-extension ratios of 0.75 to 0.76, and bilateral lateral flexion ratios of 0.96 to 1.0 in a make test fashion with a load cell device via cable in a seated position (K. Geary et al., 2013; Naish et al., 2013a). Noteworthy is that these ratios are marginally greater than those presented elsewhere using different methods of testing (isokinetic and break test), wherein flexion-to-extension ratios in Rugby Union ranged, on average, from 0.65 to 0.7 (D. F. Hamilton & Gatherer, 2014a, 2014b; Olivier & Du Toit, 2008). Results of previous studies at different levels of competition have shown greater absolute values in extension compared to flexion in Rugby Union players (C. Chavarro-Nieto et al., 2021b), with younger players possessing lower strength ratios compared to senior players (Davies et al., 2016), and forwards exhibiting lower ratios than backs (Konrath & Appleby, 2012; Olivier & Du Toit, 2008). These imbalances in neck musculature are a potential risk factor for neck injuries, where flexion-to-extension ratio imbalances have been associated with higher head angular and linear accelerations in other cohorts (Dezman et al., 2013). Promoting strength symmetry between muscles is a strategy used in practice to mitigate injury risk in other anatomical parts of the body (e.g., knee) (Croisier et al., 2008), and should be explored further as a mean to mitigate concussion and neck injury risk in Rugby Union.

4.5. Conclusion

Assessing isometric neck strength with a head harness and a cable with a load cell device in a seated position in semi-professional Rugby Union players is feasible, and demonstrates good-to-excellent intrasession and fair intersession relative reliability. Absolute reliability is good intrasession (CV ≤ 10%) and acceptable intersession (CV ≤ 20%). Although the load cell approach appears less reliable than using a handheld dynamometer based on reliability values reported in the literature, the load cell approach can be reliably used to assess isometric neck strength in extension, flexion, and bilateral lateral flexion, as well as to derive flexion-to-extension and left-to-right lateral flexion ratios in male Rugby Union players. A direct comparison of reliability data from the same cohort using both the handheld dynamometer and cable load cell approach is needed to confirm that one method is more reliable than the other. We provide data from Rugby Union players to inform practice, and assist standardisation of testing methods. Further experimentation with the load cell device to improve intersession reliability and stability of measures in neck isometric testing is recommended. Intersession reliability might be improved using three-axial load cells, ensuring an initial familiarisation session, and further attention to individualised and repeatable neck positions.

SECTION 2. Hamstring

CHAPTER 5

Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review

Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review. The Physician and Sportsmedicine. 2021. doi: 10.1080/00913847.2021.1992601. (Appendix A2)

Prelude: The main role of this chapter was to summarise the hamstring strength in Rugby Union, and cover hamstring strain injury incidence, risk factors, injury prevention, and strengthening strategies in this population. This chapter provides an overview of hamstring strength values reported in the literature, and outlines the various protocols used for testing. This information may be useful for practitioners to inform injury prevention and return to play strategies. This chapter also provides a contextual background on strengthening programmes used to increase hamstring strength and decrease bilateral strength imbalances in Rugby Union players. This literature review helped inform which test method could be used in a practical setting to assess hamstring strength in Rugby Union players, as well as informed the strengthening programme used in Chapter 8. Given that Nordic eccentric strength measures were identified as a relevant physiological and functional test of hamstring strength, this method of assessment was used for the remainder of the thesis to assess hamstring strength.

5.1 Introduction

Hamstring strain injuries are one of the most common injuries in Rugby Union and represent 6 to 15% of all sustained injuries (2006b). With respect to the epidemiology of hamstring injuries, acute hamstring strains have the highest recurrence rate of any muscle injury (Brukner & Khan, 2016). A previous hamstring injury is a paramount risk factor to sustaining another hamstring injury (Freckleton & Pizzari, 2013a) and the elevated risk is proposed to be due to residual neuromuscular inhibition, strength deficits, altered muscle tendon morphology, and modified contractile mechanics (Brukner & Khan, 2016).

The 2019 Rugby World Cup injury surveillance data revealed lower limb injuries accounted for almost 50% of all players absence days (2020). Hamstring strains were the second most common match injury after concussion, with hamstring injuries representing 9.8% of all match injuries and causing 467 missed days. The England Rugby Football Union reported that hamstring strains were their most common injury during training and the second most common injury during match play with 6.4 injuries per 1000 hours (RugbyFootballUnion & Surveillance, 2019). Moreover, the Welsh injury surveillance report from 2012 to 2016 recorded an increase in posterior thigh injury from 6.7 to 7.7 per 1000 hours, as well as 155.7 to 172.6 days lost during that time frame (Bitchell et al., 2020). Hamstring strains are also of considerable concern at a younger school-age level, representing 21% of all injuries (Group, 2020) and comprising 23% of all training time-loss in male amateur players.

Regarding prevention of sport-related injuries, a multifactorial approach is required and should involve the monitoring of intrinsic and extrinsic factors (Freckleton & Pizzari, 2013b; D. A. Opar, Williams, & Shield, 2012; J. Orchard, Marsden, Lord, & Garlick, 1997). For instance, asymmetries in strength between muscle groups and limbs are commonly assessed and used as screening methods in sports (Knapik, Bauman, Jones, Harris, & Vaughan, 1991; Yeung, Suen, & Yeung, 2009). Strength imbalances between quadriceps and hamstrings have been linked to a four to five times greater risk of hamstring strain in football players, with an asymmetry in hamstring strengths between sides of 10-15% also considered to represent a risk for hamstring strains (Croisier et al., 2008). These imbalances appear more evident at slower angular velocities, and decrease at higher velocities (Wrigley & Strauss, 2000). Hamstring strength deficits and imbalances have been targeted with Nordic eccentric strengthening exercises, and a reduction of 51% in hamstring injury incidence across team sports was reported in a literature review and metanalysis of 8,459 athletes (Van Dyk N, 2019b), including in Rugby Union (Brooks et al., 2006b).

Training and playing load variables, such as the number of high-speed running events, have been associated with hamstring injury occurrence in team sports and investigated mainly in football (Buckthorpe et al., 2019; Duhig et al., 2016). Although hamstring injuries often occur during the eccentric phase of running or kicking in rugby, similar to other team sports, severe hamstring strains can also occur because of specific-game related events in rugby, such as during tackles and competing for the ball on the ground (J. W. Orchard, 2012). In the tackling position, the hamstring is stretched fully, and the addition of a collision can further stretch the muscle, leading to a tendinous-junction tear. This mechanism of injury may be responsible for the increasing severity of hamstring injuries seen in Rugby Union in recent years (RugbyFootballUnion & Surveillance, 2019), which is dissimilar to hamstring mechanisms in other sports. Thus, rugby demonstrates unique susceptibility and risk factors that require position-specific injury profiling to better target physical preparation and injury prevention strategies (C. W. Fuller et al., 2010). Given that player availability correlates with team success (S. Williams et al., 2016b), research that targets injury prevention also has performance implications.

To prevent such injuries, it is important to identify how individual characteristics and game dynamics relate to contact and non-contact injury incidence. Therefore, we sought to critically examine and summarize the existing scientific literature on the topic of hamstring strain injuries in Rugby Union specifically. In particular, we aimed to systematically review and summarize the scientific literature that addressed hamstring strain injury incidence, risk factors, injury prevention and strengthening strategies, and strength or asymmetry measures in Rugby Union.

5.2 Materials and Methods

5.2.1 Information sources and search strategy

We conducted a systematic review of the literature following the Preferred Reporting Items for Systematic Reviews and Metanalysis guidelines (Page et al., 2021). One author (CC) performed a systematic search on September 4th, 2020 to locate published peer-reviewed articles from four electronic databases: PubMed, SciVerse Scopus, SPORTDiscus™, and Web of Science®. The search strategy consisted of the following keywords and Boolean operators entered in the main search bar of each e-database: “hamstring AND rugby”. The exact resulting search syntax in PubMed was: ("hamstring muscles"[MeSH Terms] OR ("hamstring"[All Fields] AND "muscles"[All Fields]) OR "hamstring muscles"[All Fields] OR "hamstring"[All Fields] OR "hamstrings"[All Fields]) AND ("football"[MeSH Terms] OR "football"[All Fields] OR "rugby"[All Fields]), SciVerse Scopus was: TITLE-ABS-KEY(hamstring AND rugby), SPORTDiscus™ was: Boolean/Phrase: (hamstring AND rugby), and Web of Science® was: TOPIC: (hamstring AND rugby).

5.2.2 Inclusion and exclusion criteria

Articles were included when they were original, peer-reviewed research studies written in the English language, involved Rugby Union players, and included one or several of the following hamstring-related information: hamstring injury incidence, risk factors, strengthening or injury prevention programmes, and/or hamstring strength or asymmetry measures in Rugby Union players, regardless of sex, age, and level of competition. Articles were excluded if these were not in the English language or did not involve Rugby Union players.

5.2.3 Screening process

Duplicates from the initial database search were removed first. Subsequently, two reviewers (CC, KHL) independently screened all remaining titles, abstracts, and full texts sequentially for inclusion. The study selection process was replicated for articles that were located through other sources (e.g. Google Scholar) and reference lists of included full-text articles. The two reviewers met to discuss any disagreements during the screening process and agreed on the articles to be included.

5.2.4 Quality assessment

Two reviewers (CC, IH) independently assessed the methodological quality of included studies (n = 24) using the Newcastle – Ottawa Scale (NOS) (Modesti et al., 2016). The reliability of the NOS for case-control and cohort studies has fair to good inter-rater reliability and validity (Hootman, Driban, Sitler, Harris, & Cattano, 2011). This tool was used as it is recommended by the Cochrane Collaboration (Hoegberg et al.), is a suitable alternative to other available tools to assess risk of bias (Sterne JAC, updated February 2021), and could be used across the included studies. Prior to assessment, the two reviewers met to discuss and familiarise themselves with the scales. All identifiable information (i.e., authors, affiliations, countries, and sources of publication) were removed from articles to reduce likelihood of assessment bias. Disagreements in the scores were resolved by discussion between the two reviewers, and consensus scores are presented in this article.

The tool uses a “star system”, wherein more stars indicate a superior methodological quality and lower risk of bias. The NOS awards a maximum of 10 stars: five stars for selection (representativeness of the sample, sample size, non-respondents, and ascertainment of the exposure), two stars for comparability, and three stars for outcome (assessment of outcome and statistical test). Reviewers agreed that for the statistical test item, the highest star rating would be allocated for the reporting of confidence intervals, quartiles, or limits of agreement. The methodological quality of studies was divided into three groups based on the number of stars awarded: *weak* (0 to 3 stars), *moderate* (4 to 6 stars), and *strong* (7 to 10 stars) (Peterson et al., 2011). The design of each study was classified as cohort studies, case series, cases and controls, or randomised controlled trial.

5.2.5 Data extraction and synthesis

The first author (CC) extracted data from the selected full-text articles using a standardised form, and the last author (KHL) verified the data extracted. For each study, study design, participant information, level of competition, location of the study, study characteristics, assessment methods, and outcome data specific to hamstrings were extracted. Data were grouped and extracted under main themes of interest: (1) hamstring injury incidence and risk factors; (2) hamstring strengthening and injury prevention programmes; and (3) hamstring strength or asymmetry assessment methods and measures. Data were managed and analysed using Microsoft® Office Excel 2016 (Redmond, Washington). Conducting a meta-analyses on data was not considered given differences in injury definitions, study aims, and testing procedures used.

5.3 Results

5.3.1 Included studies

The flow diagram from the search strategy and screening process is shown **Figure 7**. Twenty-four studies met the eligibility criteria.

5.3.2 Study characteristics

The main characteristics of the 24 studies that met inclusion are presented in **Table 10**. Based on Newcastle-Ottawa Scale NOS, most studies were of *moderate* quality (*n* = 13, 54%) (Anastasi & Hamzeh, 2011; Beyer et al., 2016; Brown et al., 2016; Brown, Brughelli, Griffiths, & Cronin, 2014; Deighan et al., 2012; Farnan, Mahony, Wilson, & Gissane, 2013; Mendiguchia et al., 2016; Mondin, Owen, Negro, & D'antona, 2018; Reid, Cowman, Green, & Coughlan, 2013; Upton, Noakes, & Juritz, 1996; Yamada & Mastumoto, 2009). Ten articles were of *strong* quality (40%) (M. N. Bourne, Opar, Williams, & Shield, 2015a; Brooks et al., 2005a, 2005b, 2006b; Brooks & Kemp, 2011; Kenneally-Dabrowski, Brown, et al., 2019; Kenneally-Dabrowski, Serpell, et al., 2019b; Roberts, Trewartha, England, Shaddick, & Stokes, 2013; Severo-Silveira et al., 2018; Turl & George, 1998), and one study was defined as *weak* quality (6%) (Dobbs et al., 2017). Item-by-item NOS ratings for each study are presented in Appendix E1.

5.3.3 Participants

The 24 studies that met inclusion comprised of 2866 participants, male players were involved in 21 studies (Abdelfettah et al., 2019; Beyer et al., 2016; M. N. Bourne et al., 2015a; Brooks et al., 2005a, 2005b, 2006b; Brooks & Kemp, 2011; Brown et al., 2016; Brown et al., 2014; Deighan et al., 2012; Farnan et al., 2013; Kenneally-Dabrowski, Brown, et al., 2019; Kenneally-Dabrowski, Serpell, et al., 2019b; Mendiguchia et al., 2016; Mondin et al., 2018; Reid et al., 2013; Roberts et al., 2013; Severo-Silveira et al., 2018; Turl & George, 1998; Upton et al., 1996; Yamada & Mastumoto, 2009), one study involved female players (Anastasi & Hamzeh, 2011), and two studies included both males and females (Dobbs et al., 2017; Yeomans et al., 2019). Eleven articles were conducted with professional players (M. N. Bourne et al., 2015a; Brooks et al., 2005a, 2005b, 2006b; Brooks & Kemp, 2011; Kenneally-Dabrowski, Brown, et al., 2019; Kenneally-Dabrowski, Serpell, et al., 2019b; Mendiguchia et al., 2016; Mondin et al., 2018; Reid et al., 2013; Severo-Silveira et al., 2018), ten with amateur players (Abdelfettah et al., 2019; Anastasi & Hamzeh, 2011; Berry, Harrison, Yeo, Cripps, & Stephenson; Beyer et al., 2016; Brown et al., 2016; Brown et al., 2014; Deighan et al., 2012; Dobbs et al., 2017; Farnan et al., 2013; Roberts et al., 2013; Yamada & Mastumoto, 2009; Yeomans et al., 2019), two with semi-professional players (Roberts et al., 2013; Turl & George, 1998), and not enough information about the level of competition was available in one study (Upton et al., 1996). The articles were designed as cohort studies in 18 cases (75%) (Abdelfettah et al., 2019; M. N. Bourne et al., 2015a; Brooks et al., 2005a, 2005b, 2006b; Brooks & Kemp, 2011; Brown et al., 2016; Brown et al., 2014; Dobbs et al., 2017; Farnan et al., 2013; Kenneally-Dabrowski, Brown, et al., 2019; Kenneally-Dabrowski, Serpell, et al., 2019b; Roberts et al., 2013; Upton et al., 1996; Yamada & Mastumoto, 2009; Yeomans et al., 2019), case series in three (13%) (Beyer et al., 2016; Mendiguchia et al., 2016; Reid et al., 2013), case–controls in two (8%) (Anastasi & Hamzeh, 2011; Turl & George, 1998), and a randomised control trial (4%) (Severo-Silveira et al., 2018). Studies were conducted in the United Kingdom (n=9) (Anastasi & Hamzeh, 2011; Brooks et al., 2005a, 2005b, 2006b; Brooks & Kemp, 2011; Deighan et al., 2012; Mondin et al., 2018; Roberts et al., 2013; Turl & George, 1998), Australia (n=4) (M. N. Bourne et al., 2015a; Kenneally-Dabrowski, Brown, et al., 2019; Kenneally-Dabrowski, Serpell, et al., 2019b; Severo-Silveira et al., 2018), New Zealand (n=3) (Brown et al., 2016; Brown et al., 2014; Mendiguchia et al., 2016), Ireland (n=3) (Farnan et al., 2013; Reid et al., 2013; Yeomans et al., 2019), USA (n=2) (Beyer et al., 2016; Dobbs et al., 2017), Morocco (n=1)(Abdelfettah et al., 2019), Japan (n=1) (Yamada & Mastumoto, 2009), and South Africa (n=1) (Upton et al., 1996) (Table 10).

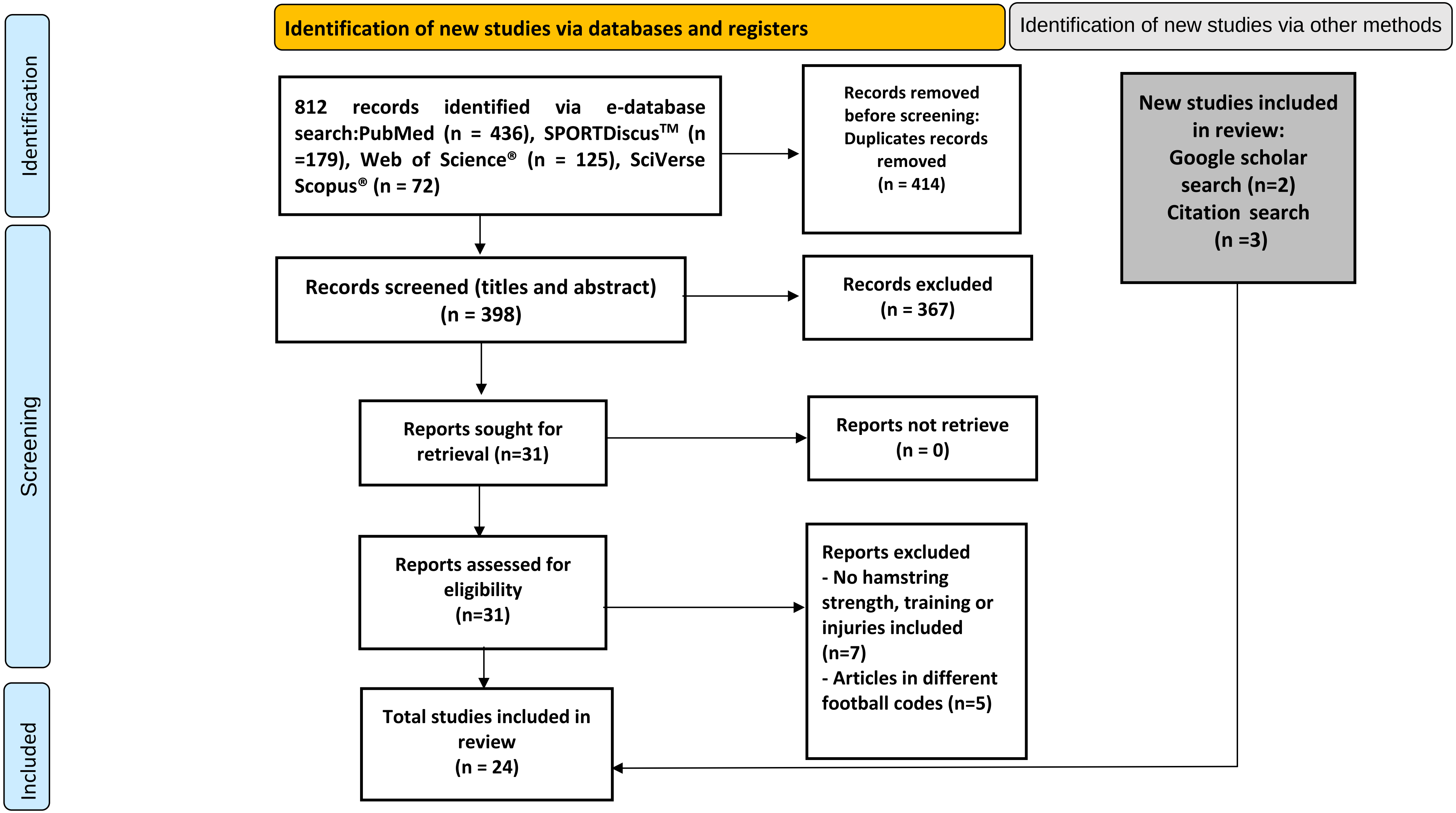

Figure 6. Preferred reporting items for systematic reviews and meta-analyses flow chart.

Table 10. Characteristics of the 24 included studies.

Study	NOS rating*	Player characteristics	Study design Location	Study aims	Key study characteristics
Abdelfettah et al. (2019)	Moderate 5 stars	10 male amateur players Age: 26.4 ± 5.1 y Mass: 83.2 ± 15.3 kg Height: 177.9 ± 8.3 cm	Cohort (cross-sectional) Morocco	Compare the strength of the knee flexors and extensors between soccer and rugby players and the level of strength by playing positions	Duration: 1 season Injuries: No Intervention: No
Anastasi and Hamzeh (2011)	Moderate 5 stars	24 female amateur players (13 test players and 11 controls) Age: 25.2 ± 5.3 y Mass: 69.5 ± 10.9 kg Height: 166 ± 5.0 cm	Case control United Kingdom	Evaluate the effect of hamstring eccentric program on leg strength imbalance and maximal vertical jump height	Duration: 1 season Injuries: No Intervention: Yes

Beyer et al. (2016)	Moderate 4 stars	25 male amateur players. Age: 20.7 ± 2 y Mass: 86.8 ± 15.4 kg Height: 179 ± 8.0 cm	Case series (laboratory investigation) USA	Compare isotonic versus isometric strength measures between players with < 2 years and ≥ 2 years of experience	Duration: 1 season Injuries: No Intervention: No
M. N. Bourne et al. (2015b)	Strong 8 stars	178 male players (75 professionals and 103 semi-professionals subdivided in 65 sub-elite and 38 under 19s) Age: 22.6 ± 3.8 y Mass: 96.5 ± 13.1 kg Height: 185.0 ± 6.8 cm	Cohort (prospective) Australia	Determine the thresholds of hamstring strength imbalance in eccentric Nordic exercises and association with hamstring injuries	Duration: 1 season Injuries: Yes Intervention: No
Brooks et al. (2005a)	Strong 9 stars	546 male professional players Age: 25.3 ± 4.1 y	Cohort (prospective)	Study match injuries in professional players and	Duration: 2 seasons

		Mass: 100.0 ± 12.1 kg Height: 185.1 ± 7.4 cm	United Kingdom	define incidence, aetiology, and severity	Injuries: Yes Intervention: No
Brooks et al. (2005b)	Strong 9 stars	502 male professional players Age: 25.3 ± 4.1 y Mass: 100 ± 12.1 kg Height: 185.1 ± 7.4 cm	Cohort (prospective) United Kingdom	Study training injuries in professional players and define incidence, aetiology, and severity	Duration: 2 seasons Injuries: Yes Intervention: No
Brooks et al. (2006b)	Strong 9 stars	546 male professional players Age: 25.3 ± 4.1 y Mass: 100 ± 12.1 kg Height: 185.1 ± 7.4 cm	Cohort (prospective) United Kingdom	Describe incidence, risk factors, and severity of hamstring injuries and the impact of hamstring strengthening and stretching exercises on injury incidence and severity	Duration: 2 seasons Injuries: Yes Intervention: No

Brooks and Kemp (2011)	Strong 7 stars	899 male professional players Age: 25.3 ± 4.1 y Mass: 100 ± 12.1 kg Height: 185.1 ± 7.4 cm	Cohort (prospective) United Kingdom	Examine match injury profile of professional players by playing positions	Duration: 2 seasons Injuries: Yes Intervention: No
Brown et al. (2014)	Moderate 4 stars	25 male professional players Age: 25 ± 3 y Mass: 103 ± 12 kg Height: 186 ± 7.0 cm	Cohort (cross-sectional) New Zealand	Determine lower-limb strength profiles and compare isokinetic knee and hip strength of professional players	Duration: 1 season Injuries: No Intervention: No
Brown et al. (2016)	Moderate 4 stars	30 male amateur players (15 forwards and 15 backs) **Forwards** Age: 20 ± 1 y Mass: 103 ± 11 kg	Cohort (cross-sectional) New Zealand	Determine lower-limb strength profile and compare isokinetic measures between limbs and positions	Duration: 1 season Injuries: No Intervention: No

		Height: 190 ± 1.0 cm **Backs** Age: 24 ± 4 years Mass: 90 ± 8 kg Height: 180 ± 0.0 cm			
Deighan et al. (2012)	Moderate 4 stars	11 male amateur players Age: 19.3 ± 0.8 y Mass: 92.8 ± 12.6 kg Height: 182.2 ± 8.0 cm	Cohort (cross-sectional repeated measure laboratory test) United Kingdom	Determine differences in peak torque and strength ratios between positions (seated and supine) and examine the relation of position with joint velocity	Duration: 1 season Injuries: No Intervention: No
Dobbs et al. (2017)	Weak 2 stars	19 amateur players (11 females and 8 males)	Cohort (cross-sectional)	Measure H:Q and DCR in male and female amateur	Duration: 1 season Injuries: No

		Males Age: 22.0 ± 2.6 y Mass: 80.3 ± 11.1 kg Height: 172.7 ± 6.1 cm **Females** Age 24.7 ± 3.7 y Mass: 74 ± 18.1 kg Height: 164 ± 5.2 cm	USA	players and assess differences in muscle strength and imbalance	Intervention: No
Farnan et al. (2013)	Moderate 5 stars	54 male amateur players Age: 21 ± 2 y Mass: 88.1 ± 10.7 kg Height: 183 ± 5.2 cm	Cohort (prospective) Ireland	Determine hamstring injuries incidence, and severity	Duration: 1 season Injuries: Yes Intervention: No

Kenneally-Dabrowski, Serpell, et al. (2019b)	Strong 7 stars	74 male professional players Age: NR Mass: NR Height: NR	Cohort (retrospective) Australia	Describe hamstring injuries (severity, grade, and location) and the relationship with game demands	Duration: 5 seasons Injuries: Yes Intervention: No
Kenneally-Dabrowski, Brown, et al. (2019)	Strong 7 stars	10 male professional players Age: 27.3 ± 3.2 y Mass: 100.9 ± 13.1 kg Height :193 ± 9.0 cm	Cohort (prospective) Australia	Analysis of the relationship between overground high-speed running mechanics and hamstring injury	Duration: 1 season Injuries: Yes Intervention: No
Mendiguchia et al. (2016)	Moderate 4 stars	1 male professional player Age: 23 y Mass: 94 kg Height: 187 cm	Case series (laboratory investigation) New Zealand	Determine the changes in sprinting mechanics in relation to hamstring injuries	Duration: 1 season Injuries: No Intervention: No
Mondin et al. (2018)	Moderate 4 stars	10 male professional players and 14 healthy controls	Cohort	Measure hamstring strength with a sphygmomanometer	Duration: 1 season Injuries: No

		Age: 23.1 ± 2.5 y Mass: 88.4 ± 8.5 kg Height: 180.9 ± 8.2 cm	(repeated-measures reliability) United Kingdom and Italy	test and the correspondence with an isokinetic dynamometry test.	Intervention: No
Reid et al. (2013)	Moderate 6 stars	8 male professional players Age: 27.9 ± 4.8 y Mass: 99.1 ± 9.9 kg Height: 185 ± 8.0 cm	Case series Ireland	Demonstrate the application of GPS technology in the management of return to play	Duration: 1 season Injuries: No Intervention: No
Roberts et al. (2013)	Strong 7 stars	189 male community players Group A: semi-professional Group B: amateur Group C: recreational	Cohort (prospective) United Kingdom	Establish injury incidence and severity in community rugby and assess differences between levels	Duration: 3 seasons Injuries: Yes Intervention: No

		Age: NR Mass: NR Height: NR			
Severo-Silveira et al. (2018)	Strong 8 stars	21 male professional players (11 in the Constant group and 10 in the Progressive group) **Constant group** Age: 27.2 ± 3.4 y Mass: 90.1 ± 14.3 kg Height: 175 ± 0.1 cm **Progressive group** Age: 25.2 ± 3.3 y Mass: 88.6 ± 12.8 kg Height: 176 ± 0.1 cm	Randomised control trial Brazil and Australia	Study the effect of 2 different Nordic hamstring training programs (constant versus progressive) on multiple risk factors for hamstring strain injury	Duration: 1 season Injuries: No Intervention: Yes

Turl and George (1998)	Strong 7 stars	28 male semi-professional (14 tested players and 14 controls) Age: 29 ± 3 y Weight: 88 ± 12 kg Height: 181 ± 1.0 cm	Cases and controls (cross sectional) United Kingdom	Existence of adverse neural tension in players with grade I hamstring injuries	Duration: 1 season Injuries: Yes Intervention: No
Upton et al. (1996)	Moderate 5 stars	44 male NR level players Age: 23 ± 3 y Weight: NR Height: NR	Cohort (prospective) South Africa	Determine if the use of thermal pants reduce the risk of hamstring injuries.	Duration: 1 season Injuries: Yes Intervention: Yes
Yamada and Mastumoto (2009)	Moderate 5 stars	21 male amateur players Age: 21.3 ± 0.3 y Weight: 71.8 ± 6.3 kg Height: 172.2 ± 4.1 cm	Cohort (laboratory investigation) Japan	Determine the relationship between motor imagery and hamstring injuries.	Duration: 1 season Injuries: Yes Intervention: No

Yeomans et al. (2019)	Moderate 6 stars	137 amateur players (13 males and 24 females) **Males** Age: 22.7 ± 3.9 y Weight: Forwards 102.8 ± 10.9; Backs 85.4 ± 7.9 kg Height: Forwards 180.5 ± 23.6; Backs 179.5 ± 4.8 cm **Females** Age: 25.6 ± 4.9 y Weight: Forwards 87.3 ± 14.1; Backs 69.5 ± 11.3 kg Height: Forwards 169.8 ± 3.8; Backs 165.9 ± 7.1 cm	Cohort (prospective) Ireland	Determine risk factors associate to injuries.	Duration: 1 season Injuries: Yes Intervention: No

Notes. Values are means ± standard deviations.

Abbreviations: DCR, isokinetic dynamic control ratio; H:Q, isokinetic hamstring quadriceps ratio; GPS, global positioning system; NOS, Newcastle-Ottawa Scale; NR, not reported.

* Weak: 0 to 3 stars; moderate: 4 to 6 stars; strong: 7 to 10 stars.

5.3.4 Hamstring injuries: Incidence and risk factors

5.3.4.1 Professional level

Hamstring strain injuries caused the greatest number of days of absence diagnosed in backs and was ranked third in forwards after shoulder and lumbar disc injuries (2005b). In a two-part study involving professional players across two seasons, Part one monitored match injuries and Part two monitored training injuries. In the first part, the incidence of hamstring strain injuries of backs were nearly three times greater than forwards (Brooks et al., 2005a). Additionally, hamstring injuries were the most severe diagnosed injury in the backs and resulted in 17 days of absence. The lower limb was the most common anatomical site injured, with hamstring strains being the second most common injury in backs after thigh hematomas. Running was the most frequent mechanism of hamstring injury in game. In contrast to matches, forwards and backs had a similar incidence and mechanism of hamstring injuries during training (2005b), with more incidence of injuries during the preseason, with running again being the most common mechanism of injury, see Table 11.

Retrospective data analysis across five seasons in professional players indicated that 6% of all injuries were to the hamstring, with most hamstring injuries occurring during training and preseason (Kenneally-Dabrowski, Serpell, et al., 2019b). Hamstring injuries occurred more whilst running, with similar incidence between forwards and backs. The median days lost for hamstring injury was 26 days, and most of the injuries were moderate (60%), or severe (37%). The running mechanics of 10 professional players were analysed. Injured players had greater ipsilateral thoracic lateral flexion, absorbed greater power at the knee, and had greater hip extension moment (Kenneally-Dabrowski, Brown, et al., 2019).

Brooks and Kemp (2011) examined player injuries by playing position. Regarding severity of hamstring injuries, fly halves were the most affected players, followed by centres, wings, and the blind side flankers who presented with the most severe hamstring injuries whilst running. Data regarding hamstring injuries were also collected when implementing different hamstring training programs (Brooks et al., 2006b). The incidence was similar between dominant and non-dominant legs. Overall, the most severe hamstring injuries happened during kicking. During matches, hamstring injuries were most frequent and severe in the last 20 minutes, and substitute players had twice as many injuries as starting players; however, both starters and substitutes had similar rates of recurrence.

Another study on hamstring strain injuries in professional players found that backs were the most affected players, with 21 days of absence overall (M. N. Bourne et al., 2015b). The majority (45%) of injuries were recurrences from the past season and 24% recurred in the same season. Most of the injuries involved the biceps femoris and occurred while running. Comparing the players with a recurrent injury, players with a previous hamstring injury in the last 12 months had 4.1 times higher risk of suffering a recurrent injury compared with players with no history of hamstring injury. Imbalances between legs of more than 15% increased the risk of having a hamstring injury by 2.4 times; moreover, imbalances of more than 20% increased this figure to 3.4 times.

Regarding return to play after injuries, a five-week program to return to play with GPS technology was designed (Reid et al., 2013), and the recommendation to return to play after a hamstring injury was based on the ability to reach a running speed and intensity similar to pre-injury. The rehabilitation therapy recommended focusing on achieving maximum speed and long distances; involving cutting, passing, kicking, grappling, tackle drills, and wrestling; and achieving full training activities before returning to play. In one case study, a professional male Rugby Union player demonstrated an "abnormal" force-velocity profile during a 40-m sprint that resulted in an acute hamstring strain. The injurious sprint was characterised by an increase in horizontal force production compared to velocity when contrasted to his previous sprints and force-velocity profiles of his uninjured teammates (Mendiguchia et al., 2016).

5.2.4.2. Semi-professional, amateur, and school level

A community-level investigation across three seasons identified that hamstring strain injuries occupied the fifth place in terms of total injuries (Roberts et al., 2013). Running was the most frequent action of the game to produce hamstring injuries, and backs had a higher incidence than forwards. Hamstring injuries more frequently occurred in the first quarter of the game. At the amateur level, a prospective study with 65 players involving questionnaires found that 21% of all match and 30% of all training injuries were hamstring strain injuries (Farnan et al., 2013).

With regards to the risk factors for hamstring injuries, three investigations have been conducted; the first followed semi-professional players with grade I hamstring strain injuries (Turl & George, 1998). Their protocol comprised of two parts, one flexibility test and a slump test (validated for neural tension). In the group with a previous hamstring injury, 57% of the players had a positive slump test, whereas no positives were found in the control group. The results suggested that adverse neural tension should be assessed as a risk factor of hamstring injury and could be considered in return to play practices.

A prospective analysis of the relationship between motor imagery capacity of senior players (the ability to mentally perceive a rotated object) and hamstring injuries was undertaken (Yamada & Mastumoto, 2009). Motor function was assessed with isokinetic hamstring quadriceps ratio (H:Q), straight-leg raise angle, and a vertical jump test on one leg. Six players had symptoms of hamstring injuries (7 legs). The injured group (occurred in non-contact actions) had longer reaction times for the 0° dorsal and -90° plantar views compared to the non-injured group (delay in 2.48 seconds) based motor imagery capacity test, with none of the motor function tests associated with injury. The third study in this area provided the option to players with previous hamstring injuries to wear or not wear thermal pants in training and matches during a season (Upton et al., 1996). The incidence of injuries was significantly lower in players who chose to wear thermal pants.

Table 11. Hamstring injury studies involving Rugby Union players.

Study	Participants	Incidence	Severity	Training	Playing matches	Intervention/ Test	Outcome
Brooks et al. (2005a)	546 professional players	**All:** 5.6 injuries / 1000 player-hours **Forwards:** 3 injuries / 1000 player-hours **Backs**: 8.6 injuries / 1000 player-hours	**All**: 17 days of absence **Forwards:** 15 days of absence **Backs:** 1176 total days of absence 18 days of absence 151 days absence/1000 hours	0%	100%	No	Hamstring injuries were the second most common injury. Hamstring injuries were the most severe injury.
Brooks et al. (2005b)	502 professional players	**All:** 0.30 injuries /1000 player-hours **Forwards**: 0.28 injuries /1000 player-hours **Backs:** 0.32 injuries/1000 player-hours	**All:** 17 days absence **Forwards:** 478 total days. 15 days of absence. 4.3 days absence/1000 hours **Backs:** 502 total days. 19 days of absence. 6 days	100%	0%	No	The most common injury mechanism for forwards and backs was running.

			absence/1000 hours				
Brooks et al. (2006b)	546 professional players	**All:** 164 injuries (94 match and 70 training injuries) 122 players (22%) at least one injury. -5.6 injuries/1000 player-hours -Each of the 12 teams 7.5 hamstring injuries (5.8% new and 1.7% recurrent) **New**: 127 injuries **Recurrent**: 37 injuries 24% match 20% training	**All:** 2707 total days lost. 17 days lost per injury Each of the 12 teams 123 days absence (81 days for new and 42 days for a recurrent injury). **New:** 1775 total days. 14 [12-16] days lost per injury **Recurrent:** 932 total days. 25 [17-33] days lost per injury	70 injuries 42%	94 injuries 58%	Stretching, strengthening, and Nordic eccentric exercises	The group performing Nordic exercises had a lower incidence of hamstring injuries compared to the group performing strengthening exercises

Brooks and Kemp (2011)	899 professional players	**All:** 164 injuries 5.6 injuries/1000 player-hours	**Blind side flankers:** 99 days absence per 1000 player-hours **Fly halves**: 241 days absence per 1000 player-hours **Centres**: 173 days absence per 1000 player-hours **Wingers:** 157 days absence per 1000 player-hours **Full backs**: 161 days absence per 1000 player-hours	**NR**	**NR**	**NR**	Absence due to thigh injuries was high for most backs and a consequence of the faster running speed. While absence due to hamstring muscle injuries was high in wingers, it was the absence due to thigh haematomas that was most significant.
M. N. Bourne et al. (2015b)	178 professional players	**All:** 20 injuries **Forwards**: 40% **Backs:** 60% **New:** 55% **Recurrent:**45%	21 days lost average	**NR**	**NR**	**Nordic eccentric test**: Injured players: Injured limb 355 N and for the uninjured limb 410 N imbalance 17.37%	80% affected the biceps femoris as the primary site of injury, 85% resulted from high-speed running.

						Non-injured: the raw average strength was 367 N with 10% imbalance.	Previous hamstring strain injury and limb imbalance was associated with an increased risk of future hamstring injury in Rugby Union
Farnan et al. (2013)	54 amateur players	**All:** 13.1 injuries /1000 player-hours	**NR**	1.2 /1000 player-hours	7.9 /1000 player-hours	No	Severe injuries were not common at the amateur level. The injury risk was like the professional level.
Kenneally-Dabrowski, Serpell, et al. (2019b)	74 professional players	**All:** 6% = 30 injured players **Forwards:** 47% **Backs:** 53% **New:** 93%	Median of days lost: 26 days In average 207 days were lost per season. **Severity** **Slight** (0-1 day): 0%	11 injuries **Preseason** 0 **Early season** 4 (36%) **Late season** 6 (55%) **Off-season**	19 injuries **Preseason** 9 (47%) **Early season** 3 (16%) **Late season**	**MRI injury test** **Grade II** 80% **Grade III** 20%	The incidence of injuries in the late season was almost double that of early season injuries (12 and 7

		Recurrent: 7% at days 157 and 166	**Minimal** (2-3 days): 0% **Mild** (4-7 days): 3% **Moderate** (7-28 days): 68% **Severe** (more than 28 days): 37% **Career ending**: 0%	1 (9%)	6 (31%) **Off-season** 1 (5%)		injuries, respectively).
Kenneally-Dabrowski, Brown, et al. (2019)	10 professional players	**All:** 4 injured players	**NR**	**NR**	**NR**	**Biomechanical analysis** Hamstring injuries classification OSICS diagnosis codes: TMHX (Hamstring strain), TMHS (Hamstring strain – semimembranosus/ tendinous strain, grade 1–2), TMHB (Hamstring strain – biceps femoris strain, grade 1–2)	Compared to uninjured athletes recurrent injured athletes demonstrated a tendency for greater thoracic lateral flexion, greater hip extension moments and greater knee power

						and TMHR (Grade 3 hamstring strain).	absorption during running.
Mendiguchia et al. (2016)	1 professional player	1 hamstring strain injury	**NR**	**NR**	**NR**	**Test:** Instantaneous sprint velocity **Protocol:** The test comprised of ten 40 m sprints on 30 s running cycle, and the speed was recorded with a sport radar.	**Injured player** Change in force and velocity relationship (from –0.76 to –0.92; **+21.1%**) associated with an increase in force (from 7.6 N/kg to 8.7 N/kg, **+14%**) and a minor decrease in velocity (from 10.1 m/s to 9.5 m/s, **–6%**).
Reid et al. (2013)	8 professional players	**NR**	**NR**	**NR**	**NR**	**RTP Strategies** **Phase I and II** (0-6 days) Return to run with no pain and medium intensities **Phase III and IV** (7-12 days)	**RTP Program** **Phase I and II** **AD:** 0.6-5 m/sprint **Distance** 2500-5500 m **Phase III and IV**

						High intensity running and agility, return to sprinting and skills **Phase V** (13-17 days) Full team training, skills, and contact	**AD:** 0.6-5 m/sprint **Distance** 3500-4700m **Phase V** **AD:** 0.6-5 m/s **Distance** 4000-4500m
Roberts et al. (2013)	189 community players	**All:** 1.4 [1.2, 1.7] injuries/1000 player-hours **Backs:** 1.4 [1.1, 1.8] injuries/1000 player-hours **Forwards:** 0.5 [0.3,0.7] injuries/1000 player-hours	**All:** 5.9 mean weeks missed (4.6 to 6.4). 41 days lost	**First quarter** 1.9 [1.4 ,2.5] injuries/1000 player-hours **Third quarter** 1.1 [0.7 ,1.6] injuries/1000 player-hours	**NR**	No	Hamstring strains are the most common non-contact injury. Backs had higher incidence than forwards. Running actions accounted for 10% of all injuries and of those 54% were hamstring strain injuries

Turl and George (1998)	28 semi-professional players (14 tested players and 14 controls)	**All:** 14 injured players	**NR**	**NR**	**NR**	**Slump test:** In a seated position, with the knees and hips at 90 degrees, the player had to slump forward with the chin flexed to the chest. Pressure is applied to the thoracic spine while extending the ipsilateral leg.	A positive slump test reproduced radicular symptoms 57% positive in test group, 0% in control group.
Upton et al. (1996)	44 players NR level players	**All:** 3 users vs 57 non-users **Recurrent**: 42%	275 matches hours 832 training hours	55%	45%	Thermal pants	Significant reduction in hamstring injury incidence wearing thermal pants sometimes: 3 injuries/1000 hours playing wearing thermal pants vs 57 injuries/1000 hours playing

							without thermal pants.
Yamada and Mastumoto (2009)	21 amateur players	**All:** 6 injured players	**NR**	0%	100%	**H:Q 60°/s** Injured 0.63 ± 0.03 Non injured 0.60 ± 0.10 **H:Q 180°/s** Injured 0.91 ± 0.57 Non injured 0.64 ± 0.13 **DCR 60°** Injured 0.74 ± 0.13 Non injured 0.70 ± 0.13 **DCR 180°** Injured 1.07 ± 0.59 Non injured 0.79 ± 0.16	Motor imagery capacity, and the time to identify the foot picture was defined as the reaction time (ms). Motor imagery influences the development of hamstring strain.
Yeomans et al. (2019)	137 amateur players	**All:** Hamstring muscle strains 9%	**NR**	**NR**	**NR**	**Test:** Hamstring flexibility **(**higher score more flexibility) **Protocol:**	**NR** results regarding hamstrings straight leg raise measures and injuries

			Straight leg raise test Hamstring board scores **Males:** Forwards: 78.6° ± 8.1 Backs: 80.9°± 5.3 **Females:** Forwards: 73.3° ± 11.3 Backs: 78.9° ± 10.1

Abbreviations: AD, average distance; N Newton; NR, not reported; RTP, return to play.

Notes. Values are means ± standard deviation, means [95% confidence intervals], and minimum – maximum range

5.3.5 Hamstring strength and asymmetry assessment: methods and measures

Overview

All methods and outcome measures used to assess hamstring strength are summarized in Table 12. Isokinetic testing is considered the "gold standard" method to measure hamstring and quadriceps strength (Reid et al., 2013)**,** with most of the studies assessing strength in rugby using isokinetic methods (Abdelfettah et al., 2019; Anastasi & Hamzeh, 2011; Beyer et al., 2016; Brown et al., 2016; Deighan et al., 2012; Dobbs et al., 2017; Severo-Silveira et al., 2018). All of these isokinetic studies were conducted at 60°/s, with a subset also using 180°/s (Abdelfettah et al., 2019; Beyer et al., 2016; Deighan et al., 2012) and one 35°/s (Dobbs et al., 2017). Concentric hamstring strength was examined across all isokinetic studies, with five subjects considering eccentrics (Beyer et al., 2016; Brown et al., 2016; Deighan et al., 2012; Dobbs et al., 2017; Severo-Silveira et al., 2018). Nine studies measured the hamstring to quadriceps ratio (H:Q) (Abdelfettah et al., 2019; Anastasi & Hamzeh, 2011; Beyer et al., 2016; Brown et al., 2016; Brown et al., 2014; Deighan et al., 2012; Dobbs et al., 2017; Mondin et al., 2018; Severo-Silveira et al., 2018; Yamada & Mastumoto, 2009) and five included dynamic control ratio (DCR) (Beyer et al., 2016; Brown et al., 2016; Deighan et al., 2012; Dobbs et al., 2017; Severo-Silveira et al., 2018). The H:Q is conventionally measured concentrically and used to quantify strength and imbalance between muscles and limbs. The dynamic control ratio is considered more functional, calculated as the *eccentric* hamstrings to concentric quadriceps strength ratio. There were no H:Q and DCR thresholds specifically established for Rugby Union players in the literature here reviewed. The Rugby Union literature cited thresholds from track and field that recommended H:Q values exceed 0.6 and DCR of 1.0 or above (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998). Other forms of hamstring strength testing methods used in rugby included eccentric (M. N. Bourne et al., 2015b), isometric (Dobbs et al., 2017), isotonic (Beyer et al., 2016), and sphygmomanometer (Mondin et al., 2018).

Protocols

Isokinetic strength tests

Concentric hamstring strength at 60°/s ranged from 89 to 252 Nm in amateur to professional players across positions and genders, and at 180°/s ranged from 71 to 121 Nm in male amateurs (no data for professionals or females). Eccentric hamstring strength across at 60°/s from ~135 to 220 Nm, and 209 to 220 Nm at 180°/s in male amateurs (no data for professionals or females). Key findings were that professionals were stronger than academy Rugby Union players(Brown et al., 2016), forwards were stronger than backs (Abdelfettah et al., 2019; Brown et al., 2014). In amateur players, experience had little effect on hamstring values (Beyer et al., 2016) and effect of leg dominance was inconsistent across studies (Abdelfettah et al., 2019; Brown et al., 2014) (Brown et al., 2016).

In amateur players, H:Q values ranged from 0.45 to 0.56, with no difference based on years of experience (Beyer et al., 2016) or playing position (Brown et al., 2016). Professional players displayed H:Q values of 0.52 to 0.68 (Brown et al., 2014; Severo-Silveira et al., 2018), with again no difference between playing positions (Brown et al., 2014), but the potential to increase with progressive Nordic eccentric training (Severo-Silveira et al., 2018). Concerning DCR values in amateur players, ratios ranged from 0.64 to 1.17, and was significant greater in experienced players (Beyer et al., 2016), but not affected by playing position or limb dominance (Brown et al., 2016). DCR in professionals ranged from 0.74 to 0.81 (Severo-Silveira et al., 2018), and was greater subsequent progressive Nordic eccentric hamstring training. Two studies undertook isokinetic knee strength assessment in amateur female athletes (Anastasi & Hamzeh, 2011; Dobbs et al., 2017). These studies identified that non-dominant limb H:Q (0.81) and DCR values were significantly greater than the dominant limb (0.74).

Deighan et al. (2012) examined how conducting testing in seated vs supine influenced isokinetic knee extensor and flexor strength. The DCR at 180°/s and mean peak torque values seated were significantly greater than supine. Furthermore, knee extensors were stronger than flexors, and eccentric produced superior values than concentric. The study highlighted the significance of testing eccentric isokinetic strength with a hip flexion angle of approximately 10° to determine imbalances and to screen for risk of injuries. Analysis in amateur players with both isometric and isokinetic strength tests in experienced and inexperienced player indicated experienced players had greater DCR at 60°/s values (Beyer et al., 2016). No significant differences were observed between players in DCR and H:Q at 180°/s velocity, which the authors attributed to an adaptation to the high sprint demands of Rugby Union. At the same level of competition, Deighan et al. (2012) found similar H:Q 60°/s, but lower DCR values when compared to the results by Beyer et al. (2016)

Forward amateur rugby players had greater peak torque ratios than backs in a study comparing the H:Q isokinetic ratios between soccer and Rugby Union players at 60 and 180°/s

(Abdelfettah et al., 2019). Although rugby players demonstrated superior values on average, the difference to soccer players was not significant. Rugby Union forwards were significantly stronger in peak knee flexion torque in both limbs when compared to rugby league forwards, as well as stronger in knee extension torque on their dominant side (Brown et al., 2014).

Eccentric strength test with Nordic exercises

Preseason Nordic hamstring eccentric testing performed with a load cell device (M. N. Bourne et al., 2015b), see Figure 8, indicated that weaker players (bilateral average < 267.9 N) were at a similar risk of sustaining a hamstring injury than stronger players. Forwards were stronger than backs. Injured players demonstrated a bilateral strength imbalance of 17.4 % that was significantly greater than injury-free players who displayed an imbalance of ≤10%.

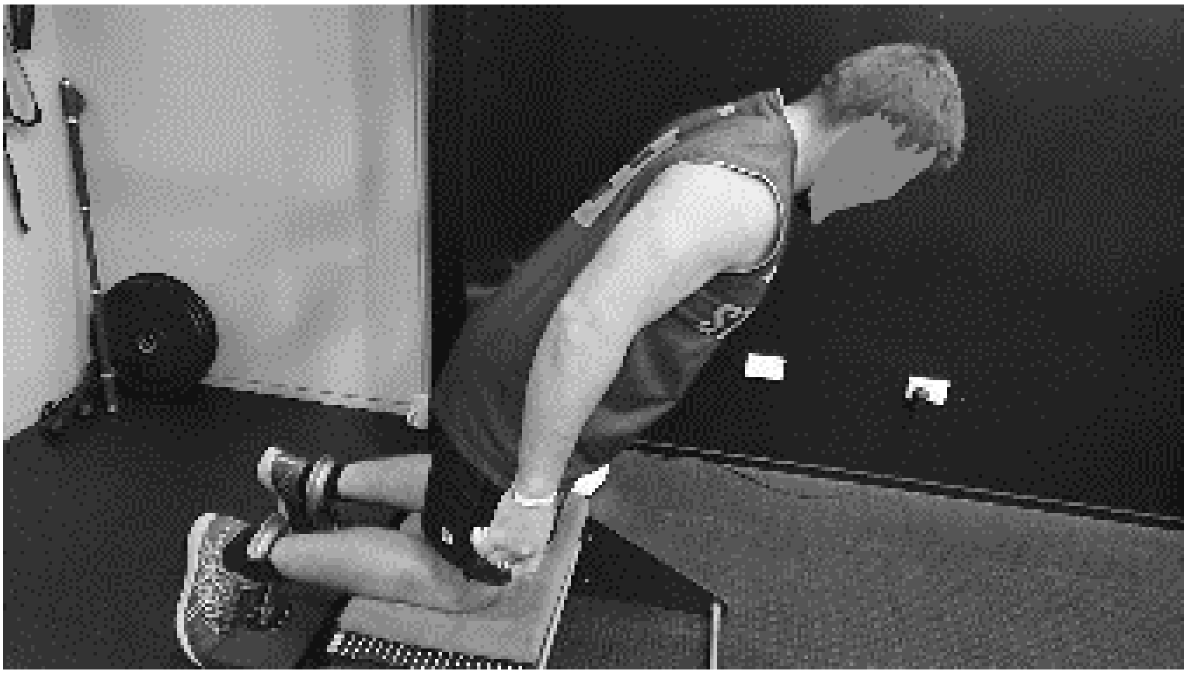

Figure 7. Illustration of a Nordic hamstring exercise.

Table 12. Hamstring strength measures and imbalances

Study	Strength assessment protocols	Hamstring Measures	Bilateral strength imbalances and values (H:Q, DCR, Newtons, etc)	Key findings
Abdelfettah et al. (2019)	**Male amateur players** **Test:** Isokinetic (concentric) **Equipment:** Cybex Norm isokinetic dynamometer **Protocol:** Peak 1RM at 60 and 180°/s for series of successive movements of 5 and 30 repetitions.	**Dominant limb** **Concentric hamstring 60°/s** Backs 101.5 ± 10.4 Nm Forwards 133.1 ± 30.4 Nm **Concentric hamstring 180°/s** Backs 70.7 ± 8.9 Nm Forwards 91 ± 21.3 Nm **Non dominant limb** **Concentric hamstring 60°/s** Backs 98 ± 21.8 Nm Forwards 130.5 ± 35 Nm **Concentric hamstring 180°/s** Backs 72.7 ± 15.6 Nm Forwards 83.7 ± 14.2 Nm	**Average value of the H:Q ratio in percentages** **H:Q 60°/s** **Dominant limb** 56.4 ± 9.5% **Non dominant limb** 53.9 ± 10.2% **H:Q 180°/s** **Dominant limb** 56.1 ± 10.25% **Non dominant limb** 56 ± 6.6%	Peak torque values in extension of the non-dominant limb were higher in forwards than backs.
Anastasi and Hamzeh (2011)	**Female amateur players** **Test:** Isokinetic (concentric) **Equipment:** Cybex Norm isokinetic dynamometer	**Dominant limb** **Pre-intervention** 89.2 ± 19.9 Nm **Post intervention** 102.2 ± 21.2 Nm **Non dominant limb** **Pre-intervention**	**Bilateral strength imbalances in percentage** **Pre-training** 10.4 ± 3.5% **Post-training**	Intervention group had a significant decrease in the percentage of bilateral strength imbalances.

	Protocol: Peak during pre- and post-training in both legs at 60°/s	93.15 ± 20.0 Nm **Post intervention** 104.23 ± 18.8 Nm	4.7 ± 2.2%	
Beyer et al. (2016)	**Male amateur players** **Test:** Isokinetic (concentric, eccentric). Isotonic test (squatting). **Equipment:** Biodex Medical System isokinetic dynamometer **Protocol:** 10 experienced players (≥ 2 years) and 14 inexperience players (< 2 years). **Isokinetic:** Peak of 3 RM measured at 60°/s and 180°/s **Isotonic:** 1 RM squat	**Dominant leg** **Concentric hamstring 60°/s** Inexperienced 114.3 ± 4.8 Nm Experienced 119.3 ± 5.8 Nm **Concentric hamstring 180°/s** Inexperienced 91.9 ± 3.9 Nm Experienced 92.8 ± 4.7 Nm **Eccentric hamstring 60°/s** Inexperienced 207.3 ± 8.2 Nm Experienced 225.8 ± 9.9 Nm **Eccentric hamstring 180°/s** Inexperienced 208.8 ± 9.6 Nm Experienced 220.4 ± 11.4 Nm **Squat 1RM** Inexperienced 132.4 ± 9.5 kg Experienced 143.9 ± 11.8 kg	**H:Q 60°/s** Inexperienced 0.45 ± 0.02 Experienced 0.50 ± 0.02 **H:Q 180°/s** Inexperienced 0.47 ± 0.02 Experienced 0.50 ± 0.03 **DCR 60°/s** Inexperienced 0.81 ± 0.04 Experienced 0.95 ± 0.05 **DCR 180°/s** Inexperienced 1.07 ± 0.05 Experienced 1.17 ± 0.06	Experience group had a significantly greater DCR 60°/s than the inexperienced group. No significant differences in mass, age, eccentric hamstring strength values at H:Q 60°/s, 180°/s, or DCR 180°/s between groups.
M. N. Bourne et al. (2015b)	**Male professional players** **Test:** Nordic eccentrics **Equipment:** Nordic board with custom-made uniaxial load cells	**Professional** 366.9 ± 76.9 N **Semi-professional (sub-elite)** 387.9 ± 96.3 N **(under 19)**	**Bilateral strength imbalances** **Injured** 17.3 ± 16.1% **Uninjured** 10.0 ± 9.8%	No significant difference was found between professional and semi-professional players; whilst among semi-professionals, sub-elites were significantly stronger than under 19s. Relative to body mass, these

	Protocol: Peak of 3RM of bilateral Nordic exercises	342.8 ± 81.5 N **Combined:** **Forwards** 388.5 ± 95.5 N **Backs** 353.1 ± 74.9 N		values significantly differed from professional to semi-professional players, the sub-elite and the under 19s were significantly stronger than the former players, whilst among sub-elite and under 19 players no significant difference was found. Forwards were stronger than backs; but relative to body weight, no significant differences were found.
Brown et al. (2014)	**Male professional players** **Test:** Isokinetic (concentric) **Equipment:** Humac Norm dynamometer **Protocol:** Average peak torque from 4 RM measured at 60°/s during seated knee-extension/ flexion and supine hip-extension/flexion at 60°/s.	**Leg Extension** **Forwards** Dominant 281 ± 45 Nm Non-dominant 268 ± 44 Nm **Backs** Dominant 244 ± 29 Nm Non-dominant 247 ± 38 Nm **Leg Flexion** **Forwards** Dominant 184 ± 27 Nm Non-dominant 180 ± 20 Nm **Backs** Dominant 157 ± 27 Nm Non-dominant 156 ± 27 Nm	**H:Q** **Forwards** Dominant 0.66 ± 0.09 Non-dominant 0.68 ± 0.10 **Backs** Dominant 0.64 ± 0.10 Non-dominant 0.64 ± 0.08	In two rugby codes, forwards were taller and heavier than backs. Professional Rugby Union forwards had significantly larger peak torque during knee flexion in both dominant and non-dominant limbs compared to professional rugby league forwards and Rugby Union backs.

Brown et al. (2016)	**Male amateur players** **Test:** Isokinetic (concentric and eccentric) **Equipment:** Humac Norm dynamometer **Protocol:** 1 RM with the dominant and nondominant limb in sitting and in a supine position at 60°/s. Dominant limb was defined as the limb that the player preferred to kick the ball or could kick the ball the farthest.	**Leg Extension Concentric** **Forwards** Dominant 252 ± 62 Nm Non-dominant 228 ± 38 Nm **Backs** Dominant 225 ± 38 Nm Non-dominant 214 ± 53 Nm **Leg Flexion Concentric** **Forwards** Dominant 129 ± 25 Nm Non-dominant 124 ± 19 Nm **Backs** Dominant 115 ± 14 Nm Non-dominant 118 ± 28 Nm **Leg Flexion Eccentric** **Backs** Dominant 148 Nm Non-dominant 125 Nm **Forwards** Dominant 155 Nm Non-dominant 145 Nm	**H:Q** **Forwards** Dominant 0.52 Non-dominant 0.55 **Backs** Dominant 0.52 Non-dominant 0.56 **DCR** **Forwards** Dominant 0.65 Non-dominant 0.64 **Backs** Dominant 0.65 Non-dominant 0.66	Professionals were stronger in all the peak torque measures compared to academy players. In forwards, the dominant limb was stronger than the non-dominant limb. The average H:Q ratio was less than 0.6 and the DCR was more than 0.6. In the isokinetic eccentric knee strength test, results showed forwards were stronger in the dominant leg compared to the non-dominant leg. Backs had similar strength torque values in both legs in flexion, however the dominant leg was stronger in extension. No differences between positions and limbs were found. Isokinetic concentric hip strength in forwards were similar between dominant and non-dominant legs. Forwards displayed greater values in the dominant leg during flexion compared to backs.
Deighan et al. (2012)	**Male amateur players**	**Seated peak torque** **Hamstring concentric**	**H:Q** **Seated**	In a seated position, concentric peak torque was greater compared

	Test: Isokinetic (Concentric) **Equipment:** Biodex System 3 dynamometer **Protocol:** 1RM isokinetic seated. For supine, participants were placed lying on their backs at 60 and 180°/s.	60°/s: 144 ± 26 Nm 180°/s: 121 ± 16 Nm **Hamstring eccentric** 60°/s: 179 ± 45 Nm 180°/s: 186 ± 60 Nm **Supine peak torque** **Hamstring concentric** 60°/s: 123 ± 19 Nm 180°/s: 109 ± 18 Nm **Hamstring eccentric** 60°/s: 147 ± 20 Nm 180°/s: 138 ± 30 Nm	60°/s: 0.53 ± 0.07 180°/s: 0.56 ± 0.07 **Supine** 60°/s: 0.47 ± 0.06 180°/s: 0.51 ± 0.09 **DCR** **Seated** 60°/s: 0.66 ± 0.09 180°/s: 0.86 ± 0.23 **Supine** 60°/s: 0.58 ± 0.07 180°/s: 0.68 ± 0.15	to supine eccentric. The H:Q in the seated position showed no significant difference compared supine.
Dobbs et al. (2017)	**Female and male amateur players** **Test:** Isokinetic (concentric and eccentric) and isometric (leg pull) **Equipment:** Biodex Pro 4 dynamometer **Protocol:** **Isokinetic tests:** Average of 3RM at 60°/s; 1RM isometric quadriceps strength at 60°/s, and	**NR**	**H:Q** **Non-dominant limb :** 0.81 ± 0.13 **Dominant limb :** 0.74 ± 0.14 **DCR** 0.81 ± 0.14	The non-dominant limb H:Q ratio was significantly greater than the dominant leg whilst the DCR was significantly greater than the simple H:Q

	1RM isometric hamstring strength at 35°/s **Isometric:** Bilateral and unilateral leg isometric mid-thigh pull. 3RM for both legs, and 2RM for a single leg were recorded on force plates. Dominant limb was defined as the preferred leg to kick a ball.			
Mondin et al. (2018)	**Male professional players** **Test:** Sphygmomanometer measures of maximal isometric strength. Isokinetic dynamometry (concentric) strength. **Equipment:** Humac Norm dynamometer and an adapted sphygmomanometer **Protocol:** **Isokinetic tests:** Peak of 3RM at 60°/s. **The sphygmomanometer test:** Subjects in supine with knees flexed at 30° or 90° and heel of one leg on the cuff, and opposite	**NR**	ICC (95% CI): **Quadriceps 90° right** 0.64 (-0.28–0.91) **Quadriceps 90° left** 0.81 (0.21–0.95) **Hamstrings 90° right** 0.83 (0.30–0.96) **Hamstrings 90° left** 0.87 (0.45–0.97) **Hamstrings 30° right** 0.92 (0.69–0.98) **Hamstrings 30° left** 0.87 (0.45–0.97)	A positive correlation in 90° of knee flexion between sphygmomanometer and isokinetic tests was found, as well as hamstring strength at 90° and 30° of knee flexion for both measures. No relation in strength asymmetry between legs or tests at 30° or 90° when testing the efficacy of the sphygmomanometer compared to the isokinetic test. No correlation in hamstring to quadriceps ratio at 90° between test for dominant and non-dominant leg. The group found reliability and validity measuring hamstring

	leg resting on the floor and extended. 3RM isometric strength of hamstring at 30° and 90° were recorded.			strength with the adapted sphygmomanometer test, although the test was not valid or reliable assessing bilateral or hamstrings to quadriceps asymmetries.
Severo-Silveira et al. (2018)	**Male professional players** **Test:** Isokinetic (concentric and eccentric) **Equipment:** ultrasound assessment B-mode ultrasonography and Biodex Pro 4 dynamometer **Protocol:** Peak of 3RM of flexion-extension at 60°/s	**Pre-intervention** **Quadriceps concentric** Constant group: 275.5 ± 27.1 Nm Progressive group: 278 ± 48.8 Nm **Hamstrings concentric** Constant group: 142.2 ± 19.6 Nm Progressive group: 146.6 ± 24.3 Nm **Hamstrings eccentric** Constant group 204.5 ± 43.3 Nm Progressive group 211.1 ± 31.8 Nm	**Pre-intervention** **H:Q** Constant group: 0.52 ± 0.05 Progressive group: 0.53 ± 0.07 **DCR** Constant group: 0.74 ± 0.14 Progressive group: 0.76 ± 0.06	After the training intervention only the progressive group had an increased in hamstring concentric and eccentric peak torques, H:Q and DCR.

Notes. Values are means ± standard deviations.

Abbreviations: DCR, isokinetic dynamic control ratio; H:Q, isokinetic hamstring quadriceps ratio; Nm, Nanometre; NR, not reported; RM, repetition maximum.

5.3.6 Hamstring strengthening programs

During two seasons, 12 professional male teams followed a training program with stretching and strengthening exercises in one of three groups: 1) strengthening, 2) strengthening and stretching, and 3) strengthening, stretching, and Nordic exercises (Brooks et al., 2006b), see **Table 13.** The group performing Nordic exercises had a lower incidence of hamstring injuries compared to the group performing strengthening exercises alone. Although no significant differences were found in severity, there were less absence days in the Nordic exercise group. Second row players displayed the lowest incidence and severity of hamstring injuries.

In another study, two Nordic exercise 8-week training programs were examined: progressive and constant workload (Severo-Silveira et al., 2018). Along with the Nordic exercises, ultrasonography of the biceps femoris long head was performed. Both Nordic exercises strategies significantly increased the muscle thickness and length, without pennation angle changes. The progressive routine significantly increased the strength values by 7 to 8%, H:Q from 0.53 to 0.57, and DCR from 0.76 to 0.81; but not the constant workload group.

Intervention strategies with Nordic exercises have also been implemented in female rugby players (Anastasi & Hamzeh, 2011). Following a 10-week Nordic hamstring training intervention, isokinetic strength at 60°/s improved 11-13%. Also of interest was that, following the training period, a significant reduction in bilateral strength imbalance from 10.3 % to 4.6% was observed.

Table 13. Hamstring training protocols and results

Study	Participants	Duration and exercises	Protocol	Outcome
Brooks et al. (2006b)	492 professional males	**1st group (n=148)** **Strengthening** **Proportion of weeks:** 87% of weeks strengthening	**1st group strengthening** Sessions per week: 1.2 ± 0.2 Sets per session : 3.6 ± 0.4 Reps per set: 8.2 ± 2.5	The group performing Nordic exercises had a lower incidence of hamstring injuries compared to the group performing strengthening exercises. The incidence of injuries in matches and training was not significantly different between the group performing Nordic exercises (0.39 injuries per 1000 hours player) and the group with stretching and strengthening exercises (0.59 injuries per 1000 hours player).
		2nd group (n=148) **Strengthening and stretching** **Proportion of weeks:** 77% of weeks strengthening and 87% of weeks stretching	**2nd group strengthening and stretching** **Strengthening** Sessions per week: 1.8 ± 0.4 Sets per session : 3.3 ± 0.3 Reps per set: 7.5 ± 1.0 **Stretching** Sessions per week: 2.6 ± 0.4 Sets per session : 2.8 ± 0.3	

			Reps per set: 2.5 ± 9.0	
		3rd group (n=200) Proportion of weeks: 44% of weeks strengthening, 87 % of weeks stretching, and 65% of weeks Nordic exercises	**3rd group strengthening stretching and Nordic exercises** **Strengthening** Sessions per week: 1.3 ± 0.3 Sets per session : 3.0 ± 0.4 Reps per set: 7.5 ± 2.1 **Stretching** Sessions per week: 1.8 ± 0.2 Sets per session: 2.6 ± 0.4 Reps per set: 28 ± 20 **Nordic exercises** Sessions per week: 1.3 ± 0.5 Sets per session: 2.8 ± 0 .7 Reps per set: 6.7 ± 1.5	
Anastasi and Hamzeh (2011)	24 females amateur (11 tested players, 11	10 weeks Nordic exercises performed in couples of	**Program** Weeks 1 – 2: 3 sets x 6 reps Weeks 3 – 4: 3 sets x 7 reps Weeks 5 – 7: 3 sets x 8 reps	The 10-week training program significantly decreased the bilateral strength imbalances from: 10.38 ± 3.53% to 4.69 ± 2.18%.

	control players)	players, 3 times per week	Weeks 8 -10: 3 sets x 10 reps	The Nordic exercise group displayed a significant change in the mean maximal vertical jump height from 31.22 to 35.93 cm
Severo-Silveira et al. (2018)	21 male professionals	8 weeks Nordic exercises	**Training Constant [Progressive]** Week 1: 2 sets x 6 reps [2 sets x 6 reps] Week 2: 3 sets x 6 reps [3 sets x 6 reps] Week 3: 3 sets x 6 reps [3 sets x 8 reps] Week 4: 3 sets x 6 reps [3 sets x 10 reps] Week 5: 3 sets x 6 reps [4 sets x 8-10 reps] Week 6: 3 sets X 6 reps [4 sets x 8-10 reps] Week 7: 3 sets X 6 reps [4 sets x 10 reps] Week 8: 3 sets X 6 reps [4 sets x 10 reps]	An 8-week training program significantly increased hamstring strength values by 7 – 8%, and H:Q from 0.53 to 0.57 and DCR from 0.76 to 0.81 in the progressive training group only.

Notes. Values are means ± standard deviation.

Abbreviations: DCR, dynamic ratio; H:Q Hamstring to quadriceps ratio

5.4 Discussion

5.4.1 Hamstring injuries

5.4.1.1 Incidence

We aimed to examine the scientific literature specific to Rugby Union and hamstring with focus on injury incidence, risk factors, injury prevention and strengthening strategies, and strength and asymmetry measures. Comparing levels of competition, the overall incidence of hamstring injuries in professional players (Brooks & Fuller, 2006) was four times higher than the incidence in community levels (Roberts et al., 2013). In both levels, backs suffered more hamstring injuries than forwards (M. N. Bourne et al., 2015a; Brooks et al., 2006b; Roberts et al., 2013). When divided by position, the incidence in professional backs and forwards was six times greater compared to amateurs. The hamstring severity in community players (41 average days lost) was approximately 2 to 2.5 times higher than professionals (17 to 21 average days lost) (M. N. Bourne et al., 2015a; Brooks et al., 2006b) suggestively due to lack of appropriate warm-up and hamstring training interventional strategies in these cohorts (Roberts et al., 2013). In professional players, from 23 to 45% of hamstring injuries reported were recurrences from either the current or previous season (M. N. Bourne et al., 2015b; Brooks et al., 2006b). Recurrences had more days lost (25 days) compared to new injuries (17 days) (Brooks et al., 2006b). In professionals the majority of the injuries occurred in the preseason and the late part of the season (Kenneally-Dabrowski, Serpell, et al., 2019b; Upton et al., 1996).

Running was the most common action of the game to produce a hamstring strain injury across levels, ranging from 68 to 85% of all injuries during high speed running in professionals (M. N. Bourne et al., 2015a; Brooks et al., 2006b; Kenneally-Dabrowski, Serpell, et al., 2019b) and 54% in amateur (Roberts et al., 2013). In professionals, the majority of the injuries in backs occurred in the last part of each half and in forwards increased throughout the game (Brooks et al., 2006b). In contrast, the higher incidence of injuries occurred in the first quarter of the game in amateur players. These contrasting results (i.e., greatest incidence later in the game in professionals vs first quarter in amateurs) suggest insufficient warming-up or game preparation at lower levels of competition potentially contributing to injury rates, whereas fatigue may be a greater contributor at higher levels. This proposition relating to warm-up strategies is indirectly supported by findings of a significant decrease in hamstring injuries when previously injured players wore warm pants during training and matches (Upton et al., 1996).

5.4.1.2 Risk factors

In professional players, the highest injury recurrence occurred in the first month of returning to play after suffering a hamstring injury (Brooks et al., 2006b), suggesting that return to play was too quick and/or rehabilitation and reconditioning insufficient to meet the load demands. Similarly, 18% of the injuries have been found to recur in the first twelve days after returning to play and at the same site of the previous injury (Upton et al., 1996). Elsewhere, players with a previous hamstring strain injury have demonstrated an 4.1-fold greater risk of a recurring injury (M. N. Bourne et al., 2015b). These studies altogether indicate that there is insufficient preparation before returning to training and playing after a hamstring injury, with a previous hamstring strain being a considerable risk factor. These findings align with a meta-analysis indicating that previous hamstring injury was a significant risk factor, in addition to other injuries (Anterior Cruciate Ligament, calf, and knee) for hamstring injuries (Freckleton & Pizzari, 2013a). M. N. Bourne et al. (2015b) highlighted the significant relationship between leg imbalances in eccentric strength and a previous hamstring strain injury, and concluded that players with a previous injury had an increased risk of sustaining another injury if they returned to play with pronounced strength imbalances between legs. In contrast, when the isokinetic test was included as a tool to return to play, N. van Dyk et al. (2019) found no value in this strength measure as a criterion to return to play after a hamstring injury in football players. Whatever the tool used, rugby players should be monitored in their return to play progression and assessed periodically for imbalances, especially if they have sustained a previous hamstring injury.

Running represented the action of the game which most commonly produced hamstring strain injuries (M. N. Bourne et al., 2015a; Brooks et al., 2006b; Brooks & Kemp, 2011; Kenneally-Dabrowski, Serpell, et al., 2019b; Roberts et al., 2013). As a reminder, backs were more often injured to the hamstring than forwards. Regarding positions and severity of the hamstring injury, fly-half accounted for the greatest days lost of any back positions, due to running and kicking actions in the game (kicking actions produced the most severe injuries with 35 days lost) (2006b). Wingers often presented with hematomas in the posterior thigh due to hamstring injuries and high-speed running actions (Brooks & Kemp, 2011). Kenneally-Dabrowski, Brown, et al. (2019) showed a range of biomechanical metrics differentiated recurrent injured players, with larger thoracic lateral flexion (poor core stability), greater absorption of power at the knee, and greater extension at the hip in the late swing phase of running. Running training and high speed exposures have been postulated as an effective tool to reduce hamstring injuries (Malone, Roe, Doran, Gabbett, & Collins, 2017). One of the recommendations by Buckthorpe et al. (2019) for the prevention of hamstring injuries, as part of the strengthening program, was high speed-running routines at least twice a week at 95% of maximum speed.

Mendiguchia et al. (2016) analysed a player with a hamstring injury and identified impaired sprint accelerations with a decrease in horizontal force production, potentially due to weak hamstring or gluteal muscles, before the injury and after return to play. The authors highlighted the importance of running activities for prevention of hamstring injuries, and suggested sprint time measurement to detect deficits during the initial acceleration phase. Magnetic resonant imaging of hamstring injuries in professional players showed the biceps femoris long head fascicle was the most injured muscle (73%), and that this injury occurred most frequently in running actions (77%) (Kenneally-Dabrowski, Serpell, et al., 2019b). In contrast to football players who sustained more Proximal Myofascial junction intramuscular injuries (Crema et al., 2016), the Distal Myofascial junction site was more common in Rugby Union players, re-emphasising the importance of Nordic exercises to target this portion of the muscle (Hegyi, Péter, Finni, & Cronin, 2018).

5.4.2 Hamstring strength measures

5.4.2.1 Isokinetic assessment

Making strong inferences on the available data across studies proves challenging given the differences in playing levels and positions, study aims, and testing procedure. No H:Q and DCR thresholds have been specifically established for Rugby Union players. In track and field, H:Q values exceeding 0.6 (Aagaard et al., 1998) and DCR values of 1.0 or above are considered normal (Coombs & Garbutt, 2002) and recommended for reducing the risk of hamstring injuries (Aagaard et al., 1998). H:Q values below 0.6 have been shown to increase hamstring injuries 17-fold in sprinters (Yeung et al., 2009).

Across the Rugby Union literature reviewed, H:Q values were typically lower than 0.6 (Beyer et al., 2016; Brown et al., 2016)[42], although reported to surpass 0.6 in professional players (Brown et al., 2014). Similarly, DCR were often below 1.0 (Beyer et al., 2016; Brown et al., 2014; Severo-Silveira et al., 2018), even in professionals. Addressing these imbalances could potentially reduce the relatively high incidence of hamstring strains in Rugby Union. That said, N. van Dyk et al. (2017) found no relationship between H:Q isokinetic strength ratios in injured and uninjured football players. Furthermore, the systematic review and meta-analysis for hamstring strain injury risk factors by Freckleton and Pizzari (2013a) did not find evidence that any isokinetic ratio, at any speed or type of contraction, was associated with the risk of hamstring injuries. Therefore, it remains uncertain whether improving these ratios would actually reduce hamstring incidence in rugby.

Regarding hamstring strength tests, most of the studies assessed the strength in an isokinetic fashion and aimed to determine imbalances between limbs, profile players, evaluate training outcomes, and compare different strength tests (Abdelfettah et al., 2019; Anastasi & Hamzeh, 2011; Beyer et al., 2016; M. N. Bourne et al., 2015b; Brown et al., 2016; Deighan et al., 2012; Dobbs et al., 2017; Mondin et al., 2018; Severo-Silveira et al., 2018). In amateur female players, an increase in strength was found, as well as a reduction in imbalance between limbs, after a Nordic exercise intervention (Anastasi & Hamzeh, 2011). To date, this is the first study evaluating the effect of Nordic strengthen training on hamstring strength and imbalances in female players, consequently establishing guidelines of mean strength values and imbalances ratios pre- and post-intervention. In the systematic review by Hewett, Myer, and Zazulak (2008), no significant difference between females and males was found in isokinetic H:Q values at slow velocities; although at higher angular velocities (from 30 to 360°/s), males significantly increased their H:Q values, while female values did not change. Thus, the reduced capacity of females to control the knee joint at high speeds might increase their risk to sustain a hamstring injury during high speed running (Hewett, Myer, & Ford, 2004). These results suggest that assessing H:Q values at higher angular velocities might be more clinically-relevant in the context of Rugby Union and hamstring injuries.

Male amateur forward players were found to be stronger than back players (Brown et al., 2016). These outcomes confirmed similar findings in professional players by Brown et al. (2014). Comparing levels, professionals were stronger in the concentric peak torque values than the amateur players. The differences between playing positions and levels likely relates to the match demands of forwards requiring greater leg strength (i.e., tackling, scrummaging, rucking, mauling, and pick-and-goes) than backs, and strength increases with years of experience and higher demands at higher levels. Playing level and position have been associated with different attributes and demands (Smart, Hopkins, & Gill, 2013), including body composition, speed, strength, power, and repeated sprint performance.

5.4.2.2 Nordic eccentric assessment

Only one study measured Nordic eccentric values. M. N. Bourne et al. (2015b) found significant differences in strength between injured and uninjured limbs, with weaker limb in injured than uninjured limb. In the eccentric strength test, imbalances between legs for injured players displayed greater values compared to uninjured players. Bilateral strength imbalances of more than 15% between legs increased the risk of hamstring injuries by 2.4 times and imbalances of more than 20% between legs increased the risk by 3.4 times. A review by Kalkhoven, Watsford, McLean, and Sides (2020) found that during all the phases of sprinting, the hamstring muscles are active (from the stance phase to the swing phase). The "hamstring muscle slack", a term which suggests the hamstring act isometrically in the late swing of sprinting, does not occur. These authors concluded that the hamstring contracts in an eccentric fashion in the late swing phase, such that an eccentric test may be a more appropriate way to measure hamstring strength and capability. This interpretation of the kinematics of sprinting may also suggest that eccentric exercises are a better way to train hamstring function. That said, authors of a systematic review and meta-analysis of different devices measuring hamstring eccentric strength in different sports with the Nordbord device cautioned when assessing hamstring peak strength and imbalances to estimate hamstring injury risks (Claudino et al., 2021). This caution was due to the Nordic hamstring test not eliciting the same demands as running, and therefore, it should not be used as the sole tool to assess in-season neuromuscular status (Claudino et al., 2021).

5.4.3 Hamstring strengthening programs

Three studies evaluated the effect of Nordic eccentric exercises in hamstring strength, imbalances, and injuries in Ruby Union (Anastasi & Hamzeh, 2011; Brooks et al., 2006b; Severo-Silveira et al., 2018). Two studies showed improvement in strength from 7 to 13% and bilateral strength imbalances (Anastasi & Hamzeh, 2011; Severo-Silveira et al., 2018), and one showed a decrease in hamstring injury incidence and severity (Brooks et al., 2006b). In a 10-week training intervention program with female players, significant improvements in hamstring strength values, and decreases in the percentage of bilateral strength imbalances with a progressive training routine were found (Anastasi & Hamzeh, 2011). Similarly, an 8-week training program with Nordic exercises resulted in significant improvements in male professional players with a progressive training program, with an increase in hamstring strength values, an increase in H:Q and DCR values, as well as an increase in the biceps femoris long head fascicle length and thickness, with no significant changes in a group with constant training load (Severo-Silveira et al., 2018). As a short fascicle length has been shown to increase the risk of hamstring injuries, and longer fascicles identified as a protective factor of hamstring strain injuries in older football players with previous hamstring injuries (Timmins et al., 2016), the progressive Nordic program promoted beneficial morphological adaptations. The two progressive programs followed a similar training strategy, 2 to 3 times a week, 3 to 4 sets, with a maximum of 10 repetitions per session.

The study by Brooks et al. (2006b) implemented Nordic eccentric exercises in addition to stretching and strengthening routines once a week, with two sets of approximately six repetitions. The forces generated by the Nordic exercises were similar to those observed during sprinting (Kyrolainen, Komi, & Belli, 1999). The players performing Nordic exercises showed a significantly lower incidence of hamstring injuries compared to the group performing strengthening exercises. Although severity did not significantly differ between the groups performing strengthening and stretching exercises, there was a reduction in absence days from training and matches. Giakoumis (2020) suggested possible mechanisms underpinning the beneficial effects of Nordic exercises in athletes, including semitendinosus and biceps femoris fascicle lengthening, synergistic role of the semitendinosus in sprinting activities in conjunction with the fascicle, and hypertrophy of the short head of the biceps femoris and semitendinosus. Compared to other exercises, eccentrics elicit greater electromyographic activity, increases in strength, and muscle adaptations (Giakoumis, 2020). Therefore, although cautioned against being used as a sole screening measure (Claudino et al., 2021), the integration of Nordic exercises appear of benefit to Rugby Union and are recommended.

5.5 Conclusion

Isokinetic testing is the most common method to assess hamstring strength and imbalances in Rugby Union; however, current literature is lacking to support the evidence-based use of strength, H:Q, and DCR measures to inform injury prevention and return to play strategies for hamstrings. Regarding the isokinetic measures, professionals are stronger than amateur, and across both levels, forwards are stronger than backs. Nordic eccentric strength measures have been shown to be a better physiological and functional test, with differences in strength and imbalances predicting new and recurrent injuries. Strengthening programs with Nordic exercises significantly increased hamstring strength measures and decreased imbalance ratios in female and male players. Furthermore, a significant reduction in injury incidence and severity in professional players has been observed in players performing routines the incorporated progressive Nordic exercises.

Here, we described the incidence, severity, and epidemiology of hamstring injuries across levels in Rugby Union. The aetiology of hamstring strain injuries is multifactorial, with playing position, fatigue, previous injuries, leg imbalances, lack of readiness to return to play, and running actions identified as contributing factors across levels. Combining strategies to prevent hamstring injuries and recurrences, and to inform return to play, is likely worthwhile and should include Nordic strength assessment and Nordic exercises, high-speed running routines, running biomechanical assessments, and warm-up routines.

CHAPTER 6

Reliability of repeated Nordic hamstring strength in rugby players using a load cell device.

Prelude: The previous literature review chapter concluded that Nordic eccentric strength measures were appropriate for use in the context of Rugby Union and hamstring injury strains. As it is important that testing methods use in research and practice provide reliable outcomes, this present chapter established the intrasession and intersession reliability of Nordic eccentric hamstring strength measures in semi-professional Rugby Union players using a portable load cell device. Examining the reliability of the Nordic hamstring eccentric strength test in a Rugby Union population was important to ensure the variables examined in Chapter 7 and 8 were reliable. Establishing the between session variability in outcomes was important to interpret the outcomes from the intervention study in Chapter 8.

6.1 Introduction

Hamstring strain injuries are one of the most common injuries in Rugby Union representing up to 15% of all sustained injuries (Brooks et al., 2006b). In England Rugby Football Union, hamstring strain is the most common occurring injury during training with 15% (Kemp et al., 2021) and the second most common injury during match play after thigh hematomas (Brooks et al., 2005a). The 2019 Rugby World Cup injury surveillance data revealed lower limb injuries accounted for almost 50% of all players absence days. Hamstring strains were the second most common match injury after concussion in the tournament, with hamstring injuries representing 9.8% of all match injuries and causing 467 missed days (2020). As with any injury, intrinsic and extrinsic risk factors for hamstring strains have been identified (Brooks et al., 2006b). Hamstring strain injuries have the highest recurrence rate of any muscle injury (Brukner & Khan, 2016), for instance in Rugby Union a previous hamstring injury increased in four-fold the risk of a subsequent hamstring injury (M. N. Bourne et al., 2015b), due to residual neuromuscular inhibition, strength deficits, altered muscle tendon morphology, and modified contractile mechanics.

Hamstring injuries often occur during the eccentric phase of running or kicking in rugby, and less frequently because of a direct tackle collision in the ruck position (Kenneally-Dabrowski, Serpell, et al., 2019a). Asymmetries in strength between muscle groups and limbs are commonly assessed and used as screening methods in sports (Croisier et al., 2008).

The Nordic eccentric hamstring test assesses the maximal hamstring eccentric strength and imbalances between limbs (David A. Opar, Piatkowski, Williams, & Shield, 2013). Nordic eccentric strength assessment is a more feasible and functional test than isokinetic (gold standard method to measure hamstring strength). In Australian Football Rules, established an eccentric hamstring strength threshold value of 256 Newtons (N), below which there was a significant increase in injury risk (David A Opar et al., 2014). However, this threshold could differ with different body mass (heavier and/or taller players can reach 256 N with greater ease than smaller players). In football, Buchheit, Cholley, Nagel, and Poulos (2016) examined the effect of body mass on hamstrings eccentric strength exercises on Norbord. These authors estimated an increase in 4 N of eccentric hamstring strength per increase in 1 kg of body mass and provided a predictive equation of eccentric strength according to body mass (eccentric strength (N) = 4 X Body Mass (kg) + 26.1). Values over or below 40 N (12%) of this expected value based on body mass were considered to reflect a significant imbalance or weakness in football players. Establishing such a predictive equation for Rugby Union would be of high practical value. In Rugby Union, players with a raw average eccentric strength in both limbs of less than 267.9 N did not show more risk of having a hamstring injury when compared to the stronger players Forwards were stronger than backs [7].

In the Nordic eccentric strength exercise, injured players have been reported to show an imbalance between limbs mean of 17.37 % that was significantly higher than the players with no injuries who displayed an imbalance mean of 10.0%. In the eccentric strength test, imbalances between legs for injured players displayed greater values compared to uninjured players. Imbalances of more than 15% between legs increased the risk of hamstring injuries by 2.4 times and imbalances of more than 20% between legs increased the risk by 3.4 times (M. N. Bourne et al., 2015b). When assessing such injury risk thresholds, it is important to be cognizant of the reliability of the testing methodology to inform minimal detectable difference and smallest worthwhile changes. Previous studies have examined the reliability of a novel device designed to measure hamstring eccentric strength and bilateral strength balance in different cohorts including Rugby Union players with a Nordic hamstring eccentric exercise in a single session and demonstrated high to moderate reliability (intra-class correlation coefficient = 0.83-0.90; typical error, 21.7-27.5 N; CV 5.8%-8.5%) (David A. Opar et al., 2013).

There is evidence to support the use of Nordic eccentric strength measures to inform practice, with strength and imbalances useful in predicting injuries (David A Opar et al., 2014). Although, intersession reliability for the Nordic eccentric hamstring strength with a load cell device in Rugby Union has not been examined. Given that testing with a load cell device to assess bilateral hamstring strength and imbalances, may be a feasible surrogate method to test to the isokinetic test, we aimed to examine the intrasession and intersession reliability of Nordic eccentric hamstring strength measures in semi-professional Rugby Union players using a load cell device.

6.2 Materials and Methods

6.2.1 Study design

A repeated-measures reliability study was conducted in semi-professional male Rugby Union players. Based on methods described to establish minimum sample size requirements for reliability studies (Walter et al., 1998), a minimum of around 20 participants was needed when setting the acceptable reliability level at ρ_0=0.40 (i.e., fair reliability threshold) and desired reliability level at ρ_1>0.75 (i.e., good reliability threshold) with an α=0.05 and β=0.20 knowing that players were assessed on three occasions.

6.2.2 Participants

Twenty-five semi-professional male Rugby Union players (mean ± standard deviation (SD), age 23.8 ± 3.2 years, height 184.5 ± 7.2 cm and body mass 99.3 ± 9.8 kg) agreed to participate in this study. Inclusion criteria required all the participants to be free of knee and hamstring injuries in the last month that compromise maximal isometric contraction performance of the knee flexor musculature. All participants were informed of the purpose, benefits, and risks of the study through written and oral description and gave their written consent to participate prior to engaging in any activity. The study protocol was approved by the University of Waikato Human Research Ethics Committee (HREC(Health) 2019#74) and adhered to the latest Declaration of Helsinki.

6.2.3 Instrumentation

Tests were conducted using a customised device that contained two load cells (MT501 Meltron Millennium Mechatronics Limited, New Zealand) that measured force from the right and left leg separately with a capacity of 250 kg for each load cell (error < 0.02%, sensitivity 0.08 kg). Load cells were connected via Bluetooth to a tablet (Samsung Galaxy TAB A 10.1" 2018 Tablet 2GB Ram 32GB Storage Wi-Fi Android 9.0 – Black) and data were recorded at 520 Hz. The reliability of Nordic exercises with a load cell device showed good intra-session reliability (ICC= 0.79 to 0.90) and a fair reliability in the mean and max intersession (ICC= 0.52 to 0.64) Figure 9.

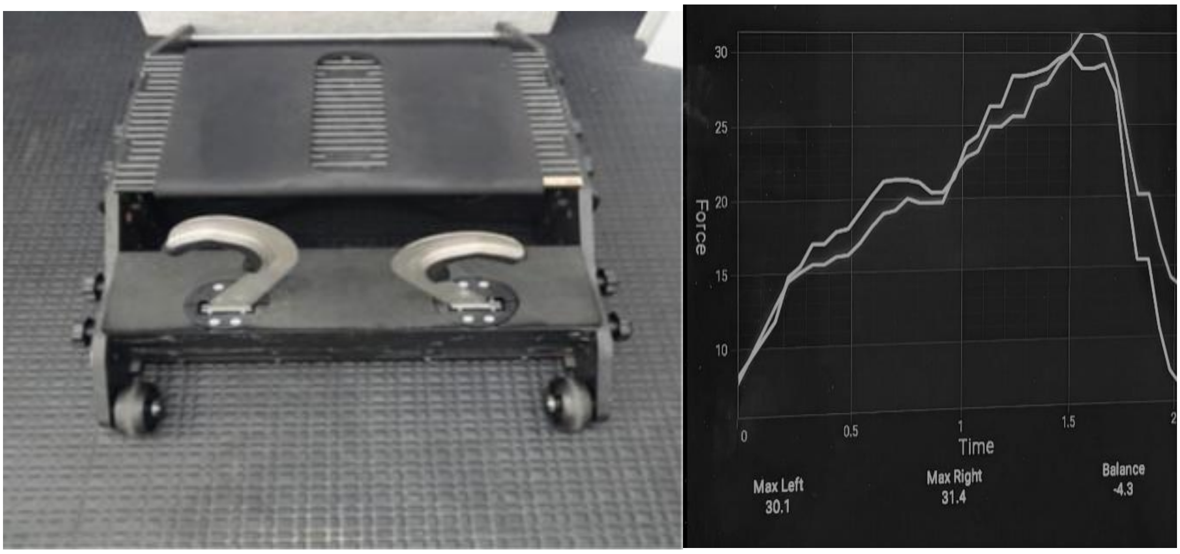

Figure 8. Illustration of the load cell device and the Real-time visual display of peak hamstring strength (N) and bilateral strength balance (%) values.

6.2.4 Procedures

This study assessed hamstring strength with semi-professional Rugby Union players with a load cell device**.** Three testing sessions were undertaken over three weeks, with each weekly session separated by seven days. The participants completed each testing session whilst performing their routine training program in a high-performance centre where they were accustoming to training. Participants knelt on a platform with the ankles attached to a load cell, and were instructed to lean forward as slow as they can whist resisting the movement with the hamstring muscles. The device measures the eccentric force exerted by the hamstring muscle complexes whilst the muscles are lengthening under load, see Figure 10.

The same examiner supervised all tests. Before the experimental procedure, all participants completed a warm-up protocol of three submaximal repetitions of Nordic eccentric exercises with a verbal command " free fall". For the experimental procedure participants completed three maximal effort repetitions of Nordic eccentric exercises with a verbal command "fall as far and as slow as you can", after each repetition a 30-second rest was given between efforts. The peak force in Newtons (N) was recorded during the maximal eccentric hold.

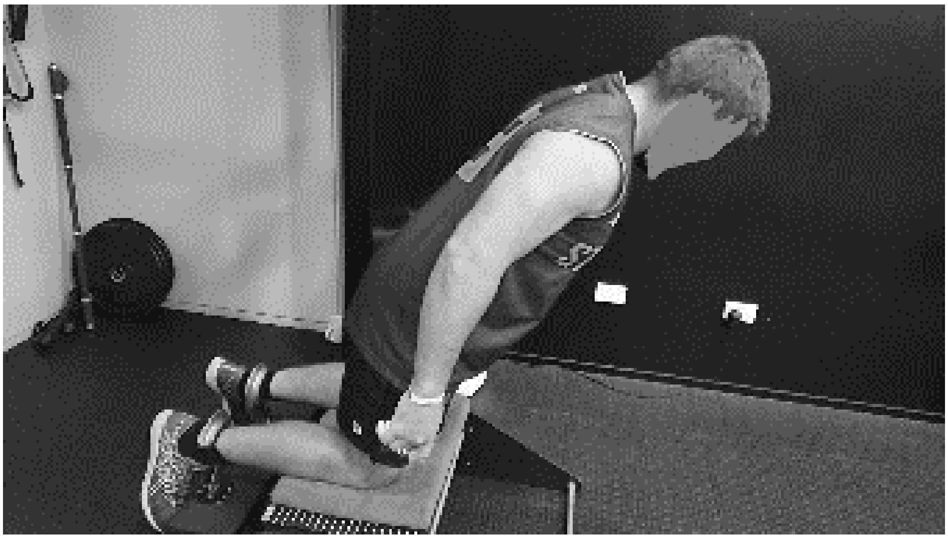

Figure 9. Illustration of Nordic eccentric test performed using a load cell device.

6.2.5 Statistical analysis

Data are described using means ± SD. The normal distribution of variables was assessed with Shapiro-Wilks's and d'Agostino-Pearson tests. Data were log-transformed for reliability analysis to reduce bias arising from non-uniformity of error when appropriate. The three repetitions completed during the first session were used to examine the intra-session reliability. The inter-session mean analysis was comprised of mean strength values for each trial, and inter-session maximal force analysis was comprised of the peak strength value collected during each trial. The intersession reliability reflects the stability of measures as it defines the day-to-day variability in measures, which typically needs more than one-day between measures in sport measures [41]. The reliability of intra-session and inter-session measurements was assessed using intra-class correlation coefficient (ICC), coefficient of variation (CV), typical error (TE), and mean change (Δ), and were calculated with their SD or 95% confidence limits [lower, upper] using a customized statistical Excel spreadsheets (Hopkins, 2017) in Microsoft Excel for Office MSO (Version 2111 Build 16.0.14701.20254). Relative reliability was interpreted as poor, fair, good, and excellent when corresponding ICCs were < 0.40, 0.40 to 0.75, > 0.75 to 0.90, and > 0.90 (Rosner, 2015). Absolute reliability was considered good and acceptable when corresponding CVs were ≤ 10% and ≤ 20% (Hébert-Losier & Beaven, 2014; Wojtys et al., 2002).

Trials and repetitions were assessed for systematic error (i.e., learning effects) using a one-way repeated measures analysis of variance (RM ANOVA) using STATA (Statics/data analysis version 16.1, StataCorp, College Station, TX). The Duncan method was applied in post-hoc testing. Statistical significance level was set at $p \leq 0.05$ for all analysis. If the assumption of sphericity was violated, the adjusted p-values were reported.

6.3 Results

Descriptive and reliability statistics related to intrasession isometric neck strength values and ratios are shown in Table 14. Those related to intersession mean values are displayed in Table 15, and intersession maximal values are reported in Table 16.

Left leg

Nordic eccentric hamstring strength demonstrated good intra-session reliability for mean eccentric Nordics (ICC = 0.90, TE=26.8N and CV=6.3%), fair inter-session reliability for mean values (ICC = 0.58, TE = 54.2 and CV= 12.5%), and good inter-session reliability for maximal values (ICC =0.87, TE= 24.9, CV= 5.7%). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.053$).

Right leg

Nordic eccentric hamstring strength demonstrated good intra-session reliability for mean eccentric Nordics (ICC = 0.76, TE=28.9N and CV=6.7%), fair inter-session reliability for mean values (ICC =0.64, TE=44.1 and CV=7.4%), and good inter-session reliability for maximal values (ICC =0.62, TE= 44.1, CV= 9.7%). There was no systematic bias for intra-session analyses based on the RM ANOVAs ($p \geq 0.058$). However, bias was detected for mean inter-session reliability analysis ($p=0.04$). Post-hoc Duncan test analysis revealed a significant difference effect for trial 3 vs 1 ($p = 0.031$) and trial 3 vs 2 ($p = 0.003$). Bias was also detected for max inter-session reliability analysis ($p=0.02$), and a post-hoc Duncan test analysis revealed a significant difference effect for trial 3 vs 1 ($p = 0.001$) and trial 3 vs 2 ($p = 0.014$).

Left-right ratio

Intra-session left-to-right ratio values demonstrated good reliability (ICC = 0.90, TE = 0.5, and CV = 5.5%), fair inter-session for mean left-to-right ratio (ICC = 0.52, TE = 0.71, and CV = 8.2%), and fair inter-session relability for maximum force (ICC = 0.53, TE = 0.78, and CV= 9.6 %). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.649$); however, intersession mean bias was detected ($p = 0.02$). The post-hoc Duncan test analysis revealed a significant difference effect for trial 2 vs 1 ($p = 0.042$) and trial 3 vs 1 ($p = 0.012$).

Table 14. Descriptive and reliabiliy statistics related to intrasession Nordic eccentric hamstring strength values. Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for left leg, right leg, and balance examined.

	Mean Nordic eccentric strength (SD)			**Δ eccentric strength (SD)**			**Reliability statistics**			
	Trial 1	**Trial 2**	**Trial 3**	**Trial 1- 2**	**Trial 2 – 3**	**Trial 1 – 3**	**ICC [95% CI]**	**TE (N) [95% CI]**	**CV (%) [95% CI]**	**p-value**
Left leg flexion (Newton)	472.9 (67.9)	466.8 (61.4)	466.4 (75.4)	-6.1 (40.3)	3.7 (42.9)	6.5 (29.2)	0.90 [0.82 – 0.95]	26.8 [22.7 -33.2]	6.3 [5.2 – 8.4]	0.783
Right leg flexion (Newton)	453.7 (48.7)	445.9 (65.1)	453.7 (63.2)	-7.6 (33.8)	10.3 (48.3)	-1.2 (39.6)	0.76 [0.60 – 0.87]	28.9 [24.5 – 35.3]	6.7 [5.5 – 8.9]	0.454
Bilateral ratio	1.04 (0.13)	1.05 (0.1)	1.0 (0.13)	-0.02	0.02	0.01	0.79 [0.62 – 0.89]	0.5 [0.4 – 0.6]	5.5 [4.4 – 7.2]	0.221

p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

Table 15. Descriptive and reliabiliy statistics related to intersession of Nordic eccentric hamstring strength values (mean of three trials). Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for left leg, right leg, and balance examined.

	Mean Nordic eccentric strength (SD)			**Δ eccentric strength (SD)**			**Reliability statistics**			
	Trial 1	**Trial 2**	**Trial 3**	**Trial 1- 2**	**Trial 2 – 3**	**Trial 1 – 3**	**ICC [95% CI]**	**TE (N) [95% CI]**	**CV (%) [95% CI]**	**p-value**
Left leg flexion (Newton)	470.2 (65.9)	454.1(114.7)	478.3 (74.8)	-13.9(83.5)	38 (91.2)	19.0(44.2)	0.59 [0.40 – 0.75]	54.2 [46.6 – 66.4]	12.5 [10.7 – 15.5]	0.175
Right leg flexion (Newton)	449.6 (54.7)	449.7 (83.4)	492.1(54.7.7)	5.6 (65.1)	50.7(70.8)	44.9(48.2)	0.64 [0.55 – 0.72]	44.1 [38.0 – 53.9]	7.4 [5.8 – 10.5]	0.003
Bilateral ratio	1.04 (0.11)	1.0 (0.13)	1.0 (0.13)	0.05	0.02	-0.06	0.52 [0.32 –0.70]	0.71 [0.6 – 0.8]	8.2 [7.0 – 10.1]	0.023

p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

Table 16. Descriptive and reliabiliy statistics related to intersession of Nordic eccentric hamstring strength values (maximal value from three trials). Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for left leg, right leg, and balance.

	Mean Nordic eccentric strength (SD)			**Δ eccentric strength (SD)**			**Reliability statistics**			
Variable	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1-2**	**Trial 2-3**	**Trial 1-3**	**ICC [95% CI]**	**TE (N) [95% CI]**	**CV (%) [95% CI]**	**p-value**
Left leg flexion (Newton)	491.1 (67.7)	420.2 (190.5)	398.8 (215.3)	-10.9 (81.9)	35.7(95.6)	-20.5 (51.7)	0.56 [0.37 – 0.73]	55.9 [48.0 – 68.7]	12.5 [10.6 – 15.4]	0.252
Right leg flexion (Newton)	474.3 (57.9)	472.3 (87.2)	506.6 (65.6)	0.5 (6.8)	4.6 (7.4)	-0.4 (4.4)	0.62 [0.44 – 0.77]	44.1 [37.2 – 53.9]	9.7 [8.2 – 11.9]	0.021
Bilateral ratio	1.03 (0.11)	1.0 (0.14)	0.98 (0.08)	0.04	0.01	-0.05	0.54 [0.33 – 0.71]	0.78 [0.65 – 1.0]	9.6 [7.9 – 12.3]	0.121

[a]p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

6.4 Discussion

We evaluated the reliability of a customized load cell device on hamstring strength and bilateral strength balance with Nordic eccentric exercises in Rugby Union players. Our results showed good intrasession reliability (ICC= 0.79 – 0.90), however, a fair intersession reliability – which here reflects the stability in measures – in the mean and the maximum values (ICC= 0.52 – 0.64). Similar to our results, the intrasession reliability of a novel load cell device using the Nordic eccentric exercises in players from different sports including Rugby Union players have shown a good test-retest intraclass reliability (ICC= 0.85 – 0.89) and a fair reliability for a single leg (ICC=0.56 – 0.73) (David A. Opar et al., 2013). The authors recommended assessment of Nordic eccentric exercises in a bilateral method to test strength and bilateral strength balance (David A. Opar et al., 2013). Assessing the intersession reliability of a novel Nordic hamstring eccentric strength device and compared with an isokinetic strength device in collegiate students, the test-retest for the novel device showed good to excellent intersession reliability (ICC= 0.76 – 0.96) for the left leg; and ICC= 0.78 – 0.96) for the right leg (Lodge, Tobin, O'Rourke, & Thorborg, 2020). The lower reliability in extension was thought due to variations in technique and body positioning between sessions [28]. Assessing Nordic eccentric hamstring strength involves attention to foot and body positions, as well as ensuring the movement is controlled while performing the Nordic exercise, the Nordics are subject to variations in position as well as in falling speed between sessions, which could explain the superior intrasession than intersession reliability outcomes.

Regarding values of absolute reliability, we exhibited intrasession TE values ranging from 26.8 N to 28.9 N, with a good absolute reliability CV ranging from 5.5 % to 6.7% . Mean and maximal force inter-session TE values ranged from 44.1 N to 55.9 N with acceptable absolute reliability CVs ranging from 7.4% to 12.5%. Comparable to our results, the reliability of a novel load cell device using the Nordic eccentric exercises showed TE values ranged from 21.7 N to 27.5 N with CV that ranged from 5.8% to 8.5% (David A. Opar et al., 2013). The test-retest reliability showed of the novel device to assess hamstring eccentric exhibited good to excellent reliability between two trials with a TE value of 14.65 N for the left leg, and with a TE value of 17.29 N for the right leg (Lodge et al., 2020). It would seem that using a load cell device on a platform to test Nordic eccentric position in Rugby Union players is also subject to small but potentially meaningful variations when tested in the same session, and that the reliability of the measures tested a week apart can be considered acceptable.

In Rugby Union, isokinetic testing was the most common method of testing hamstring strength (C. Chavarro-Nieto et al., 2021b) and is consider the 'gold standard' method to test hamstring strength and bilateral strength balance (Harding et al., 2017). Despite this, a study with soccer players that assessed the correlation of isokinetic dynamometry and a Nordic eccentric device, displayed poor correlations between the isokinetic test and the Nordic eccentric test (r=0.35), with no correlation with the bilateral strength and imbalances (r=0.037) (Nicol Van Dyk, Witvrouw, & Bahr, 2018). Another study compared the Nordic hamstring eccentric strength measured with a load cell device to a Biodex isokinetic dynamometer with healthy student participants showed a good correlation (r=0.823 – 0.840). The test-retest showed good to excellent reliability of the hamstring eccentric device and concluded that the device was valid and reliable when compare with the 'gold standard' method (Lodge et al., 2020). However, when comparing Isokinetic dynamometry and a Nordic eccentric hamstring load cell device in healthy student athletes assessed with eccentric peak torque, bilateral strength balance and hamstring electromyography; there was a poor correlation between the two methods (r=0.58), with lower values in isokinetic test (∼28%), high TE (∼ 19%), and proportional and systematic differences. The study concluded that these devices are not appropriate to reliably determine bilateral eccentric balance (Wiesinger, Gressenbauer, Kösters, Scharinger, & Müller, 2020). When the reliability of an isokinetic Cybex Norm was assessed using hamstring strength and bilateral strength balance, a study with healthy participants found poor test-retest relative reliability of imbalance ratios (ICC= 0.69) and suggested caution when the results are interpreted in this cohort. In addition the authors recommended that in order to extrapolate these results to other populations, it was necessary to assessing isokinetic test alongside other measures to increase reliability of bilateral strength balance ratios (Impellizzeri, Bizzini, Rampinini, Cereda, & Maffiuletti, 2008). Furthermore, the eccentric hamstring strength measured with a Nordbord was able to identify clinically relevant bilateral strength imbalances that were not identified by isokinetic concentric testing during the first year in patients treated with an ACL reconstruction using a hamstring tendon autograft (Högberg et al., 2022). It could be valuable to compare isokinetic test outcomes to Nordic eccentric strength outcomes specifically in Rugby Union players to determine their interchangeability, which could confirm the validity of using a Nordic load cell device for testing in Rugby Union players.

Regarding the bilateral strength balance ratios, our results showed good intra-session reliability (ICC= 0.62 – 0.89) with good absolute intra-session reliability CV ranging from 4.4%

to 7.2%. The inter-session reliability for mean and maximal values was fair (ICC= 0.52 – 0.54) with good absolute inter-session reliability CV ranging from 8.2% to 9.6%. We found hamstring strength values ranging from 398 to 506 N with bilateral strength balance ratios of 0.98 to 1.0. A study with a load cell device with Nordic eccentric exercises in semi-professional Rugby Union players, showed a peak value of 387.9 ± 81.5 in both legs, and a bilateral strength balance difference of 10 ± 9.8% (M. N. Bourne et al., 2015b). Our results demonstrated greater measures of Nordic eccentric hamstring strength values compared to measures in different sport athletes tested with a cell load device ranging from 321 to 391N, and similar bilateral strength balance ratio ranging from 0.92 to 0.97 (David A. Opar et al., 2013). Regarding strength and imbalances assessed with Nordic eccentric load cell devices, the studies by Wiesinger et al. (2020) and Impellizzeri et al. (2008) agreed that measures of hamstring eccentric strength and bilateral strength balance were acceptable to detect large strength changes. Importantly, it was suggested that these changes are particularly important to clinicians implementing rehabilitation programs, but not appropriate to detect small changes induced by training strategies in athletes or healthy individuals. Identification of normative hamstring strength and bilateral strength balance values is of the upmost for clinicians interested in in Rugby Union to screen and to determine the relationships between specific hamstring strength, imbalances, and hamstring injury risk.

6.5 Conclusion

Assessing the Nordic eccentric hamstring strength and the bilateral strength balance in Rugby players using a load cell device is a feasible method to test and demonstrated good intra-session and fair intersession relative reliability. Absolute reliability is good intrasession (CV ≤

10%) and acceptable intersession (CV ≤ 20%). It could be argued that Nordic eccentric strength assessment is a more practical and functional test than the typically utilised isokinetic assessments, further studies comparing isokinetic testing and Nordic eccentric strength test with a load cell are needed in Rugby Union. Here, we provide data from Rugby Union players to inform clinicians, and to establish normative values in this cohort. Additional research with Nordic eccentric load cell device to improve intersession reliability and stability of measures ensuring an initial familiarisation session, testing players off-season and with further attention to foot and body positions, as well as ensuring the movement is controlled while performing the Nordic exercise is advised.

SECTION 3. Characterisation

CHAPTER 7

Isometric neck strength and eccentric hamstring strength in male and female Rugby Union players

> **Chavarro-Nieto C**, Beaven M, Gill N, Hébert-Losier K. Isometric neck strength and eccentric hamstring strength in male and female Rugby Union players. (*under review*) 2022.

Prelude: This chapter combines all the knowledge gained from the previous chapters, and implements this knowledge in a large cross-sectional study. Specifically, this chapter provides data on isometric neck and Nordic hamstring eccentric strength values from the largest cohort of male and female semi-professional and professional Rugby Union players thus far examined in the literature. This chapter uses the methods most commonly used in the literature (as determined by the two systematic reviews) that were also shown reliable (as determined by the conducted reliability studies). Noteworthy is that the female data presented in this chapter was the first to assess isometric neck strength and hamstring eccentric strength in highly trained female Rugby Union players. The dataset from this large cohort of athletes should assist in the development of evidence-based targeted physical preparation and injury prevention strategies to manage both injured, previously injured, and uninjured Rugby Union players to the neck and hamstring areas. The dataset provides practitioners with an idea of what "normal" neck and hamstring strength values are in male and female Rugby Union players based on position.

7.1 Introduction

Among English professional Rugby Union players, the brain continues to be the most affected area of the body, with concussion being the most frequently diagnosed match injury since 2011 (West et al., 2020a). Data indicate an increasing incidence and severity of concussions across seasons from 2009 to 2020 in the England Rugby Football Union (West et al., 2020a), as well as a decline in cognitive function due to contact actions following a single season in Welsh Rugby Union players (Owens et al., 2021). In women, between 2019 and 2020, neck strain injuries occupied the second place as the most commonly diagnosed match injury (14% of injuries) in Irish Rugby Union (The Irish Rugby Injury Surveillance Project (IRIS), 2019). Clearly, these data indicate that head and neck injuries are of concern in Rugby Union (RU).

In terms of training injuries in the England Rugby Football Union, hamstring strain injuries represented the most common injury (15% of injuries). The impact in terms of playing time lost due to hamstring injuries has increased over the last three years (Kemp et al., 2021), indicating an increasing severity of these injuries. The 2019 Rugby World Cup injury surveillance data showed lower limb injuries accounted for almost 50% of all player absence days. Hamstring strains were the second most common match injury, representing 10% of all match injuries after concussion and caused 467 missed days. Running was the most frequent mechanism of hamstring injury in game (2020). Alongside head and neck injuries, hamstring injuries are of increasing concern in RU.

To prevent musculoskeletal and brain injuries, it is important to identify how individual characteristics relate to contact and non-contact injury incidence. There is a need for a comprehensive understanding of injury epidemiology and the relationship between injury incidence and player characteristics. To this effect, activation and strengthening of the neck muscles before a head impact might be a protective modifiable risk factor preventing concussion in athletes. Necks with greater cross-sectional areas and stiffness can reduce head linear and angular accelerations, displacements, and peak velocities due to impacts (J. T. Eckner et al., 2014). In contact sports, prior activation of neck muscles before a collision has been shown to significantly decrease the peak linear velocity and change in acceleration of the head (J. T. Eckner et al., 2014). Noteworthy is that sex differences in neck and head impacts in university Rugby Union players have been detected using electronic mouthguards (E. M. Williams et al., 2021). Specifically, female players displayed greater whiplash actions during impacts than males. Encouragingly, isometric strengthening of neck muscles in Rugby Union players has been shown to decrease the incidence of neck and head injuries (Naish et al., 2013a). These exercises are also useful during the rehabilitation of injured rugby players, can contribute to informing return to play, and have been shown to increase neck strength in male Rugby Union players subsequent a 6-week training intervention with a hand-held dynamometer (K. Geary et al., 2014). In contrast, there are currently no neck strengthening interventional studies in the literature involving female Rugby Union players (C. Chavarro-Nieto et al., 2021b), and implementing a 13-week isometric neck strengthening programme using a hand-held dynamometer in female football codes (namely soccer and Australian football) resulted in no neck strength gains (Deng, Pearce, Mentiplay, Middleton, & Clarke, 2021). These results combined emphasise the lack of research in neck strength in female

Rugby Union players, and the disparity between neck strength, neck kinematics, and strengthening results in female and male Rugby Union players.

Hamstring strength of female and male Rugby Union players has been assessed using isokinetic tests (generally laboratory-based), and eccentric tests (e.g., laboratory- or gym-based using Nordic drops) (C. D. Chavarro-Nieto et al., 2021). Traditionally, the aim of testing has been to determine imbalances between limbs, profile player performance and injury risk relative to established benchmarks, evaluate training outcomes, and compare different strength test measures (Abdelfettah et al., 2019; Anastasi & Hamzeh, 2011; Beyer et al., 2016; M. N. Bourne et al., 2015b; Brown et al., 2016; Deighan et al., 2012; Dobbs et al., 2017; Mondin et al., 2018; Severo-Silveira et al., 2018). When assessing Nordic hamstring eccentric values with a load cell device, a significant difference in strength between injured and uninjured legs has been reported, with the injured leg weaker than the uninjured leg (M. N. Bourne et al., 2015b). Imbalances of more than 15% between legs were estimated to increase the risk of hamstring injuries by 2.4 times, and imbalances of more than 20% between legs to increase the risk by 3.4 times (M. N. Bourne et al., 2015b). In male professional Rugby Union, hamstring injuries were the most severe injury diagnosed in backs and resulted in 17 days of absence (Brooks, Fuller, Kemp, & Reddin, 2006a). The difference in the susceptibility and incidence of injuries between players and their positions has been reported to warrant the need for position-specific injury profiling to better target physical preparation and injury prevention strategies (Brooks & Kemp, 2011). In Australian Football Rules, research has established an eccentric hamstring strength threshold value of 256 Newtons (N), below which a significant increase in injury risk is observed. However, this generic threshold may be overly simplistic, and could differ with different body mass (heavier and/or taller players can reach 256 N with greater ease than smaller players) (Opar et al., 2015). Therefore, there is a need to establish specific thresholds that are population dependent, with Australian Football Rules thresholds likely not appropriate for Rugby Union.

Given the increasing incidence and severity of concussion and hamstring injuries (West et al., 2020a), the limited data regarding isometric neck strength or Nordic eccentric hamstring strength values in Rugby Union, and the paucity of information regarding bilateral strength balances in male and female Rugby Union players (C. Chavarro-Nieto et al., 2021b; C. D. Chavarro-Nieto et al., 2021), further characterising neck and hamstring strength in both male and female Rugby Union players is warranting. Therefore, we aimed to establish a database of normative isometric neck strength and Nordic eccentric hamstring strength values in professional and semi-professional male and female Rugby Union players.

7.2 Materials and Methods

7.2.1 Participants

A total of 342 Rugby Union players (298 males and 44 females) volunteered to participate. The male participants comprised of 131 professional and 167 semi-professional players, whereas all 44 female participants were semi-professional players (see Table 17 for demographic characteristics). Players were further characterised as forwards (props, hookers, locks, and loose forwards) or backs (inside backs, midfield, and outside backs).

Inclusion criteria required all participants to be free of neck pain, cervical injury, or illness in the last month that could compromise maximal isometric contraction of the neck musculature. Additionally, participants were required to be free of lower limb, lower back, knee, calf, and hamstring injuries, or any illness that could compromise maximal eccentric contraction performance of the hamstring musculature. All participants were informed of the purpose, benefits, and risks of the study through written and oral description and gave their written consent to participate prior to engaging in any activity. The study protocol was approved by the University of Waikato Human Research Ethics Committee (HREC(Health) 2019#74) and adhered to the latest Declaration of Helsinki.

Table 17. Anthropometric characteristics of female semi-professionals and male professional and semi-professional Rugby Union players.

	Females	**Males**		
	Semi-professional (n = 44)	Semi-professional (n = 167)	Professional (n = 131)	All (n = 298)
Age (y)	24.0 ± 4.8	22.4 ± 3.5	24.7 ± 3.5	23.0 ± 3.7
Height SD (cm)	173.2 ± 7.4	186.0 ± 6.8	186.4 ± 7.6	185.5 ± 7.0
Mass (kg)	81.0 ± 15.6	101.6 ± 11.6	106.4 ± 14.0	103.6 ± 12.4

7.2.2 Neck strength assessment

7.2.2.1 Instrumentation

Tests were conducted using a SOUFEI digital portable load cell (SF-912 Soufei Electronic Technology Co., Ltd, China) of 100 g accuracy with the capacity set to 50 kg. The load cell was connected via Bluetooth to an iPad Model A1566 device, and data were recorded at 20 Hz. Intra-session reliability was good-to-excellent (ICC= 0.85 to 0.95), and Inter-session reliability was fair for mean and max values (ICC= 0.51 to 0.69) (Chavarro-Nieto, Beaven, Gill, & Hébert-Losier, 2022).

7.2.2.2 Procedures

Neck strength was assessed in a ‘‘make’’ test fashion in four different directions: flexion, extension, and right and left lateral side flexion (as opposed to a “break” test whereby the resistance is applied to evoke a maximal muscle contraction in all four directions using a head harness attached to a cable and dynamometer or load cell until the initiation of the movement or positional failure). The same examiner supervised all tests. Participants were seated in a standard gym bench chair with the head and neck in a neutral position, with a seat belt attached to the trunk to minimise movement. A head harness was placed around the forehead for flexion, occiput for extension, and temporal bones for side flexion. The harness was attached to the load cell via a rigid cable secured to a fixed metal frame (Figure 11). Two balance air pads were placed under the feet to minimise contribution from the lower limbs. Three submaximal isometric repetitions were performed in each direction prior to the maximal testing. For data collection, players completed three maximal isometric contractions of 5 second duration in each of the four directions tested. The instruction before performing the maximal isometric contractions was “pull as hard as you can with 100% strength and hold for 5 s”. After each repetition, a 30-second rest was given, and 60-second rest was allocated between each direction tested, we followed the same testing direction order for each participant. The peak force in kilograms (kg) was recorded during the maximal isometric hold and used as the main outcome measure.

Figure 10: Illustration of the isometric make neck strength test experimental setup for extension.

7.2.3 Hamstring strength assessment

7.2.3.1 Instrumentation

Tests were conducted using a customised device that contained two load cells (MT501 Meltron Millennium Mechatronics Limited, New Zealand) that measured force from the right and left leg separately with a capacity of 250 kg for each load cell (error < 0.02%, sensitivity 0.08 kg). Load cells were connected via Bluetooth to a tablet (Samsung Galaxy TAB A 10.1" 2018 Tablet 2GB Ram 32GB Storage Wi-Fi Android 9.0 – Black) and data were recorded at 520

Hz. The reliability of Nordic exercises with a load cell device showed good intra-session reliability (ICC= 0.79 to 0.90) and a fair for intersession (ICC= 0.52 to 0.64) for mean and maximal values.

7.2.3.2 Procedures

Eccentric hamstring strength was assessed using a “Nordic” drop. Participants knelt on a platform with the ankles attached to the instrumented device (

Figure **11**). The same examiner supervised all tests. All participants completed a warm-up protocol of 3 submaximal Nordic eccentric exercise repetitions prior to the testing. After the warmup, the players performed three maximal eccentric contractions with a verbal command “fall as far and as slow as you can”. After each repetition a 30-second rest was given. The combined peak force in Newtons (N) was recorded during the Nordic hamstring eccentric exercise, as well as the forces for the individual legs.

Figure 11. Illustration of Nordic eccentric test on a customised load cell device.

7.2.3.3 Statistical analysis

The average of the three trials from isometric neck strength and Nordic hamstring eccentric strength assessments were used for statistical analysis. Isometric neck strength values in each direction were reported in kilograms, and extension-to-flexion and left-to-right side flexion ratios were calculated. For hamstring strength, peak strength data from the left and right legs were averaged, following procedures previously described (Brooks et al., 2006a; Severo-Silveira et al., 2018). Absolute values were reported in Newtons (N) and relative to body mass reported in Newtons per kilogram ($N \cdot kg^{-1}$). Furthermore, bilateral strength balance was calculated as the absolute difference between left and right legs over the left leg strength value expressed as a percentage (%): abs[(left leg – right leg)/left leg]*100]. Mean and standard deviation (SD) values were calculated for all data, and normal distribution of variables confirmed using Shapiro-Wilks's and d'Agostino-Pearson tests (i.e., $p > 0.05$).

In a first instance, a one-way analysis of variance was carried out that compared the strength values between the six subgroups of participants: male professional forwards, male professional backs, male semi-professional forwards, male semi-professional backs, female semi-professional forwards, and female semi-professional backs. In presence of a main effect of group, independent sample t-tests were then applied to compare strength values between playing level (semi-professional and professional) and position (forwards and backs). The alpha level for significance was set at $p \leq 0.05$.

7.3 Results

For all strength variables analysed, the one-way analysis of variance revealed a significant main effect of group ($p < 0.001$). Hence, independent sample t-tests were carried out to further explore positional and level differences.

7.3.1 Isometric neck strength

7.3.1.1 Males

Descriptive statistics related to isometric neck strength values in male semi-professional and professional players are shown in Table 18 alongside positional and level differences. Descriptive data for the forwards (props, hookers, locks, and loose forwards) and backs (inside backs, midfield, and outside backs). Are presented as supplementary material (Table F1 for semi-professionals and Table F2 for professionals).

Male professional players were significantly stronger than semi-professional in all directions except for extension. Across levels, forwards were significantly stronger than backs in all directions. On average for males, the flexion to extension ratio was 0.76 and a lateral side flexion left to right ratio of 1.0.

Table 18. Descriptive and statistics related to isometric neck strength values for male semi-professional and professional players. Values include mean, standard deviation, and t tests for the four different directions examined.

	Semi-professionals				Professionals				Semi-professionals vs professionals			
	Backs	Forwards	t-test	p-value	Backs	Forwards	t-test	p-value	Semi-professionals	Professional	t-test	p-value
Extension (kg)	29.3 ± 6.0	34.0 ± 7.1	t(156.2)=4.5	**0.001***	28.7 ± 6.6	36.2 ± 6.6	t(112.5)=6.0	**<0.001**	31.6 ± 6.9	32.5 ± 7.5	t(272.4)=7.3	0.321
Flexion (kg)	21.6 ± 5.9	26.2 ± 7.5	t(152.3)=1.9	**0.001***	24.8 ± 6.8	30.2 ± 8.4	t(111.3)=3.8	**<0.001**	23.9 ± 8.1	27.5 ± 7.1	t(279.0)=3.9	**<0.001***
Left LF (kg)	21.4 ± 6.5	24.2 ± 7.4	t(159.6)=2.5	**0.001***	22.9 ± 6.4	27.9±11.8	t(113.9)=3.8	**0.001**	22.9 ± 7.0	25.4 ± 7.3	t(274.1)=4.4	**0.004***
Right LF (kg)	21.6 ± 6.6	24.0 ± 7.1	t(160.6)=2.2	**0.002***	21.7 ± 6.7	26.7 ± 7.5	t(112.4)=3.7	**0.001**	22.8 ± 6.9	24.6 ± 7.6	t(271.9)=4.1	**0.042***

* Significant differences (p ≤ 0.05). LF = lateral flexion.

7.3.1.2 Females

Descriptive statistics related to female isometric neck strength values are shown in Table 19 alongside positional differences. Descriptive data for the forwards (props, hookers, locks, and loose forwards) and backs (inside backs, midfield, and outside backs) are presented as supplementary material (Table F3). In females, there were no significant differences between forwards and backs, except in extension where backs were stronger than forwards. On average for females, flexion to extension ratio was 0.83, and lateral side flexion (left to right) ratio was 1.0.

Table 19. Descriptive and statistics related to isometric neck strength values for women players. Values include mean, standard deviation, and t tests for the four different directions examined.

	Females			
	Backs (SD)	**Forwards (SD)**	**t-test**	**p-value**
Extension (kg)	16.4 ± 6.0	21.0 ± 6.1	t(27.8)=3.1	**<0.003***
Flexion (kg)	14.0 ± 5.0	14.0 ± 6.1	t(27.9)=0.9	0.953
Left lateral flexion (kg)	16.9 ± 5.5	16.3 ± 6.4	t(27.6)=0.36	0.722
Right lateral flexion (kg)	17.1 ± 5.6	16.4 ± 6.1	t(27.9)=1.45	0.422

* Significant differences ($p \leq 0.05$)

7.3.2 Nordic eccentric hamstring strength and bilateral strength balance

7.3.2.1 Males

Descriptive statistics related to eccentric hamstring strength values in male semi-professional and professional players are shown in Table 20 alongside positional and level differences. Descriptive data for the forwards (props, hookers, locks, and loose forwards) and backs (inside backs, midfield, and outside backs) are presented as supplementary material (Table F4 for semi-professionals and Table F5 for professionals).

There was a significant difference in Nordic eccentric absolute strength between levels for both absolute ($t(280.4)=2.07$, $p = 0.038$) and relative to body mass ($t(179.1)=3.5$, $p < 0.001$) strength values (Table 20). In both cases, professionals were stronger than semi-professionals. In terms of positional differences, forwards were significantly stronger than backs ($t(289.3)=3.57$, $p < 0.001$) in absolute terms. However, backs were significant stronger than forwards ($t(174.5)=0.463$, $p < 0.001$) in relative terms (Table 20).

Table 20. Descriptive related to men eccentric hamstring strength. Values include mean, standard deviation, and examined Nordic hamstring strength variables for each level of competition and player position.

	Semi-professionals				Professionals				Semi-professionals vs professionals			
	Backs	Forwards	t-test	p-value	Backs	Forwards	t-test	p-value	Semi-professionals	Professional	t-test	p-value
Absolute (kg)	416.2 ±107.7	423.3 ± 97.4	t(164.7)=1.9	**0.05***	426.5 ±112.3	441.3 ± 81.2	t(117.6)=3.0	**0.002***	398.7 ± 97.2	422.1±96.1	t(280.4)=2.0	**0.038***
Relative ($N \cdot kg^{-1}$)	4.1± 1.0	4.06 ± 0.9	t(161.2)=1.8	**0.06***	3.5 ± 2.7	4.05 ± 0.82	t(59.2)=4.6	**0.001***	3.87 ± 0.9	4.57 ± 2.05	t(179.1)=3.5	**<0.001***
Strength balance (%)[a]	10.34 ± 9.0	10.26 ± 7.0	t(160.3)=0.07	0.94	9.2 ± 7.0	11.18 ± 8.11	t(104.1)=1.2	0.205	10.3 ± 9.0	10.4 ± 4.6	t(254.2)=0.1	0.898

* Significant differences ($p \leq 0.05$).

[a] Difference between left and right legs over the left leg strength value expressed as a percentage (%): abs[(left leg – right leg)/left leg]*100].

7.3.2.2 Females

Descriptive statistics related to eccentric hamstring strength values in female semi-professional players are shown in Table 21 alongside positional and level differences. Descriptive data for the forwards (props, hookers, locks, and loose forwards) and backs (inside backs, midfield, and outside backs). Are presented as supplementary material (Table F6). There were no significant differences between forwards and backs in absolute values (t4.2)=1.2, p=0.27), as well as in relative to body mass (t(2.9)=1.8, p=0.15) (Table 21).

Table 21. Descriptive related to women eccentric hamstring strength values by player position. Values include mean and standard deviation.

	Females			
	Backs	Forwards	t-test	p-value
Absolute (kg)	262.6 ± 53	299.7 ± 63.2	t(4.2)=1.2	0.27
Relative ($N \cdot kg^{-1}$)	3.3 ± 0.4	3.2 ± 0.8	t(2.9)=1.8	0.15
Strength balance (%)[a]	11.2 ± 7.0	10.5 ± 9.0	t(160.3)=0.07	0.94

7.4 Discussion

We aimed to establish a database of normative values for isometric neck strength and Nordic eccentric hamstring strength and bilateral strength balance values in Rugby Union players including female and male players. Regarding neck strength values for males across directions, our results showed that mean values for professionals ranged from 22 to 39 kg and in semi-professional players, from 20 to 35 kg. Male professional players were stronger in in all directions than semi-professional players except in extension . Forwards (range: 22 to 39 kg) possessed greater neck strength compared to backs (range: 22 to 31 kg) in all directions tested. Previous research with similar protocols conducted in professional Rugby Union players showed mean values ranging from 29 to 39 kg in flexion, extension, and bilateral side flexion (Naish et al., 2013a). When semi-professional Rugby Union players were tested using a mounted handheld dynamometer, mean values ranged from 17 to 23 kg for flexion, extension and bilateral flexion (Ashall et al., 2021). In amateur players, when the participants were tested in a scrummaging position in four different directions with a load cell and a fixed-frame dynamometer, mean values ranged from 17 to 34 kg (Salmon et al., 2018). In the literature, studies in Rugby Union have assessed neck strength by playing position comparing forwards and backs (Geary et al., 2013; D. F. Hamilton & Gatherer, 2014a; Konrath & Appleby, 2012; Olivier & Du Toit, 2008; Salmon et al., 2018). Across these studies, forwards were stronger than backs, although not in all directions. For instance in amateur players, and in agreement with our results, forwards were stronger compared to backs in all four directions tested (Olivier & Du Toit, 2008); whilst in a different study at the same level of play, forwards were stronger only in extension than backs (Geary et al., 2013). In professionals, a study in the 'make' test fashion assessed neck strength with a customised neck device with a load cell and 219velcro head strap and reported significantly stronger necks in extension and flexion for forwards (range: 30 to 33 kg) than backs (range: 23 to 24 kg) (Konrath & Appleby, 2012). Differences between studies may be linked with testing methods, as well as sample size. Our study had a considerably large sample size, and hence able to detect differences between positions with a greater power.

To our knowledge, this the first study examining the isometric neck strength in female Rugby Union players. The test performed in a make test manner used a rigid cable, a head harness with load cell device in a seated position. Our results indicate forwards and backs exhibited similar neck strength values that ranged from 14 to 23 kg, except for extension values. We observed a significant difference in neck extension strength with stronger backs (mean:21kg) than forwards (mean: 16.4kg). Overall, female players showed greater values for extension (range: 19 to 23 kg) compared to other directions tested. Here, we provide data from male semi-professional, and professional, as well as with female Rugby Union players to inform practice, and to establish values for clinicians interested in rehabilitation and return to play protocols, to standardise a method of testing in a make test fashion with a load cell device in a seated position.

Regarding ratios of neck strength, the flexion to extension ratio for males was 0.76 on average and 1.0 for the left-to-right side flexion ratio. Similar to our results, the flexion-to-extension ratio in professional Rugby Union players in a make test fashion with a load cell device via cable in a seated position ranged from 0.75 to 0.76; whereas left-to-right ratio ranged from 0.96 to 1.0 (Naish et al., 2013a). In the literature, flexion-to-extension ratio performed in the 'break' test and isokinetic test fashion ranged from 0.65 to 0.7 and were slightly greater than those presented here (D. F. Hamilton & Gatherer, 2014a, 2014b). Results of previous studies at different levels of competition have shown greater values in extension compared to flexion (C. Chavarro-Nieto et al., 2021b). Age-grade players also had lower flexion-to-extension ratio than senior players, with lesser neck flexor strength (41%) compared to senior players, and forwards exhibiting lower ratio than backs (Konrath & Appleby, 2012; Olivier & Du Toit, 2008), suggesting that forwards have greater extension strength relative to flexion strength. Regarding flexion to extension ratio in females, the results showed a ratio of 0.81, and a bilateral side ratio of 1.0. Extension was stronger compared to all directions tested. We establish here a benchmark for practitioners interested in implementing strengthening routines to increase neck strength and to decrease imbalances ratios. Strengthening the neck has the potential to significantly reduce medial and lateral angular and linear accelerations of the head in players, as shown in players with stronger flexion and extension necks (Duma et al., 2005). Our neck strength and ratio values are similar with those noted in a previous study using a comparable methodology in professional Rugby Union players, whereby a reduction in match neck injuries was observed after an intervention program with neck strengthening strategies (Naish et al., 2013a).

For the Nordic eccentric hamstring strength test, the results revealed stronger professionals (422.1 ± 96.1 N) than semi-professionals (398.7 ± 97.2 N) in terms of absolute strength. When relative eccentric strength to mass was assessed, professionals (4.57 ± 2.05 $N \cdot kg^{-1}$) were stronger than semi-professionals (3.87 ± 0.98 $N \cdot kg^{-1}$). When position was assessed, forwards (426.8 ± 89.3 N) were significantly stronger than backs (387.2 ± 95.6 N). However, when expressed relative to mass, backs (4.67 ± 1.87 $N \cdot kg^{-1}$) were significantly stronger than forwards (3.78 ± 0.87 $N \cdot kg^{-1}$). In the literature only one study assessed Rugby Union players performing Nordic hamstring eccentric strength test with a load cell device (C. Chavarro-Nieto et al., 2021b), and displayed values for elite professional of 366 ± 76 N, sub-elite players of 387 ± 96 N, and under 19s players of 342 ± 81 N, with no significant differences between levels; while forwards displayed values of 388 ± 95 N and backs of 353 ± 74 N (M. N. Bourne et al., 2015b). When relative eccentric strength to mass was assessed, the elite displayed values of 3.65 ± 0.7 N·kg^{-1}, sub-elite of 4.0 ± 0.9 N·kg^{-1}, and under 19s of 4.0 ± 0.9 N·kg^{-1}, and forwards 3.8 ± 0.9 N·kg^{-1}and backs 3.9 ± 0.8 N·kg^{-1}. The aforementioned study also examined injured and uninjured players and indicated that weaker players (bilateral average < 267.9 N or 3.18 N·kg^{-1}) were at a similar risk of sustaining a hamstring injury than stronger players (M. N. Bourne et al., 2015b). As the aetiology of hamstring strain injuries is multifactorial, with playing position, fatigue, previous injuries, leg imbalances, lack of readiness to return to play, and running actions identified as contributing factors across levels (C. Chavarro-Nieto, M. Beaven, N. Gill, & K. Hébert-Losier, 2021a). Combining strategies to prevent hamstring injuries and recurrences, and to inform return to play, is likely worthwhile and should include Nordic strength assessment and Nordic exercises, high-speed running routines, running biomechanical assessments, and warm-up routines (C. Chavarro-Nieto et al., 2021a).

To our knowledge this is the first study determining Nordic eccentric hamstring strength values in female Rugby Union players, the strength values ranged from 226 ± 41 N to 320 ± 0 N and relative to mass from 2.8 ± 0.5 N·kg^{-1} to 3.8 ± 0.6 N·kg^{-1}. When position was assessed, forwards showed a range from 255 ± 107 N to 320 ± 0 N whilst values for backs ranged from 226 ± 41 N to 295 ± 65 N, with no significant difference between the playing positions. Nordic eccentric strength assessment with a portable load cell device or a Norbord™ is a more feasible and functional test than isokinetic testing (gold standard test). We provide data from Rugby Union players to inform clinicians, and to establish values in this cohort. However, a systematic review and meta-analysis of different devices measuring hamstring eccentric strength in different sports concluded that the Norbord™ as the most common device to test hamstring function, and advised caution when assessing hamstring peak strength and imbalances to estimate hamstring injury risk, thus, not to use it as the only tool; however, the review did recommend the Nordbord^{TM} as a tool to assess in-season neuromuscular status of players [48].

Considering bilateral strength balance, professional players had a balance ranging from 7.0 ± 7.0% to 12 ± 10%, whist semi-professional balance ranged from 9.0 ± 9.0% to 12.0 ± 7.0%. Our results coincided with the bilateral strength balance results from the study with healthy uninjured Rugby Union players 10.0 ± 9.8% performing Nordic hamstring eccentric test with a load cell device (M. N. Bourne et al., 2015b). When the study assessed injured players, the bilateral strength balance was 17.9 ± 16.1% and the group found significant differences in strength between injured and uninjured limbs, with weaker limb in injured than uninjured limb, the incidence of hamstring strain injuries of backs were nearly three times greater than forwards (Brooks et al., 2005a). The female bilateral strength balance results ranged from 8.0 ± 3.8% to 15.0 ± 10%. A previous study in female Rugby Union players, assessed bilateral strength balance with isokinetic test prior to an intervention programme with Nordic exercises (Anastasi & Hamzeh, 2011). Following a 10-week Nordic hamstring training intervention, the bilateral strength balance improved from a baseline of 10.3 % to 4.6% after the intervention. The current bilateral strength balance results may well correspond to data for uninjured male and female Rugby Union players, therefore, could be used for screening players in preseason for injury risk.

7.5 Conclusion

We provide data of normative isometric neck and hamstring Nordic eccentric strength values from male professional, male semi-professional, and female semi-professional Rugby Union players to inform practice. In addition, our study is the first to assess isometric neck strength and hamstring eccentric strength in women's Rugby Union players. We establish values for practitioners interesting in rehabilitation, return to play protocols, and strengthening routines to decrease injury risk, with two feasible methods of testing with load cell devices.

SECTION 4. Intervention

CHAPTER 8

Effect of 6-week Nordic eccentric training with or without feedback on hamstring strength and bilateral strength balance in Rugby Union players – A randomised control trial.

Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Effect of 6-week Nordic eccentric training with or without feedback on hamstring strength and bilateral strength balance in Rugby Union players – A randomised control trial. (*under review*) 2022.

Prelude: This chapter presents the results of a randomised-controlled trial conducted with semi-professional Rugby Union players. The trial aimed to evaluate the effectiveness of an isometric and Nordic eccentric hamstring strengthening programme to increase hamstring strength and decrease bilateral strength imbalances using feedback and non-feedback strategies. The method used to assess hamstring strength in this chapter was the same as the previous chapter, and therefore informed from the previously presented literature review and reliability study.

8.1 Introduction

Hamstring strain injuries are one of the most common injuries in Rugby Union and represent 6 to 15% of all injuries in professional Rugby Union players (M. N. Bourne et al., 2015b; Brooks et al., 2006a). Professionals sustain four times more hamstring strain injuries than amateurs, with recurrent injuries accounting for 23% of hamstring injuries in professional players with more days lost (25 days) compared to new injuries (17 days) (Brooks et al., 2006a). Running has been identified as the most common action to cause hamstring injuries across all levels of competition (Brooks et al., 2006a; Kenneally-Dabrowski, Serpell, et al., 2019a). The aetiology of hamstring strain injuries in Rugby Union is multifactorial, with playing position, fatigue, previous injuries, leg strength imbalances, lack of readiness to return to play, and running actions identified as contributing factors to hamstring strain injuries across playing levels in the scientific literature (C. D. Chavarro-Nieto et al., 2021).

Modifiable risk factors for Rugby Union hamstring injuries have been identified. For instance, there is a significant relationship between bilateral Nordic eccentric strength imbalance of the hamstring muscles when returning to play and sustaining a recurrent injury (M. N. Bourne, Opar, Williams, Al Najjar, & Shield, 2016). Specifically, greater than 15% of hamstring strength imbalance between legs has been reported to increase the risk of hamstring injuries by 2.4 times; and an imbalance greater than 20% to increase the risk by 3.4 times (M. N. Bourne et al., 2015b). Accordingly, hamstring strengthening strategies with Nordic eccentric exercises have been implemented in male and female Rugby Union players (Anastasi & Hamzeh, 2011; Brooks et al., 2006a; Severo-Silveira et al., 2018), with improvements in hamstring strength and side-to-side balance measures observed in females (Anastasi & Hamzeh, 2011), and reductions in hamstring injury incidence and severity in both training and matches in males (Brooks et al., 2006a). Unfortunately, there are no standardised hamstring strengthening protocols used across Rugby Union studies to provide a one-size-fits-all recommendation. In general, these strengthening protocols incorporate progressive training sets, repetitions, and loads of eccentric Nordic exercises (Anastasi & Hamzeh, 2011; Severo-Silveira et al., 2018), with some adding stretching and other strengthening exercises in addition to eccentric Nordic exercises (Brooks et al., 2006a).

Magnetic resonance imaging of hamstring injuries in professional Rugby Union players identify the biceps femoris long head fascicle as the most commonly injured hamstring muscle (73%), with this injury occurring most frequently while running (77%) (Kenneally-Dabrowski, Serpell, et al., 2019b). Nordic eccentric exercises have been shown to increase the cross-sectional area and length of the biceps femoris and length of the semitendinosus fascicles in recreational male athletes and Rugby Union players (Matthew N Bourne et al., 2017; Severo-Silveira et al., 2018). Nonetheless, there is concern around Nordic eccentric hamstring exercises among practitioners and athletes with regards to the undesirable effects of this type of contraction, such as delay-onset muscle soreness (DOMS) and muscle damage, which are less significant with isometric or concentric exercises (Chen et al., 2018). However, the benefits of eccentric exercises should outweigh these concerns. For instance, a randomised-controlled trial in football players compared performing Nordic eccentric hamstring exercises against concentric hamstring curl exercises and found that Nordic eccentric routines increased isokinetically-measured eccentric (+11%), isometric (7%), and hamstring-to-quadriceps strength measures, whilst no changes were detected in the concentric group (Mjølsnes, Arnason, Østhagen, Raastad, & Bahr, 2004).

Visual feedback during isokinetic testing of the quadriceps has been shown to enhance maximal strength outputs, leading to recommendations in favour of using feedback during isokinetic strength testing for valid results and maximal efforts (Kellis & Baltzopoulos, 1996a). Previous studies have investigated the effect of feedback versus non-feedback training on jump and sprint performances in Rugby Union players, with significant improvements in performance seen in the feedback group (Randell, Cronin, Keogh, Gill, & Pedersen, 2011). In Rugby Union players, verbal feedback used during a bench throw power strength test resulted in *small* effect size increases in mean peak power and velocity compared to no feedback (Argus, Gill, Keogh, & Hopkins, 2011). Since resistance training can induce beneficial changes in muscle properties likely to impact the modifiable risk factors linked with hamstring injuries, maximising the potential effect of resistance training is desirable. Therefore, there is justification for hypothesising that combining eccentric strengthening with feedback might be an effective tool in preventing injuries in sports, more so than eccentric strengthening alone. This randomised-controlled trial aimed to examine the effect of a six-week Nordic eccentric and isometric hamstring exercise programme performed with and without visual feedback on hamstring eccentric peak strength and bilateral strength balance in male Rugby Union players, whilst including a training as usual control group. We hypothesised superior gains in the feedback than non-feedback group, with both groups experiencing greater gains than the control group.

8.2 Materials and Methods

8.2.1 Participants

We conducted a randomised-controlled study. Sample size was based on previous experiments examining the effect of two Nordic hamstring exercise training programmes in Rugby Union players that involved ten players per group, identifying moderate-to-large effect size differences between training groups across strength measures examined (Cohen's *d* range: 0.39 to 0.62, $p < 0.05$) (Severo-Silveira et al., 2018).

Thirty male Rugby Union players from two semi-professional local rugby teams agreed to participate in the current study [mean ± standard deviation (SD), age 23.2 ± 3.1 y, height 184.0 ± 6.7 cm, and body mass 100.2 ± 11.1 kg], see Table 28. Twenty players from one team were randomly assigned to one of two hamstring strengthening interventions (*feedback* or *non-feedback*). These two groups of ten players performed a six-week hamstring strengthening routine that incorporated eccentric Nordics and isometric exercises. The *feedback* group received real-time visual feedback on their maximal eccentric strength, whereas the *non-feedback* group received no feedback during their hamstring exercises. Ten players from the second team acted as controls and completed their usual training with no prescribed hamstring exercises. Both teams competed at the same level of competition and continued their habitual in-season training routines. There was no significant difference in player characteristics between *feedback*, *non-feedback*, and *control* groups based on repeated measures analysis of variance (RM ANOVA, $p > 0.05$).

Table 22. Anthropometric characteristics of the three groups (mean ± SD).

Characteristics	**Feedback (n = 10)**	**Non-feedback (n = 10)**	**Control (n = 10)**
Age (y)	23.9 ± 2.9	23.9 ± 3.6	21.9 ± 2.3
Mass (kg)	97.2 ± 7.8	98.0 ± 11.8	105.4 ± 12.4
Height (cm)	181.0 ± 5.4	185.0 ± 8.3	186.1 ± 5.7

Inclusion criteria required participants to be free of pain, lower extremity injuries, back injuries, or illness that could compromise maximal hamstring eccentric contractions. All participants were informed of the purpose, benefits, and risks of the study through written and oral description, and gave their written consent prior to engaging in any activity. The University of Waikato Human Research Ethics Committee (HREC(Health) 2019#74) approved the study protocol, which complied with the Declaration of Helsinki.

8.2.2 Instrumentation

Tests were conducted using a customised device that contained two load cells (MT501 Meltron Millennium Mechatronics Limited, New Zealand) that measured force from the right and left legd separately with a capacity of 250 kg for each load cell (error < 0.02%, sensitivity 0.08 kg). Load cells were connected via Bluetooth to a tablet (Samsung Galaxy TAB A 10.1" 2018 Tablet 2GB Ram 32GB Storage Wi-Fi Android 9.0 – Black) and data were recorded at 520 Hz.

8.2.3 Procedures

8.2.3.1 Hamstring strength assessment

All participants completed a baseline (*Pre*) and post-intervention (*Post*) testing session six weeks later with the lead researcher (CCN). To assess hamstring eccentric strength, participants knelt on a platform with the ankles attached to a metal hook connected to the load cells of the custom-built device (Figure 13). The participants received real-time visual feedback with regards to their peak strength (N) and bilateral strength balance (%) to maximise performance (Figure 13). Prior to testing, all participants completed a warm-up protocol of three submaximal Nordic eccentric exercise repetitions with a verbal command to "free fall". After three submaximal warm-up repetitions, the players performed three maximal eccentric contractions with a verbal command to "fall as far and as slow as you can". After each repetition, a 30-second rest was allowed**.**

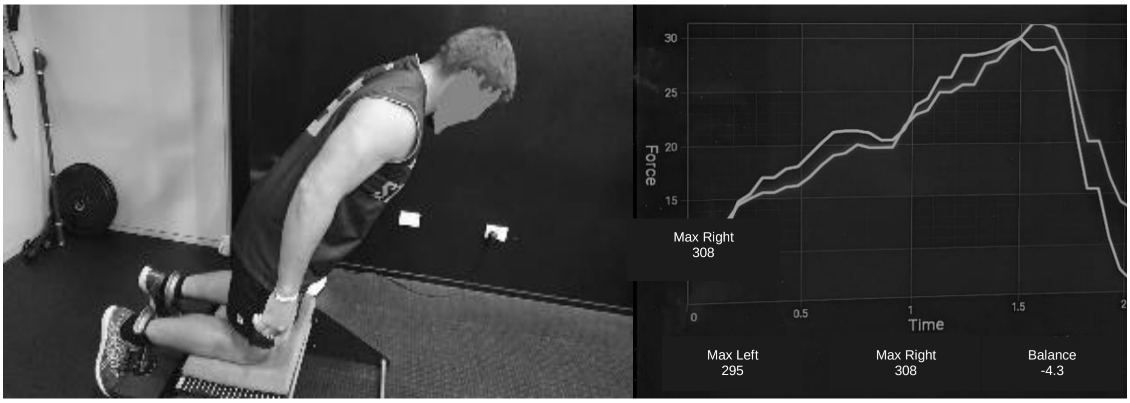

Figure 12. Illustration of the Nordic eccentric test performed using load cell devices and real-time visual display of peak hamstring strength (N) and bilateral strength balance (%) values.

8.2.3.2 Hamstring training intervention

Feedback and *non-feedback* groups undertook a familiarisation session in the week prior to the start of the intervention during which their respective strengthening programmes were explained to them and proper execution of exercises was verified. Both the *feedback* and *non-feedback* groups continued with their normal exercise routines and added Nordic eccentric strengthening and hamstring isometric exercises. These exercises were performed once a week each in two separate sessions. Their repetitions maximum (RM) was tested in the first training session, and the initial training load was based on this test following a previous protocol (Mjølsnes et al., 2004). The Nordic exercises were performed in a similar manner to the *Pre* and *Post* strength assessments (Figure 14). The isometric exercise consisted of a prone plank-hold with activation of the hamstring muscles. Participants knelt in a quadruped position with palms on the floor under their shoulders, and contracted their hamstring muscles isometrically in an upward direction against the hooks for 10 seconds to assess peak force (Figure 15). The isometric exercises as part of the training programme was performed in a similar manner for the *feedback* group, whereas the non-feedback group performed the isometric exercise using an incline bench, contracting their hamstrings isometrically against the pads. The strength training sessions were progressed weekly to ensure incremental increases in load. For the *feedback* group, progression was based on the measured peak force and the target to achieve was given with visual feedback whilst performing the exercise. For the *non-feedback* group, progression was based on perceived effort, per the outlined training schedule shown in Table 29. The *feedback* group completed these two exercises on the load cell platform and received real-time visual feedback on their performance (Figure 14 and Figure 15). The *non-feedback* group performed these exercises using a multi-workout incline bench (Figures 14 and Figure 15). The lead researcher and the Strength and Conditioning staff of the players supervised all training sessions.

Table 23. Training protocol for the hamstring eccentric Nordic and isometric exercises.

Week	Sessions per week	Sets and repetitions	Load (% of 1 RM)
1	1	2 x 5	70%
2	1	2 x 5	75%
3	1	2 x 5	80%
4	1	2 x 5	90%
5	1	2 x 5	100%
6	1	2 x 5	100%

Figure 13. Illustration of the Nordic hamstring eccentric exercises performed on an incline bench (left image) and using the load cell device (right image) for the non-feedback and feedback group, respectively.

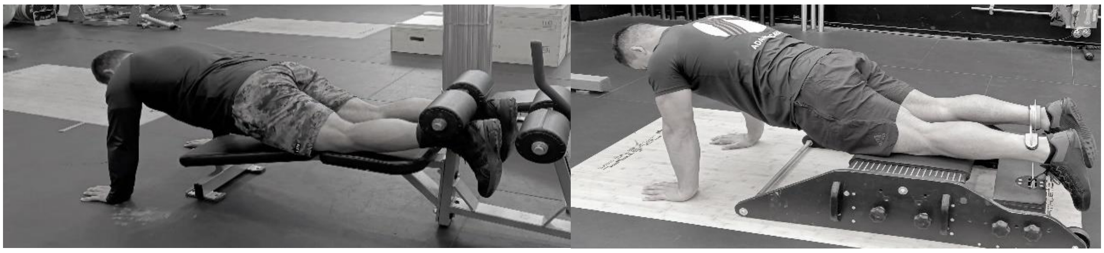

Figure 14. Illustration of isometric exercise performed on the incline bench (left image) and using the load cell device (right image) for the non-feedback and feedback groups, respectively.

8.2.4 Statistical analysis

The average of the three trials from *Pre* and *Post* strength assessments were used for statistical analysis. Peak eccentric strength data from the left and right legs were averaged for the peak strength value, following procedures previously described (Brooks et al., 2006a; Severo-Silveira et al., 2018). The bilateral strength balance was calculated as the absolute difference between left and right legs over the left leg strength value expressed as a percentage: abs[(left leg – right leg)/left leg]*100] . Means and SD values were calculated for all data for the three groups separately, and normal distribution of variables confirmed using Shapiro-Wilks's and d'Agostino-Pearson tests (i.e., $p > 0.05$).

Differences within and between groups in peak eccentric strength and bilateral strength balance measures were examined using a two-way RM ANOVA that considered time (*Pre, Post*), group (*feedback*, *non-feedback*, *control*), and their interaction (time x group). A significant interaction effect would reflect differences in response between groups from *Pre* to *Post* timepoints. In presence of a significant effect, Bonferroni-adjusted pairwise comparisons were undertaken and the magnitude of differences within and between groups quantified using Cohen's *d* effect size (ES) values and 95% confidence intervals [lower, upper]. For within-group comparisons, Cohen's *d* for paired samples using an average variance was used, whereas conventional Cohen's *d* was computed for between-group differences. Effects were considered trivial when $d < 0.20$, small when $d \geq 0.20$, moderate when $d \geq 0.50$, and large when $d \geq 0.80$ (Cohen, 2013). The alpha level for significance was set at $p \leq 0.05$ for all analysis with statistical analyses performed using Microsoft Excel 2019 (Microsoft Corp., Redmont, WA, USA) and STATA version 16.1 (StatCorp, College Station, TX, USA).

8.3 Results

Descriptive data of *Pre* and *Post* measures for peak strength and bilateral strength balance per group are shown in Table 30 alongside RM ANOVA results. A graphical representation of the descriptive data is provided as supplementary material (Appendix F1).

The RM ANOVA time x group interaction was not significant for both peak strength and bilateral strength balance measures, indicating similar changes between groups from *Pre* to *Post* timepoints. In addition, there was no main effect of time on outcomes, indicating no significant difference in strength or balance from *Pre* to *Post* timepoints. There was a significant main effect of group on peak strength, with controls identified as being significantly weaker than the other two groups during post-hoc pairwise comparisons. The *non-feedback* and *feedback* groups showed similar peak eccentric strength values ($p = 1.000$) and were 94.0 N [43.9, 144.0] (ES 1.40 [0.70, 2.10]) and 89.3 N [39.0, 139.1] (ES 1.39 [0.69, 2.08]) stronger than *controls,* respectively. There was no significant main effect of group on bilateral strength balance measures.

Table 24. Pre and Post assessment values for peak eccentric strength and bilateral strength balance for each group, and repeated measures analysis of variance (RM ANOVA) outcomes.

	Pre-intervention Mean (SD)			Post-intervention Mean (SD)			RM ANOVA		
							Time	**Group**	**Interaction**
	FEED	NFEED	CTRL	FEED	NFEED	CTRL	F (p-value)	F (p-value)	F (p-value)
Peak eccentric strength (N)[a]	475.8 (57.1)	484.4 (20.7)	385.7 (24.5)	465.5 (61.7)	466.8 (20.6)	377.5 (20.1)	3.30 (0.080)	7.05 (0.003)*	0.18 (0.836)
Bilateral strength balance (%)[b]	12.1 (1.8)	12.3 (2.3)	10.5 (2.6)	8.9 (1.7)	7.2 (1.4)	10.1 (1.8)	3.68 (0.065)	0.05 (0.947)	0.83 (0.448)

[a] Mean of right and left leg. [b] abs[(left leg – right leg)/left leg]*100]. *Significant effect ($p \leq 0.05$). CTRL: control; FEED: feedback; NFEED: non-feedback; RM ANOVA: repeated measures analysis of variance; SD: standard deviation.

8.4 Discussion

We aimed to examine the effect of a six-week progressive Nordic eccentric and isometric hamstring training programme performed with and without visual feedback on hamstring eccentric strength and bilateral strength balance measures in male Rugby Union players, whilst including a control group. Our results refute our hypothesis of superior gains in the feedback than non-feedback group, with none of the groups experiencing gains. Although controls showed no change in peak eccentric hamstring strength and bilateral strength balance measures over six weeks, neither did the Rugby Union players following a progressive six-week strength training programme, regardless of whether players were provided with visual feedback or not.

Our results showed no significant improvements in hamstring strength when performing a total of 60 Nordic eccentric repetitions (10 repetitions/week) and 60 isometric hamstring repetitions (10 repetitions/week) over a six-week period. It could be that this prescription of hamstring exercise was insufficient to increase hamstring strength and to reduce bilateral strength imbalances in semi-professional male Rugby Union players when undertaken in a regular season, despite existing literature in Rugby Union suggesting otherwise (Anastasi & Hamzeh, 2011; Brooks et al., 2006b; Severo-Silveira et al., 2018). In male professional Rugby Union players, an eight-week progressive training programme with a total of 70 repetitions of Nordic eccentric exercises across the eight weeks (~9 repetitions/week) resulted in significant improvements in hamstring concentric and eccentric peak torque, increases in isokinetic hamstring-to-quadriceps ratio, as well as an increase in the biceps femoris long head fascicle length and thickness, with no significant changes observed in players allocated a constant training load (Severo-Silveira et al., 2018). In female Rugby Union players, a 10-week progressive training programme resulted in a significant improvement in hamstring concentric isokinetic peak torque and bilateral strength balance with a total of 90 repetitions across 10 weeks (average nine repetitions per week) (Anastasi & Hamzeh, 2011). A progressively loaded Nordic eccentric exercise training programme in recreational active male athletes of low-volume (total 48 repetitions across six weeks, average eight repetitions per week) was sufficient to increase Nordic eccentric hamstring strength, but was insufficient to increase the biceps femoris fascicle length and cross-sectional area (Behan et al., 2022). When comparing the effectiveness of low (10 repetitions per week) vs high (40 repetitions per week) volume of hamstring eccentric exercises performed over six weeks in football players, training volume was not a key determinant of hamstring strength (Lacome et al., 2020). In our *feedback* and *non-feedback* intervention groups, hamstring strength was greater than controls; therefore, it is plausible that the programme had a strength maintenance effect in a pre-conditioned group of athletes rather than a conditioning effect. The intervention group might of experienced a prior ceiling effect with regards to hamstring strength compared to controls (Lacome et al., 2020). As such, it remains unclear what prescription of Nordic eccentric exercise would be appropriate in pre-conditioned professional and semi-professional male Rugby Union athletes to increase hamstring eccentric strength and to decrease imbalances.

We found no significant changes in hamstring eccentric strength or bilateral strength balance following a six-week intervention, regardless of whether real-time visual feedback was provided or not. Acute real-time visual feedback has been shown effective to increase eccentric isokinetic hamstring and quadricep strength (Kellis & Baltzopoulos, 1996a), with acute real-time visual feedback using Nordic eccentric exercises previously implemented in male cricket players (Chalker, Shield, Opar, Rathbone, & Keogh, 2018). The latter crossover study observed that providing visual feedback across two sessions led to significant increases (*small* ES) in hamstring strength, particularly in the weaker leg, whereas providing no feedback during eccentric exercises did not lead to strength gains (Chalker et al., 2018). Similarly, *small* improvements were observed in a bench throw power strength test acutely when verbal feedback was supplied compared to no feedback in professional Rugby Union players (Argus et al., 2011). In professional Rugby Union players, a six-week real-time visual feedback intervention was shown to be effective in enhancing performance, with *small* to *moderate* improvements in peak velocity of vertical and horizontal jump performances compared to non-feedback (Randell et al., 2011). Based on this literature, we anticipated feedback training to lead to superior strength gains than non-feedback training. Previous studies assessing Nordic hamstring eccentric strength in male Rugby Union players with a load cell device reported mean peak strength values of 366 N, 387 N, and 342 N for professionals, semi-professional, and under-19 players, with no significant differences between levels (M. N. Bourne et al., 2015b). Our semi-professional players in the *control* group averaged 382 N, whereas those in the *feedback* and *non-feedback* groups averaged 471 and 476 N, respectively. On this basis, it appears that our semi-professional male Rugby Union players in the intervention groups were stronger and might have required a more aggressive intervention to induce further gains, regardless of feedback strategy.

Regarding hamstring bilateral strength balance, there was a non-significant reduction in imbalances in the *feedback* group from 12.1% to 8.9% (Δ 3.2%) and *non-feedback* group from 12.3% to 7.2% (Δ 5.1%), with nearly no change in the *control* group (i.e., 10.5% to 10.1%, Δ

0.4%)). In female Rugby Union players, following a 10-week Nordic eccentric hamstring training intervention significantly reduced bilateral strength imbalances from 10.3 % to 4.6% (Δ 5.7%) (Anastasi & Hamzeh, 2011). In a prospective cohort study involving professional and local club male Rugby Union players, injured players demonstrated significantly greater between-limb imbalances in peak eccentric strength (mean: 17.4%) during pre-season testing compared to uninjured players (mean: 10.0%) (M. N. Bourne et al., 2015b). A between-limb eccentric strength imbalance of 15% or greater increased hamstring strain injury risk by 2.4-fold, whereas an imbalance of 20% or greater increased the risk by 3.4-fold (M. N. Bourne et al., 2015b). Although the reduction in strength imbalances seen in our intervention groups were not statistically significant, the reduction could have hamstring injury risk mitigation ramifications. That said, it remains uncertain whether improving these ratios would actually reduce hamstring incidence in Rugby Union players (David A. Opar et al., 2021). A meta-analysis of studies found no strong evidence that any isokinetic ratio, at any speed or contraction mode, was associated with the risk of hamstring injuries (Freckleton & Pizzari, 2013b). Nordic eccentric strength assessments are more feasible to implement in sports and more functional than isokinetic testing. Although Nordic strength assessments can be used as a mean to assess the neuromuscular status of players in-season, it remains unclear whether bilateral strength balance from this assessment method is a reliable estimator of injury risk, which is exacerbated due to the inconsistencies in testing methods and parameters used across the literature (C. D. Chavarro-Nieto et al., 2021).

Despite finding no significant improvements in peak hamstring eccentric strength measures or bilateral strength balance subsequent the six-week intervention programme, Nordic exercises should not be considered useless in Rugby Union. Indeed, there is a high incidence of hamstring injuries in Rugby Union (Brooks et al., 2006a; Tondelli, Boerio, Andreu, & Antinori, 2021). Players performing Nordic eccentric exercises in addition to stretching and habitual strengthening exercises once a week, with two sets of approximately six repetitions, had a lower incidence of hamstring injuries compared to players performing habitual strengthening exercises alone (Brooks et al., 2006b). A meta-analysis of studies implementing Nordic eccentric exercises indicated that performing these exercises reduced hamstring injury incidence by 51% across team sports, including Rugby Union (Brooks et al., 2006a). Noteworthy, however, a recent study revisited and reanalysed the aforementioned meta-analysis data and found a significant bias in the methodology and results, hence cautioned against the blanket statement that performing Nordic eccentric exercises will reduce hamstring injury risk (Impellizzeri, McCall, & van Smeden, 2021; Van Dyk N, 2019a). Therefore, it is important that practitioners and researchers in Rugby Union continue to monitor the potential effect of Nordic eccentric exercises on hamstring injury incidence.

There are limitations to the current study that should be acknowledged. Sample size was based on a previous study (Severo-Silveira et al., 2018); however, our study was potentially underpowered to detect significant differences with a sample size of ten players per group. Indeed, with ten players per group, the study would be sufficiently powered to detect very large effect size differences (Cohen's *d* 1.36) with an 80% power ($\beta = 0.20$) at the 5% level of significance ($\alpha = 0.05$) using two-sided tests (Serdar, Cihan, Yücel, & Serdar, 2021). Our *Pre* and *Post* assessments were undertaken during the competitive season and it is known that hamstring strength will likely fluctuate across different timepoints within as competitive season (Prendergast, Hopper, Finucane, & Grisbrook, 2016). The players in the intervention groups had greater peak eccentric strength measures than the *control* group, as well as than reported elsewhere (M. N. Bourne et al., 2015b), suggesting our players were pre-conditioned and had reasonable hamstring strength levels before the intervention programme. We did not monitor hamstring injury incidence during the season, and hence cannot say whether the intervention programmes mitigated risk of hamstring injuries compared to the *control* group. To validate the effectiveness of a Nordic eccentric hamstring training programme on the incidence of hamstring injuries in Rugby Union, hamstring injuries need to be monitored throughout an entire season.

8.5 Conclusion

A six-week progressive training programme in semi-professional Rugby Union players that incorporated eccentric Nordic and isometric hamstring exercises was insufficient to increase peak eccentric strength or decrease bilateral eccentric strength imbalances, regardless of whether visual feedback was provided during training or not. These results suggest that either the progression, load, or programme duration was insufficient to lead to change in our cohort of semi-professional athletes that had reasonable baseline strength levels. Hence, the exploration of alternative strength training programmes and strategies to implement in male Rugby Union players is warranted to address hamstring strength and strength balance, particularly when performed in-season.

CHAPTER 9

GENERAL DISCUSSION

9.1 OVERVIEW

This thesis presents a compilation of studies focusing on neck and hamstring strength as modifiable risk factors for concussion, neck, and hamstring injuries in Rugby Union players. This thesis implemented two strength testing methods using portable load cell devices, namely isometric make test for the neck and Nordic eccentric test for the hamstring muscles, and verified their intrasession and intersession reliability. The thesis also provides data on isometric neck and Nordic eccentric hamstring strength values from professional male, and semi-professional male and female Rugby Union players. This data can be useful to inform practice, and of particular interest to practitioners for rehabilitation, return to play, and strengthening of the neck and hamstring to decrease injury risk. The effect of a six-week progressive isometric hamstring and Nordic eccentric hamstring training programme with and without feedback performed in-season in semi-professional Rugby Union players was examined, and compared to a control group. None of the groups showed improvements in eccentric bilateral strength or a decrease in bilateral strength imbalances at the hamstring, warranting the exploration of alternative programmes or strength training strategies.

9.1.1 Section 1. Neck

As concussion continues to be the number one ranked injury in terms of incidence in Rugby Union (Peek et al., 2020) and neck strength identified as a modifiable injury risk factor to mitigate concussion incidence (Elliott et al., 2021), comprehensively exploring the neck strength literature in Rugby Union was deemed important. Therefore, a systematic review of the literature that addressed neck strength in Rugby Union players was conducted to establish the potential role of neck strength on injury incidence, as well as to determine the neck strength assessment protocols, measures, and strengthening exercises used (Chapter 2). The literature review on neck strength in Rugby Union players highlighted a gap in regard to neck strength in female athletes, with all the studies carried out in male Rugby Union players. This gap was partly addressed in Chapter 7 as the characterisation study involved semi-professional female Rugby Union players, therefore providing new insights on isometric neck strength values in this population group. Another gap identified in the Rugby Union literature on neck strength was the lack of agreement on the method used to assess neck strength, with two methods predominantly implemented to test: the break (Davies et al., 2016; K. Geary et al., 2013; K. Geary et al., 2014; D. F. Hamilton & Gatherer, 2014b; D. F. Hamilton et al., 2012; D. F. Hamilton et al., 2014b) or the make (Konrath & Appleby, 2012; Naish et al., 2013a) test. In general, the break test was more common and tended to result in greater strength values in the scientific literature when compared to studies reporting make test values, although no direct comparison of these two methods had been undertaken.

The literature review also indicated that, overall, senior professional Rugby Union players possessed stronger necks than younger-aged counterparts, most likely due to the latter group not yet reaching musculoskeletal maturity and/or their lesser training experience (D. F. Hamilton et al., 2014b). Forwards were stronger in extension than any other direction assessed; and when compared to backs, were generally stronger and possessed larger necks and greater cross-sectional areas (Konrath & Appleby, 2012; Olivier & Du Toit, 2008; Salmon et al., 2018). Regarding strength ratios, flexion to extension ratios ranged from 0.65 to 0.70

(Konrath & Appleby, 2012; Olivier & Du Toit, 2008; Salmon et al., 2018) and bilateral side ratios ranged from 0.96 to 1.0 (Naish et al., 2013a) in Rugby Union players across all levels of competition, with lower ratios for younger players compared to adult and senior players (Davies et al., 2016)

The training programmes implemented in the literature across playing levels varied in terms of neck strengthening exercises and protocols, and resulted in different outcomes. Two studies reported a significant increase in neck strength of players post training intervention (Geary et al., 2014; Maconi et al., 2016), whereas two other studies reported no improvements (Barrett et al., 2015; Naish et al., 2013a). In all cases, isometric exercises where implemented, with one study including concentric exercises (Maconi et al., 2016). Regarding neck strength as a modifiable risk factor for concussion, limited evidence of a direct relationship between neck strength and concussion existed at the time of the systematic review (C. Chavarro-Nieto et al., 2021b). Two studies addressed the relationship between neck strength values, neck strengthening exercises, and the incidence of neck and head injuries (Naish et al., 2013a; Snodgrass et al., 2018). Although a decrease in neck match injuries after a six-week strengthening programme was observed, this decrease was not associated with changes in neck strength values (Naish et al., 2013a). Since the completion of the formal review, a prospective study identified that Rugby Union players with lower isometric neck strength in extension were at greater risk of sustaining a concussion, with a 13% reduction in concussion rate for every 10% increase in neck extension strength (Farley et al., 2022). Overall, the systematic review identified areas for future work, notably to standardise and develop reliable neck strength testing protocols, establish benchmark values, as well as develop training protocols to improve neck strength across age groups and performance levels.

The lack of agreement regarding the methods to assess neck strength in Rugby Union found in the literature review, as well as the lack of experimental comparison between the make and break test, warranted examining neck strength test in a make and break fashion. Isometric neck strength values were compared in Chapter 3, and their intrasession reliability established in a cohort of healthy individuals and Rugby Union players. This study assessed the neck strength in a make and break test fashion in four different directions: flexion, extension, and right and left lateral flexion**.** In both methods of testing, participants were seated with the head and neck in a neutral position. Peak isometric force was recorded using a load cell connected to a head harness via a rigid cable.

Based on the Passing-Bablock regression analysis (Bilic-Zulle, 2011), the correlation between the two methods was good and no proportional or systematic difference was detected in any of the directions tested. The Bland-Altman plots indicated mean biases ranging from 0.85 to 1.9 kg across directions, with small effect size differences in flexion and left lateral flexion between make and break methods. Mean break test values ranged from 21.0 to 26.7 kg and were generally greater than make test values, which ranged from 19.1 to 25.8 kg. It has been suggested that the higher values of the break test are due to angle variations, with the interaction between the tester, device, and participant likely to influence results (Stratford & Balsor, 1994). Both methods demonstrated excellent intrasession reliability (ICC = 0.95 – 0.97, CV = 5.7 – 12%). This level of intrasession reliability is superior to other neck testing methods used in Rugby Union players (K. Geary et al., 2013) (e.g., handheld dynamometer), which indicates it might be procedurally advantageous for use in Rugby Union.

Overall, the findings from Chapter 3 suggest the make and break test performed in a seated position to assess isometric neck strength can be used relatively interchangeably, although a *small* group-level difference exists in flexion and left lateral flexion. There are some procedural advantages of using the make test rather than the break test to assess isometric neck strength, including decreasing the potential for test-related injuries, enhancing participant comfort and confidence in testing procedures, and reducing the influence of the tester on outcome measures. Ultimately, these considerations led to recommending use of the make test to assess isometric neck strength. This method was hence used for the remainder of this thesis.

A subsequent reliability study with 23 male Rugby Union players was carried out in Chapter 4 to reassess intrasession reliability in a cohort of semi-professional Rugby Union players, establish intersession reliability, and examine reliability of flexion-to-extension and left-to-right ratios. Specifically, three testing sessions were undertaken over three consecutive weeks using the previously described methods. Mean neck strength values in the cohort of semi-professional Rugby Union players ranged from 22 to 33 kg across directions, which was superior to the means reported in Chapter 3. Intrasession reliability was good-to-excellent in flexion, extension, and left and right lateral flexion for mean and maximum values (ICC = 0.85 – 0.95, CV = 6.4 – 8.8%), whereas intersession reliability was fair (ICC= 0.51 – 0.69, CV = 14.5 – 19.8%). Intrasession reliability was good for flexion-to-extension ratio (ICC = 0.86, CV =

11.5%) and fair for left-to-right ratio (ICC = 0.75, CV= 11.5%). Intersession reliability of ratios were fair (ICC= 0.52 – 0.55, CV = 16.8 – 24%).

Assessing isometric neck strength with a head harness and a cable with a load cell device in a seated position in semi-professional male Rugby Union players was feasible, and demonstrated good-to-excellent intrasession (ICC ≥ 0.75) and fair (ICC 0.50 – 0.75) intersession relative reliability. Absolute reliability was good intrasession (CV ≤ 10%) and acceptable intersession (CV ≤ 20%). Although the load cell approach appeared less reliable between sessions than using a handheld dynamometer based on reliability values reported in the literature (K. Geary et al., 2013), the load cell approach can be reliably used to assess isometric neck strength in extension, flexion, and bilateral lateral flexion, as well as to derive flexion-to-extension and left-to-right lateral flexion ratios in male Rugby Union players. A direct comparison of reliability data from the same cohort using both the handheld dynamometer and cable load cell approach is needed to confirm that one method is more reliable than the other within and between sessions. The reliability study provided data from semi-professional male Rugby Union players to inform practice, assist in standardisation of testing methods, and aid in determining the smallest worthwhile changes in isometric neck strength. Further experimentation with the load cell device to improve intersession reliability and stability of measures in neck isometric testing is recommended. The intersession reliability might be improved by using three-axial load cells, ensuring an initial familiarisation session, and paying further attention to individualised and repeatable neck positions.

9.1.2 Section 2. Hamstring

The second section of this thesis focused on hamstring injuries and strength in Rugby Union, firstly in a systematic review of the literature looking at the current scientific evidence on hamstrings injury incidence, risk factors, and prevention in Rugby Union players (Chapter 5). In terms of injury incidence, 6% of all injuries in professional male Rugby Union players were hamstring strains, with most hamstring injuries occurring during training and playing (Kenneally-Dabrowski, Serpell, et al., 2019b). Hamstring injuries were more severe in backs (17 days of absence) compared to forwards (15 days absence) (Brooks et al., 2005b). Running was the most frequent mechanism of hamstring injury (2005b). During matches, hamstring injuries were most frequent and severe in the last 20 minutes of play, and substitute players had twice as many injuries as starting players; however, both starters and substitutes had similar rates of recurrence (Brooks et al., 2006b). Players with a previous hamstring injury in the last 12 months had a 4.1 times higher risk of sustaining a recurrent injury compared to players with no history of hamstring injury (M. N. Bourne et al., 2015b). Hamstring strength imbalances based on Nordic eccentric strength tests between legs of more than 15% increased the risk of hamstring injury by 2.4 times, whereas imbalances of more than 20% increased risk by 3.4 times (M. N. Bourne et al., 2015b). Bilateral strength imbalances were significantly greater in injured players (mean 17.4%) than uninjured players (mean 10.0%) (M. N. Bourne et al., 2015b). On the other hand, weaker players based on Nordic eccentric hamstring strength tests (bilateral average < 267.9 N) were at a similar risk of sustaining a hamstring injury than stronger players (M. N. Bourne et al., 2015b). Recurrences were more severe and were associated with more days lost (25 days) compared to new injuries (17 days) (Brooks et al., 2006b). When assessing risk factors across the literature, the most relevant were playing position, fatigue, previous injuries, bilateral strength imbalances, early return to play post-injury, and running actions.

Isokinetic testing was the most common method used in the literature to assess hamstring strength and bilateral strength balance in Rugby Union (Abdelfettah et al., 2019; Anastasi & Hamzeh, 2011; Beyer et al., 2016; Brown et al., 2016; Deighan et al., 2012; Dobbs et al., 2017; Severo-Silveira et al., 2018), although arguable not the most practical. Overall, professional players were stronger than lower-level players, and forwards were stronger than backs. The only study demonstrating an association between strength measures and hamstring injury risk was based on Nordic eccentric hamstring strength tests using a load cell device (M. N. Bourne et al., 2015b), which supports the use of a more practical and functional assessment method to assess hamstring strength and imbalances in Rugby Union than isokinetic.

Strengthening programmes with Nordic eccentric exercises significantly increased hamstring strength, increased muscle thickness, and decreased imbalance ratios in female and male Rugby Union players (Anastasi & Hamzeh, 2011; Brooks et al., 2006b; Severo-Silveira et al., 2018). The intervention programmes implemented were varied. These programmes were 6 to 10-week in duration; included a mix of strengthening, stretching, and Nordic exercises; were performed 1 to 3 times per week; and included 3 to 4 sets with a maximum of 10 repetitions per set. Across intervention programmes, strength increments were observed. More specifically, male professional players increased their hamstring strength values, increased their H:Q and DCR values, as well as an increased their biceps femoris long head fascicle length and thickness when undertaking a progressive training programme (Severo-Silveira et al., 2018). In a separate study, a significant reduction in injury incidence and severity in professional players was observed in players performing routines incorporating progressive Nordic exercises (Brooks et al., 2006b). All considered, this review highlighted that combining strategies is likely worthwhile to prevent hamstring injuries and recurrences and to inform return to play. These strategies should include Nordic strength assessment and Nordic exercises, high-speed running routines, running biomechanical assessments, and warm-up routines. There was an overall lack of studies examining hamstring strength and injuries in female Rugby Union players, with only one study reporting isokinetic bilateral strength balance measures pre and post Nordic eccentric training (Anastasi & Hamzeh, 2011).

Given that Nordic eccentric hamstring strength measures were associated with hamstring strain injury risk and that adding Nordic eccentric hamstring exercises improved strength measures in Rugby Union players, this testing method was hence used for the remainder of the thesis. First, a reliability study of Nordic eccentric hamstring strength measures with 25 semi-professional male Rugby Union players was carried out using a portable load cell device (Chapter 6). Specifically, three testing sessions were undertaken over three consecutive weeks, and intrasession and intersession reliabilities were determined. Mean and maximal peak eccentric hamstring strength values demonstrated good intrasession reliability (ICC = 0.79 – 0.90, CV = 5.5 – 6.7%) and fair intersession reliability (ICC = 0.52 – 0.64, CV = 7.4 – 12.5%). Regarding the bilateral strength balance ratios, intrasession reliability was good (ICC = 0.62 – 0.89, CV = 4.4 – 7.2%), whilst intersession reliability was fair (ICC = 0.52 – 0.54, CV = 8.2 – 9.6%) based on mean and maximal values. On this basis, assessing Nordic eccentric hamstring strength and the bilateral strength balance in Rugby players using a portable load cell device was deemed feasible and reliable. This reliability study provided data from semi-professional male Rugby Union players to inform practice and aid in establishing normative values in this cohort using a more practical and functional testing approach than isokinetic.

9.1.3 Section 3. Characterisation

Once the reliability of the isometric neck and Nordic eccentric hamstring strength values using portable load cell devices was established, these methods were implemented to expand on the limited empirical data available in male and female Rugby Union players. To this effect, a cross-sectional study with a cohort of 342 Rugby Union players was carried out, which included 298 male and 44 female Rugby Union professional and semi-professional players. This was the first study examining the isometric neck strength and Nordic eccentric hamstring strength in female Rugby Union players, as well as one of the largest cohort studies conducted in Rugby Union players for both neck (C. Chavarro-Nieto et al., 2021b) and hamstring(C. D. Chavarro-Nieto et al., 2021) strength measures worldwide.

Regarding isometric neck strength, male professional players were significantly stronger in than semi-professionals except in extension; and overall, forwards ranged from 22 to 39 kg were significantly stronger than backs ranged from 22 to 31 kg in all directions. Flexion-to-extension ratio was 0.76 and side flexion ratio was 1.0, with no difference between levels or position. The neck strength and ratio values were similar to those noted in a previous study using a comparable testing method in professional Rugby Union players, whereby a reduction in match neck injuries was observed after an intervention programme with neck strengthening strategies (Naish et al., 2013a). In females, there was no significant difference between forwards and backs ranged from 14 to 23 kg in semi-professional players, except in extension (backs > forwards). Flexion-to-extension ratio was 0.83 and side flexion ratio of 1.0 (backs = forwards).

Considering Nordic eccentric strength, male professional were stronger than semi-professional players in terms of absolute strength (~422.1 vs 398.7 N), as well as in strength relative to body mass (4.57 vs 3.87 $N \cdot kg^{-1}$). Absolute strength was significantly greater in forwards than backs (426.8 vs 387.2 N), but lower when expressed relative to body mass (3.78 vs 4.67 $N \cdot kg^{-1}$). The hamstring strength values were greater than those reported in the only previous study performed in Rugby Union players using Nordic hamstring eccentric strength testing with a load cell device (C. Chavarro-Nieto et al., 2021b). Specifically, their strength values were 366 ± 76 N and 3.65 ± 0.7 $N \cdot kg^{-1}$ for elite professional, 387 ± 96 N and 4.0 ± 0.9 $N \cdot kg^{-1}$ for sub-elite, and 342 ± 81 N and 4.0 ± 0.9 $N \cdot kg^{-1}$ for under 19s players, with no significant differences between levels and playing positions (M. N. Bourne et al., 2015b). In female semi-professional players, there were no significant differences in absolute or relative hamstring strength between forwards (299.7 ± 63.2N, 3.2 ± 0.87$N \cdot kg^{-1}$) and backs (262.6 ± 53.0N, 3.3 ± 0.48$N \cdot kg^{-1}$).

This study provided data on isometric neck and Nordic eccentric hamstring strength values from male professional, male semi-professional, and female semi-professional Rugby Union players that can be used to inform practice, notably as guide to normative values that is level, position, and gender specific. This study is the first to report isometric neck strength and eccentric hamstring strength in female Rugby Union players.

9.1.4 Section 4. Intervention

In the last section, a randomised-controlled trial was conducted to examine the effect of a six-week isometric and Nordic eccentric hamstring training programme performed with or without visual feedback on hamstring strength and bilateral strength balance in Rugby Union players, inclusive of a control group. Thirty male Rugby Union players from two teams participated in the randomised-controlled trial. Players from one team were randomly assigned to one of two interventions (feedback or non-feedback) that included two hamstring strengthening sessions per week. Players from the other team acted as controls and continued their normal training. Nordic eccentric peak strength (N) and bilateral strength balance (%) were assessed Pre and Post the six-week intervention period. The time x group interaction was not significant for peak strength and bilateral strength balance, indicating similar changes between groups from Pre to Post timepoints. Additionally, there was no main effect of time on outcomes, indicating no significant difference in measures from Pre to Post. There was a significant main effect of group on strength, with controls identified as being significantly weaker than the other groups. On the other hand, there was no significant main effect of group on bilateral strength balance, suggesting comparable balance measures across groups.

A six-week training programme in male Rugby Union players with isometric and Nordic eccentric hamstring strength exercises was insufficient to increase eccentric hamstring strength or decrease bilateral strength imbalances when performed in-season, regardless of whether visual feedback was provided during training. The exploration of alternative strength training strategies in male Rugby Union players is warranted to address hamstring strength and balance, particularly when performed in-season.

9.2 ORIGINAL CONTRIBUTION TO KNOWLEDGE IN THE FIELD

This thesis provides original and significant contribution to knowledge through:

- **Providing a comprehensive overview of the scientific literature on neck and hamstring strength and injuries in Rugby Union, and identifying gaps in this literature which were subsequently addressed;**

  Neck: The scientific literature in Rugby Union lacked data with respect to neck strength in female athletes. This gap was addressed in Chapter 7 by quantifying isometric neck strength values in female players.

  Furthermore, there was no agreement in the literature regarding methods used to assess neck strength in Rugby Union. The make and break methods were predominantly used to assess isometric neck strength, but the interchangeability of these methods was not known for Rugby Union. This gap was addressed in Chapter 3 where these two methods were directly compared to inform future studies and clinical practice. Ultimately, using make test fashion to assess isometric strength was recommended mainly for methodological reasons as strength measures were relatively comparable between make and break methods.

Hamstrings: In the literature, there was an overall lack of studies examining hamstring strength in female Rugby Union players. This gap was addressed in Chapter 7 where Nordic hamstring eccentric strength values in female players were collected. These data can be used to inform practice, specifically rehabilitation, return to play, and strengthening programmes.

- **Supplying new information regarding the reliability of portable testing methods using load cell devices to assess isometric neck and Nordic eccentric hamstring strength;**

Neck and hamstrings: Chapter 4 and Chapter 6 support that using portable load cell devices to test isometric neck strength in a make test fashion and Nordic eccentric hamstring strength is reliable for assessing Rugby Union, particularly within sessions. These reliability studies also provided data from semi-professional male Rugby Union players to inform practice and aid in establishing normative values. In addition, Chapter 7 supports that portable load cell devices can be used to assess large cohorts of players.

To increase robustness and enhance reliability of measures between sessions, further attention is warranted to decreasing biological (e.g., participant condition) and tester (e.g., instructions and testing experience) variability, improving consistency in test set-up (e.g., consistent angle of cable for neck test and device stabilisation), and ensuring low measurement errors (e.g., accurate calibration). In addition, intersession reliability should improve in Rugby Union when performed during the preseason with rested players, as opposed to in season as was done in Chapter 4 and Chapter 6.

- **Carrying out an original experimental study that compared two common isometric neck strength methods (i.e., make vs break) and determining their relative interchangeability;**

  Neck: The make (concentric isometric) and break (eccentric isometric) tests were relatively interchangeable based on findings from Chapter 3. Despite the break test producing greater numbers than the make test and potentially a better reflection of the real maximal isometric capability of neck muscles, the make test was recommended based on methodological advantages. Notably, the make test was perceived as having less potential for injuries, increasing participant comfort and confidence in testing procedures, and reducing the influence of the tester on outcome measures.

- **Expanding on previous work that has identified isometric neck and Nordic eccentric hamstring strength and strength imbalances as modifiable risk factors for concussion, neck, and hamstring injuries, notably via documenting outcome measures from the use of two portable testing methods in the largest cohort of Rugby Union players inclusive of female players;**

  Neck and hamstrings: This thesis used ecologically valid neck strength testing procedures (Peek, 2022) in a large cohort of Rugby Union players, using a sport-specific test and portable device to establish an isometric neck strength profile in players. These data add to the existing knowledge with regards to isometric neck strength values in male professional, male semi-professionals, and female players in different playing positions. Similarly, a portable device was used to quantify Nordic eccentric hamstring strength and bilateral strength imbalances in the latter population of players to assist in establishing benchmark values and inform practice.

- **Conducting a randomised-controlled trial with semi-professional Rugby Union players to evaluate the effectiveness of an isometric and Nordic eccentric hamstring strengthening programme in increasing hamstring strength and decreasing bilateral strength imbalances using feedback and non-feedback strategies.**

Hamstrings: The training programme did not significantly increase peak eccentric strength or decrease bilateral eccentric strength imbalances, regardless of whether visual feedback was provided during training or not. These results suggest that either the eccentric/isometric routine, progression, load, or programme duration was insufficient to lead to change in the cohort of semi-professional athletes that had reasonable baseline strength levels. It is also possible that the testing method was not sufficiently sensitive to change. The minimal detectable change of measures from the load cell device based on Chapter 6 varied from 10 to 20%, and therefore would not detect small changes induced by training strategies. However, it may be that the testing method would detect larger changes in rehabiliting athletes where gains from rehabilitation programmes are superior to those of strength training in pre-conditioned athletes.

9.3 PRACTICAL IMPLICATIONS

Overall, this thesis sought to shed some light on neck and hamstring strength assessment and strengthening practices to inform injury prevention in Rugby Union. The data from this thesis can be useful to inform practice, and of particular interest to practitioners to inform rehabilitation, return to play, and strengthening of the neck and hamstring. The following practical implications are advanced, which can assist practitioners and guide injury prevention efforts:

9.3.1 Section 1. Neck

- Based on the literature review, strength imbalances (namely flexion to extension ratios and bilateral flexion side ratios) in Rugby Union players appear to be more linked with concussion injury incidence rather than neck strength per se and should be assessed and monitored in practice;
- Both the make and break isometric neck strength test are feasible to implement in Rugby Union players and relatively interchangeable. These tests can assist in player preparation, screening, and monitoring of modifiable risk factors for neck injuries and concussion;
- The make test is a reliable method to determine the isometric neck strength in large cohorts of Rugby Union players. The make test has some procedural advantages compared to the break test (i.e., less tester influence), and is therefore recommended for use in practice. The use of a portable load cell device for assessments makes the

test easy to implement in practice. For more reliable between session results, Rugby Union players should be tested during preseason and in a rested stated, and more work on standardising methodological testing procedures is advised.

9.3.2 Section 2. Hamstring

- Current literature is lacking to support the evidence-based use of strength, H:Q, and DCR measures to inform injury prevention and return to play strategies for hamstring injuries. Nordic eccentric strength measures have been shown to be a better physiological and functional test, with differences in strength and imbalances predicting new and recurrent injuries. Clinicians are encouraged to monitor Nordic eccentric strength regularly and to implement Nordic eccentric strengthening strategies, as a means to curb the incidence and severity of hamstring injuries in Rugby Union;
- A portable load cell device to test Nordic eccentric hamstring strength can be used by practitioners reliably and is more accessible than isokinetic testing. Testing during the preseason and players in a rested state is recommended to improve intersession reliability.

9.3.3 Section 3. Characterisation

- The isometric neck and Nordic eccentric hamstring strength data collected from professional, semi-professional male, and semi-professional female Rugby Union players as part of this thesis can be used as initial benchmark targets for uninjured male and female Rugby Union players. These data can assist practitioners in determining whether strength levels and strength imbalances of players are comparable to others in pre-season screening and identify potential areas of concern;

- These data can also inform strengthening strategies, rehabilitation management and readiness to return to play decision making processes post injury. As hamstring and concussion injuries have high recurrence rates, it is likely worthwhile to include testing of isometric neck strength, flexion to extension, and bilateral ratios, as well as Nordic eccentric hamstring strength and imbalances post rehabilitation.

9.3.4 Section 4. Intervention

Adding visual feedback to a hamstring strengthening programme was comparable to providing no feedback in terms of strength maintenance in-season with preconditioned male Rugby Union players. Hence, strengthening intervention strategies to obtain maximum gains should be implemented in preseason after the off-season. Implementing alternative strategies and prescriptions are needed to promote strength gains in-season in Rugby Union.

- There is currently limited and contradicting evidence regarding the effectiveness of hamstring strengthening strategies to increase strength and decrease strength imbalances as a mechanism for hamstring strain injury prevention in Rugby Union (C. D. Chavarro-Nieto et al., 2021). The randomised controlled trial results suggest that either the eccentric/isometric routine, progression, load, or programme duration was insufficient to lead to strength and imbalance changes in semi-professional Rugby Union athletes that had reasonable baseline strength levels. Monitoring injuries current to strengthening programmes would assist to determine their effectiveness in reducing injury incidence and severity.

9.4 STRENGTHS AND LIMITATIONS

The perceived strengths and limitations of each chapter included in this thesis and of the overall thesis are presented in the Table 1. Noteworthy, an overall strength of this thesis was the range of study designs implemented to address neck and hamstring strength as a modifiable risk factor for concussion, neck, and hamstring strain injuries in Rugby Union players. The thesis included systematic literature reviews, a cohort study comparing measures between the two most common approaches used to assess isometric neck strength in Rugby Union, reliability studies of neck and hamstring measures using load cell devices, a large cross-sectional study that characterised neck and hamstring strength measures with load cell devices in female and male semi-professional and professional Rugby Union players, and a randomised-controlled trial implementing isometric and Nordic eccentric strengthening exercises with and without feedback in Rugby Union players. Sample size was justified in all experimental studies.

Despite a strength of the thesis being researching athletes in an ecologically valid environment, doing so also presented challenges. More specifically, professional and semi-professional players were not consistently available for compliant with testing and training sessions. Furthermore, it was not possible to completely standardise or monitor training loads and schedules on a weekly basis due to player team commitments. To address this limitation, it is important for scientists and practitioners to work closely together to better address the problems Rugby Union coaches and trainers face (Sandbakk, 2018). As identified in the literature reviews focusing on neck and hamstring strength and injury in Rugby Union, there is a paucity of research involving female players. Although the current thesis does provide data on semi-professional female players with regards to neck and hamstring strength measures, no Rugby Union female players were involved in establishing reliability of measures or during the intervention phase of this thesis. Furthermore, Rugby Union was not a professional sport for females at the time the cross-sectional study (Chapter 7) was undertaken, limiting comparisons between professional and semi-professional female players

Table 25. Strengths and limitations of the thesis and for each chapter

Thesis	Strengths	Limitations
Chapter 2 **Neck literature review**	• First comprehensive systematic literature review on neck strength and strengthening programmes, and their relationship with concussion and neck injuries in Rugby Union • Clear and reproducible methodology following the PRISMA guidelines • Use of NOS to assess risk of bias • Covers a range of neck strength, neck strengthening programmes, and neck and concussion injury considerations across ages, levels, and position of play in Rugby Union	• Extracting results across studies to make strong inferences was challenging given the various testing procedures, equipment, and units used • Unable to provide normative neck strength values in Rugby Union due to the heterogeneity of methods to assess strength as well as the different units used • Meta-analysis was not possible due to the aforementioned limitations
Chapter 3 **Make vs break test**	• First study to compare the make and break tests commonly used to assess isometric neck strength in Rugby Union players • Sample size was sufficient to achieve a power of 90%	• Involvement of both non-rugby and Rugby Union participants • Results not generalisable to injured players

	• Study included relative and absolute intrasession reliability assessment for both test methods	
Chapter 4 **Reliability of neck strength test**	• First study to explore the neck strength intrasession and intersession reliability in the make test fashion in semi-professional Rugby Union players • First study to explore the neck strength reliability using a rigid cable with load cell in a seated position set-up in Rugby Union players • Provides reliability data on isometric neck strength using the make test approach specific to Rugby Union players	• Lower intersession than intrasession reliability possibly due to assessing the players whilst training and playing during the competitive season • Lower intersession reliability in extension than other directions potentially due to variations in technique and body positions between sessions
Chapter 5 **Hamstring literature review**	• First systematic literature review to summarise the scientific literature on hamstring strain injury and strength measures in Rugby Union • Clear and reproducible methodology following the PRISMA guidelines • Use of NOS to assess risk of bias	• Use of a single NOS version across a range of study designs • Meta-analysis was not possible due to differences in outcome measures and heterogeneity of populations examined

Chapter 6 **Reliability of hamstring strength test**	• First study to assess the reliability of Nordic eccentric hamstring strength and bilateral strength balance measures intrasession and intersession in semi-professional Rugby Union players with a load cell device • Provides reliability data on Nordic eccentric hamstring strength specific to Rugby Union players	• Lower intersession than intrasession reliability could be due to assessing players whilst training and playing during the competitive season
Chapter 7 **Characterisation of neck and hamstring strength**	• Study designed based on previous reliability studies conducted • Large sample size cohort of semi-professional and professional Rugby Union players • First study to determine isometric neck strength and ratios, as well as Nordic eccentric hamstring strength and bilateral strength values in male and female Rugby union players • Representation of different playing levels and inclusion of female players	• Lack of injury surveillance data prospectively due to COVID pandemic • Relatively low female participation and lack of professional female players due to the sport not having professional status at the time of data collection

Chapter 8 Randomised controlled trial hamstring strengthening	• First study to include visual feedback strategies in a six-week Nordic eccentric hamstring training programme in semi-professional Rugby Union players • Inclusion of a control group • Strengthening exercises were supervised during the six-week training study by the lead researcher and the strength and conditioning team • Implementation of strengthening exercises with the potential to reduce injuries in Rugby Union	• Sample size was based on prior study and potentially underpowered to detect significant differences • Lack of injury surveillance data prospectively due to COVID pandemic • Pre and Post assessments were undertaken during the competitive season, and it is known that hamstring strength will likely fluctuate across different timepoints within as competitive season • The intervention groups had greater peak eccentric strength measures than the control group suggesting the intervention players were pre-conditioned and had reasonable hamstring strength levels before the intervention programme • Relatively large minimal detectable change values associated with testing methods and therefore would not detect small training-related changes
Overall thesis	• Range of study designs (systematic literature review, cohort, reliability, cross-sectional, randomised control trial)	• Challenges linked with player availability and compliance to testing and training, as well as ability

	• Justified sample size for each study • Internal assessment of reliability of the main testing methods implemented • Representation of different playing levels (i.e., club to professional players) and inclusion of female players • Performing studies with Rugby Union athletes in an ecologically valid environment	to standardise or monitor weekly training loads and schedules in season • COVID pandemic interferences with originally planned thesis studies (e.g., injury monitoring and neck strength intervention study) • Relatively low female participation and inclusion across all aspects of the thesis

Notes: PRISMA**:** Preferred Reporting Items for Systematic Review and Meta-Analysis, NOS: Newcastle-Ottawa Scale

9.5 FUTURE RESEARCH DIRECTIONS

9.5.1 Section 1. Neck

Based on the literature review pertaining to the neck in Rugby Union (Chapter 2), younger school-aged Rugby Union players are likely to be greater risk of neck and concussion injuries due to their immature musculature and weaker necks. As such, future research should target this vulnerable population group and seek to implement neck strengthening exercises in school-aged Rugby Union players. There appears to be a gap in the literature with regards to the proprioceptive effect of neck strengthening exercises and the value of proprioceptive or neuromuscular exercises themselves on neck and concussion injuries. Furthermore, greater neck stiffness can improve the ability of the neck to resist deformation and absorb loads (Elliott et al., 2021). Although neck stiffness can be enhanced actively via active muscular contractions and neck strengthening, measures of passive neck stiffness in Rugby Union players might be worth exploring in relation to concussion in future studies. Lastly, recent evidence has found a relationship between lower flexion-to-extension ratios in male Rugby Union players presenting with a history of concussion (Nutt et al., 2022), highlighting the potential for a cause-effect relation between concussion and neck strength imbalances that warrants further exploration.

In terms of neck strength assessment methods, future research may consider comparing between different procedural assessment methods, such as comparing cable load cell device values between seated and scrummaging positions, to establish whether seated assessments reflect rugby-specific positions. A direct comparison of reliability data from Rugby Union players using both a handheld dynamometer and a cable load cell would confirm whether one method is more reliable than the other. Given the lower intersession than intrasession reliability of neck isometric strength testing, further experimentation with the load cell device to improve intersession reliability and stability of measures in neck isometric testing over time is needed. Reliability might be improved using three-axial load cells, ensuring an initial familiarisation session, testing players off-season and further attention to individualised and repeatable neck positions. A standardised testing protocol implemented across Rugby Union to assess neck strength would aid the field by enabling cross-study inferences and facilitate the establishment of benchmark strength values.

9.5.2 Section 2. Hamstring

The hamstring literature review in Rugby Union identified a gap pertaining to the Nordic hamstring eccentric values in female Rugby Union players as well as lack of information regarding hamstring strain injury incidence and severity in female Rugby Union across levels. There is a need for comprehensive Rugby Union Injury Surveillance data across countries, especially for females. Furthermore, additional data on Nordic eccentric strength values in Rugby Union players across genders, levels of competition, and ages are needed to provide normative data and establish benchmark values.

It could be worthwhile to compare isokinetic test outcomes to Nordic eccentric strength outcomes specifically in Rugby Union players to determine their interchangeability, which could confirm the validity of using a Nordic load cell device for testing in Rugby Union players. Similar to isometric neck assessment, further experimentation with the load cell device to improve the intersession reliability and stability of hamstring eccentric strength measures is necessary. Again, ensuring an initial familiarisation session, testing players off-season, further attention to foot and body positions, and ensuring the movement is controlled while performing the Nordic exercise should aid to improve intersession reliability. A standardised testing protocol implemented across Rugby Union to assess hamstring strength would aid the field by enabling cross-study inferences and facilitate the establishment of benchmark strength values.

9.5.3 Section 3. Characterisation

Although isometric neck and Nordic hamstring eccentric strength was examined in a relatively large cohort of Rugby Union players in Chapter 7, future research should seek to confirm normative strength values in Rugby Union players and determine whether status relates to previous injury history as well as future injury incidence and severity. Furthermore, hamstring strain is a multifactorial injury, therefore risk factor analyses should also include, bilateral strength imbalances, quadriceps peak torque, age, and past history of hamstring injuries (Freckleton & Pizzari, 2013b). This knowledge should assist in the development of evidence-based targeted injury prevention and physical preparation strategies to manage both injured, previously injured, and uninjured rugby players to the neck and hamstring.

9.5.4 Section 4. Intervention

There is a potential for Nordic hamstring eccentric strengthening exercises to decrease hamstring injuries (Brooks et al., 2006b); however, further research is needed to determine the optimal prescription of Nordic eccentric hamstring strengthening exercises both in and out of season, including progressions and regressions. Although no differences in strength and bilateral balance was observed between feedback and non-feedback training strategies in season, there may be a benefit of feedback training for hamstring strengthening in preseason or in less conditioned athletes warranting further exploration.

9.6 CONCLUSION

This thesis presents a compilation of studies focusing on neck and hamstring strength as modifiable risk factors for concussion, neck, and hamstring injuries in Rugby Union. This thesis provides data on isometric neck and Nordic hamstring eccentric strength values using two reliable test methods that use portable, low-cost load cell devices feasible for use in practice. The data collected from professional male, semi-professional male, and semi-professional female Rugby Union players can be used to inform practice and as guide regarding normative values, which can inform rehabilitation, return to play, and strengthening of neck and hamstring in Rugby Union. The six-week progressive isometric and Nordic eccentric hamstring strength training programme was not superior to usual training (control group) for improving eccentric bilateral strength or decreasing bilateral strength imbalances regardless of whether feedback was implemented, warranting exploration of alternative strength training programmes and strategies.

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APPENDICES

Appendix A. Published manuscripts presented in the thesis

Appendix A1. Neck strength in Rugby Union players: A systematic review of the literature

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REVIEW

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Neck strength in Rugby Union players: a systematic review of the literature

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ABSTRACT

The incidence and severity of concussion injuries are increasing every year. Scientific evidence indicates that neck strength and girth could play a role in preventing head and neck injuries, or at least mitigating their severity. We aimed to examine the scientific literature addressing neck strength in Rugby Union with a focus on the potential role of neck strength on injury incidence, neck assessment protocols, neck strength measures, and neck strengthening exercises.

We conducted a systematic search of the literature in January 2021 to locate published peer-reviewed articles from PubMed, SPORTDiscus™, Web of Science®, and Scopus® e-databases. Overall, senior elite male players were stronger than younger-aged players. Forwards were stronger in extension than any other directions assessed, and were generally stronger and possessed larger necks and greater cross-sectional areas when compared to backs. Implementation of isometric exercise routines in professional players was reported to improve neck strength in all directions. There were no studies evaluating the incidence of concussion and neck strength or neck strengthening strategies in Rugby Union. Strengthening the neck continues to be one of the targeted modifiable risk factors with respect to limiting the severity and temporal effects of head injuries in Rugby Union, despite limited evidence regarding direct associations between neck strength and concussion.

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KEYWORDS
Concussion; strength training; football; injuries

What we know

- Concussions and neck injuries are frequent in Rugby Union. Strengthening the neck may reduce the number of head and neck injuries.
- Front row players are most susceptible to neck injuries. Forwards typically possess greater body mass and stronger necks than backs.
- Professional senior players with elite training and more competitive international games are stronger in all neck strength measures than any other age or level of competition.

What we do not know

- Should we be doing an intervention in school-aged Rugby Union players to increase neck strength in this vulnerable population?
- There are no studies in female players; therefore, little is known regarding neck strength, strengthening programs, and neck and head injuries in female Rugby Union athletes.
- The relationship between concussion injuries, neck strength, and strengthening programs in Rugby Union is unclear.

What we need to learn

- Prescribing neck strengthening exercises could decrease neck and head injuries. We need to investigate the effective prescription of neck strengthening exercises, progressions, regressions, and associated benefits.
- The neurological changes with neck exercises (i.e. proprioception), isometric, eccentric, and concentric routines that decrease neck muscle imbalances, and relation of strength-related measures with neck and concussion injuries in Rugby Union players need further investigation.

1. Introduction

Concussions are of major concern given their short- to middle-term impacts on players, and their serious long-term sequelae with links to cognitive decline [1] and chronic traumatic encephalopathies later in life [2]. Concussion is the most common injury in professional Rugby Union with the England Rugby Football Union (RFU) reporting that approximately 21% of match-related injuries were concussions [3], with the incidence increasing for the seventh successive season. In the same period, Ireland Rugby Union reported 60 concussions in 160 professional rugby players [4]. Bitchell et al. [5] reported concussions as the most common injury in professional Welsh players, with an increase from 10.6 to 21.4 injuries/1000 hours in the annual incidence of concussion across four seasons from 2012 to 2016. Additionally, a concomitant increase in concussion severity from 86 days lost/1000 hours to 302 days lost/1000 hours was reported [5].Cross et al. [6]

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strengthening exercises in Rugby Union players, or neck strength, neck strengthening exercises, and neck injuries in Rugby Union players. Studies were not excluded based on sex, age, or level of competition. Only original peer-reviewed research articles written in English were included.

2.3 Screening process

Duplicates from the database search were removed first. Two authors (CC, KHL) independently screened all titles, abstracts, and full texts for inclusion criteria. The study selection process was replicated for articles that were included through manual searches of other databases and the reference lists of full text screened. The authors met at each screening stage (i.e. titles, abstracts, and full texts) to resolve any disagreement in terms of inclusion, with a third reviewer not needed to resolve outstanding disagreements.

2.4 Quality assessment

Two reviewers (CC, IH) independently assessed the methodological quality of included studies (n = 14) using the Newcastle – Ottawa Scale (NOS) adapted for cross-sectional studies [24]. The reliability for NOS adapted for cross-sectional studies based on intraclass correlation coefficient (ICC) and confidence interval values within (ICC, 0.98; 95% CI, 0.94–0.99) and between (ICC, 0.94; 95% CI, 0.80–0.98) raters is excellent [25]. Prior to assessment, the two reviewers met to discuss and familiarize themselves with the scales. All identifiable information (i.e. authors, affiliations, countries, and sources of publication) were removed from articles by a third party to blind the two reviewers to reduce the assessment bias. Disagreements in the risk of bias assessment scores were resolved by discussion between the reviewers and consensus scores are presented in this article.

The NOS is a methodology assessment tool for observational studies recommended by the Cochrane Collaboration [26]. The tool uses a 'star system,' wherein more stars indicate a superior methodological quality and lower risk of bias. The NOS awards a maximum of 10 stars: Five for selection (representativeness of the sample, sample size, non-respondents, and ascertainment of the exposure), two for comparability, and three for outcome (assessment of outcome and statistical test). Reviewers agreed that for the statistical test item, the highest star rating would be allocated for the reporting of confidence intervals, quartiles, or limits of agreement. The methodological quality of studies was divided into three groups based on the number of stars awarded: *weak* (0 to 3 stars), *moderate* (4 to 6 stars), and *strong* (7 to 10 stars) [27]. The design of each study was classified first as experimental or observational, and then as randomized controlled trial, cross-sectional or cohort [28–30]. No article was excluded from this review based on quality score or study design.

2.5 Data extraction and synthesis

The first author (CC) extracted data from the selected full-text articles using a standardized form, and the last author (KHL) verified the data extracted. For each study, study design, participant information, level of competition, location of the study, study characteristics, strength assessments, and outcome data were extracted. Data were grouped and extracted under three main themes of interest: neck strength measures, neck strengthening exercise programs, and incidence of injuries. Data were managed and analyzed using Microsoft® Office Excel 2016 (Redmond, Washington, USA).

3. Results

3.1 Included studies

The flow diagram from the search strategy and screening process is shown in Figure 1. Fourteen studies met the eligibility criteria.

3.2 Study characteristics

The main characteristics of the 14 studies that met inclusion are presented in Table 1. Based on the Newcastle – Ottawa Scale (NOS), most studies were of *moderate* quality (n = 11, 79%) [12,31–40]. Only two articles were of *strong* methodological quality [41,42], with one study ranked as *weak* [43]. Item-by-item NOS ratings for each study are presented as **Supplementary Material**.

3.3 Participants

The 14 articles that met inclusion involved 1066 male players (mean sample size: 76 participants). Rugby players were professional in seven of these studies (50%) [12,32,35,38,40,42,43], school-aged in three (21%) [31,33,34], amateur (e.g. club) in three (21%) [36,39,41], and semiprofessional in one (7%) [37]. Studies were conducted mostly in the United Kingdom (*n* = 5) [31–34,42] and Australia (*n* = 4) [12,35,37,40]. Ireland [41,43], Italy [39], New Zealand [36], and South Africa [38] were also represented in one to two studies each, see Table 1.

3.4 Neck strength measures

3.4.1 Overview

All studies tested neck flexion and extension. The majority of studies (*n* = 12) also included left and right lateral flexion [12,31,32,34–39,41–43]. Six studies also evaluated bilateral rotation [31,32,34,37,39,42] Table 2.

3.4.2 Protocol

Most of these studies measured peak isometric strength with a customized load cell device (see **Strength Assessment**, Table 2). Six of the studies undertook a 'break test' with the peak force measured in kilograms or Newtons [32–34,41–43]. The 'break test' measures the peak isometric strength against an incremental load resistance. For this test, the head was held in the neutral anatomical position and resistance was applied to evoke a maximal muscle contraction in the desired direction using a cable attached to a handheld dynamometer (Figure 2) until the initiation of the movement (i.e. positional failure).

Three studies performed an isometric strength test with the force measured using a head harness or strap attached indicated that players from the RFU with a traumatic brain injury had a 60% increased risk of any subsequent injury over two seasons, hypothesized to be due to impaired neuromuscular control [7].

The Irish Rugby Injury Surveillance Project (IRIS) [8] monitored over 600 male and female amateur players across the country. The most frequent match injury in males was concussion, representing 12% of all injuries reported. In females, concussion was also the most common match injury alongside ankle sprains. The loose head prop and hooker were the player positions with the most documented injuries in amateurs. These data highlight that concussion is not only of concern at the professional level, but also in amateur Rugby Union where the number of participants continues to grow worldwide [9].

In relation to costs, a report from Accident Compensation Corporation (ACC) in New Zealand highlighted that Rugby Union had the largest number of injuries and claims compared to any other sport from 2012 to 2016. This report identified the average cost associated with moderate-to-serious and serious injuries to be the greatest for the head and neck when grouped by anatomical region [10]. In the context of injury type, concussion claims were ranked third in terms of mean cost after soft tissue and fracture/dislocation injuries. Considering the socio-economic and medical impact of concussion, various strategies are being implemented and trialed to reduce the incidence and severity of these injuries. These include rule changes introduced by World Rugby in 2017; however, recent data suggest that the overall incidence of concussion has remained unchanged. In fact, the data indicate a significant *increase* in the number of concussions in the tacklers tackling below the line of the shoulders compared to games with players tackling following the previous regulations [11].

In terms of modifiable risk factors for preventing concussion in athletes at an individual level, strengthening the neck musculature and increasing neck girth is one strategy of potential protective value. Necks with greater cross-sectional areas and stiffness can protect the head from linear and angular accelerations and displacements, as well as reduce peak velocities due to impacts [12,13]. In contact sports and healthy individuals, prior activation of neck muscles before a collision has been shown to significantly decrease the peak linear velocity and change in acceleration of the head [14,15]. However, it is not always possible to anticipate a collision in a dynamic on-field environment.

The National Football League's (NFL) Head, Neck, and Spine Committee [13] examined the biomechanics of head collisions in 25 NFL male players in a laboratory experiment. Players with stronger necks had lower linear and angular head accelerations, suggestive of a lower risk of concussion due to lesser forces. The Committee highlighted the potential for an increased injury risk in populations with weaker necks, such as females and youth players. In young (17 to 19 years) NFL male players, extension neck strength was shown to be greater than flexion and bilateral flexion [16]. To reduce neck injuries, the group recommended addressing neck strength and muscle imbalances. Similarly, total neck strength in high school students participating in contact sports was a significant predictor of concussion [17]. An increase in neck strength equivalent to one pound decreased the probability of concussion by 5%. Specifically in soccer, stronger necks have also been associated with lower head accelerations when purposely heading the ball, suggesting lower risk of concussion due to the strong association of heading with concussion in this sport [18,19]. However, what type of neck strengthening program is the most effective for which level of play remains undetermined. Implementing an 8-week isotonic neck-strengthening program in university soccer players increased neck flexion strength by 15% in both males and females, and extension strength by 22.5% in females. However, this study found no significant decrease in head accelerations with force application [20]. In contrast, an 8-week neck training program involving manual resistance undertaken with high school players competing in contact sports resulted in increased neck flexion, extension, and bilateral side flexion strength, as well as a significant decrease in head acceleration [21].

Rugby is a unique field-based team sport as it is dominated by high force and frequency impacts without the use of helmets [22]. Hence, addressing neck strength specifically in Rugby should inform practice in relation to concussion. Given the potential for mitigating risk and harm, it is cogent to critically examine and summarize the existing scientific literature on the topic of neck strength in Rugby Union players. Specifically, we aimed to systematically review and summarize the scientific literature that addressed neck strength in Rugby Union players with a particular focus on the potential role of neck strength on injury incidence, neck assessment protocols, neck strength measures, and neck strengthening exercises.

2. Materials and methods

2.1 Information sources and search strategy

We conducted a systematic review of the literature following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines [23]. The first author (CC) performed a systematic search on 1st of January 2021 to locate published peer-reviewed articles from four electronic databases: PubMed, SciVerse Scopus®, SPORTDiscus™, and Web of Science®. The search strategy consisted of the following keywords and Boolean operators entered in the main search bar of each e-database: 'neck AND strength AND rugby'. The exact resulting search syntax in PubMed was: ('neck'[MeSH Terms] OR 'neck'[All Fields]) AND strength [All Fields] AND ('football'[MeSH Terms] OR 'football'[All Fields] OR 'rugby'[All Fields]).

2.2 Inclusion and exclusion criteria

The primary interest of this literature review was to identify original research studies that evaluated neck strength, neck-strengthening interventions, and/or included head or neck injury outcomes in Rugby Union. The search included articles published up until January 1st, 2021. Studies were screened for inclusion based on the following criteria: included neck strength assessment measures in Rugby Union players, neck

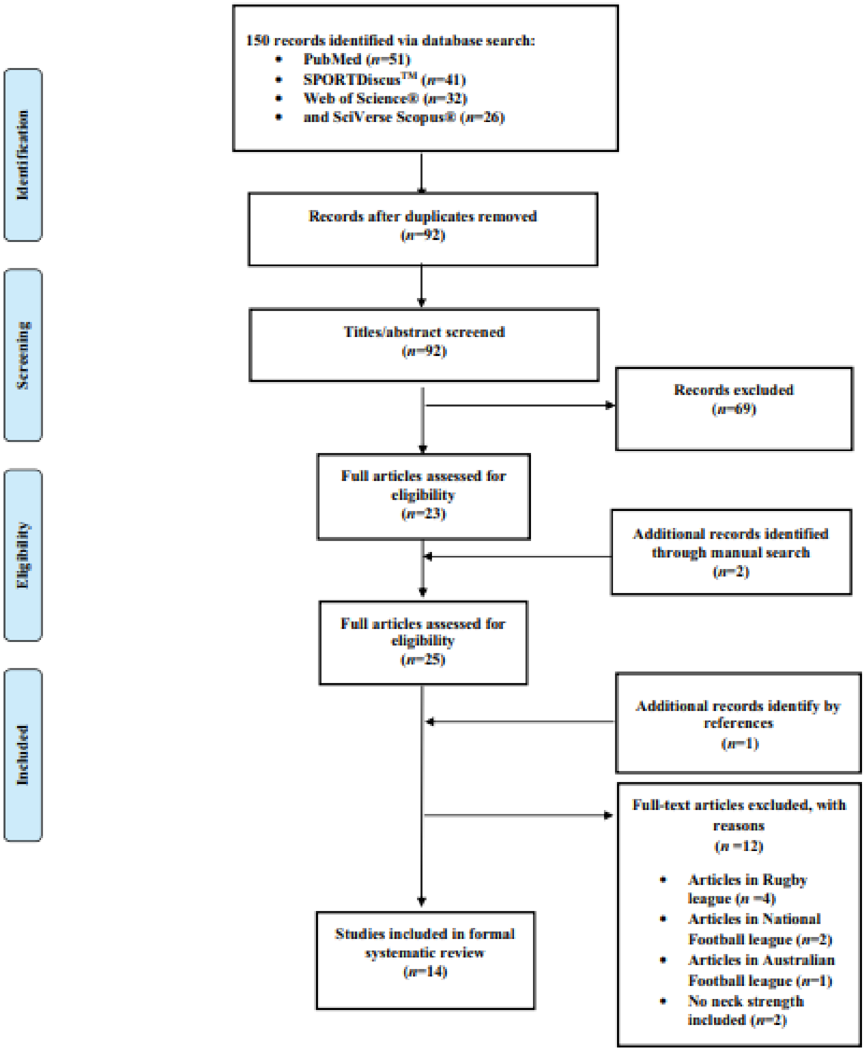

Figure 1. Preferred reporting items for systematic reviews and meta-analyses flow chart.

to a load cell device to a fixed frame in a seated or lying position in a 'make test' manner [31,35,40]. To measure neck strength, Snodgrass et al. [37] attached the hand held dynamometer to the forehead of players, and players had to press as hard as possible against the device using the neck muscles. Salmon et al. [36] and Naish et al. [35] used a fixed-frame dynamometer in a rugby-specific contact/collision position, the former assessing neck strength, and the latter performing training exercises in this position and assessing strength in a 'make test' fashion. Maconi et al. [39] measured neck strength in a seated position with the players attached to a customized ergometer with the neck strength measured against a load cell and electromyography electrodes placed on the neck muscles to determine neuromuscular activation levels. Only one study examined dynamic isokinetic neck strength using an isokinetic dynamometer [38].

The majority of studies (n = 12) evaluated neck strength sitting with the head in a neutral position [12,31–35,37–-31–35,37–39,41–43]; whilst one study assessed contact or

Table 1. Characteristics of the included studies.

Study	NOS rating*	Level of competition Location	Player characteristics	Study design	Study characteristics
Barrett et al. [31]	*Moderate* 6 stars	Senior school-aged United Kingdom	32 males Age: 17.3 ± NR y Mass: 87.59 ± NR kg Height: 181.34 ± NR cm	Randomized controlled trial (prospective)	Duration: 1 season Injuries: No Intervention: Strengthening
Davies et al. [32]	*Moderate* 6 stars	Senior professional and Age-grade professional Wales	40 males **21 seniors** Age: 19 ± 1 y Mass: 109 ± 7 kg Height: 182 ± 5 cm **19 age-grade** Age: 27 ± 5 y Mass: 114 ± 6 kg Height: 185 ± 4 cm	Cohort (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Dempsey et al. [12]	*Moderate* 4 stars	Elite professional Australia	10 males Age: NR Mass: 98 ± 10.5 kg Height: 189 ± 7 cm	Case series (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Geary et al. [41]	*Strong* 7 stars	Amateur Ireland	25 males Age: 19.3 ± 1.3 y Mass: 95.2 ± 13.2 kg Height: 185 ± 6 cm	Cohort (reliability)	Duration: 1 season Injuries: No Intervention: No
Geary et al. [43]	*Weak* 3 stars	Professional Ireland	25 males **15 professionals as subjects** Age: 19.3 ± 1.3 y Mass: 95.2 ± 13.2 kg Height: 185 ± 6 cm **10 semiprofessionals as controls** Age: 20.7 ± 1.25 y Mass: 101.3 ± 12.3 kg Height: 185 ± 2.7 cm	Case control (retrospective)	Duration: 1 season Injuries: No Intervention: Strengthening
Hamilton et al. [33]	*Moderate* 6 stars	School children Scotland	382 males Age: 15 ± 2.1 y Mass: 66.1 ± 11.3 kg Height: 172 ± 7.3 cm	Cohort (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Hamilton, Gatherer [42]	*Strong* 7 stars	Professional Wales	27 males Age: 22.3 ± 3.9 y Mass: 97.9 ± 10.7 kg Height: 186.2 ± 6.4 cm	Cohort (retrospective)	Duration: 1 season Injuries: No Intervention: No
Hamilton et al. [34]	*Moderate* 6 stars	Senior school-aged and adult senior school-aged Scotland	52 males **30 under18** Age: 16.7 ± NR y Mass: 96.0 ± 13.69 kg Height: 178.7 ± 5.54 cm **22 adults** Age: 27.2 ± NR y Mass: 107.8 ± 13.67 kg Height: 178.7 ± 5.91 cm	Cohort (cross-sectional)	Duration: 1 season Injuries: No Intervention: No

(*Continued*)

Table 1. (Continued).

Study	NOS rating*	Level of competition Location	Player characteristics	Study design	Study characteristics
Konrath, Appleby [40]	*Moderate* 4 stars	Professional Australia	40 males (22 forwards, 18 backs) Age forwards: 24.8 ± 4.1 y Age backs: 24.3 ± 3.9 y Mass forwards:109.8 ± 6.2 kg Mass backs: 92.1 ± 8.2 kg Height forwards: 187 ± 7 cm Height backs: 181 ± 9.9 cm	Case series (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Olivier, Du Toit [38]	*Moderate* 5 stars	Senior elite professional South Africa	189 males Age: 24.31 ± NR y Mass: 99.04 ± NR kg Height: 183.44 ± NR cm	Case series (cross-sectional)	Duration: 1 season Injuries: No Intervention: No
Maconi et al. [39]	*Moderate* 5 stars	Third division amateur Italy	23 males Age: NR Subjects $n = 12$ Mass: 94.3 ± 19.1 kg Height: 186 ± 6 cm Control $n = 11$ Mass: 92.5 ± 17.2 kg Height: 182 ± 8 cm	Cohort (retrospective)	Duration: 1 season Injuries: No Intervention: Strengthening
Naish et al. [35]	*Moderate* 6 stars	Professional Australia	27 males Age: 25.2 ± 3.9 y Mass: 102 ± 11.9 kg Height: 187.1 ± 6.3 cm	Cohort (retrospective)	Duration: 2 seasons Injuries: Yes Intervention: Strengthening
Salmon et al. [36]	*Moderate* 6 stars	Amateur New Zealand	41 males Age forwards: 22.6 ± 2.7 y Age backs: 21.6 ± 2.7y Mass forwards: 103.1 ± 10.8 kg Mass backs: 80.4 ± 22.2 kg Height forwards: 182.9 ± 6.1 cm Height backs: 180.1 ± 5.5 cm	Cohort (prospective)	Duration: 1 season Injuries: No Intervention: No
Snodgrass et al. [37]	*Moderate* 6 stars	Semiprofessional Australia	142 males **Past neck injury group** Age: 22 ± NR y Mass: 99 ± NR kg Height: 184 ± 0.07 cm **No past injury group** Age: 20 ± NR y Mass: 104 ± NR kg Height: 183 ± 0.06 cm	Cohort (prospective)	Duration: 1 season Injuries: Yes Intervention: No

Notes. **Values are means ± standard deviation.**
Abbreviations: NOS, Newcastle-Ottawa Scale; NR, not reported
* *Weak*: 0 to 3 stars. *Moderate*: 4 to 6 stars. *Strong*: 7 to 10 stars.

Table 2. Neck strength assessment and outcomes in Rugby Union.

Study	Participants	Strength assessment	Outcomes
Barrett et al. [31]	34 school-aged players (17 test players and 17 controls)	**Test**: Peak isometric **Equipment**: Load cell and head harness **Type**: Make test **Position**: Seated, neck neutral **Direction**: Extension, flexion, lateral left and right flexion **Protocol**: Mean of 3 RM x each direction and rest period of 30 seconds	**Peak isometric strength pre and post 6-week neck strengthening program (tested group)** **Pre/Post**: Flexion: 24.6/27.7 kg Extension: 38.7/45.6 kg Lateral left: 33.4/39.9 kg Lateral right: 33.1/39.1 kg Flexion with left rotation: 21.5/24.4 kg Flexion with right rotation: 21.8/23.6 kg Extension with left rotation: 31.4/35.9 kg Extension with right rotation: 31.6/35.8 kg **Key findings**: No significant differences in any direction between groups.
Davies et al. [32]	19 age-graded professional and 21 senior front-row forwards players.	**Test**: Peak isometric **Equipment**: Cell load and head harness **Type**: Break test **Position**: Seated, neck neutral **Direction**: Extension, flexion, lateral left and right flexion and left and right flexion and extension in 45° rotation **Protocol**: Mean of 3 RM x each direction and rest period of 15 seconds	**Peak isometric strength** **Baseline (SD) age-grade players**: Flexion: 26 ± 8 kg Extension: 52 ± 6 kg Lateral left: 35 ± 8 kg Lateral right: 38 ± 10 kg Flexion in 45° rotation left: 22 ± 4 kg Flexion in 45° rotation right: 20 ± 6 kg Extension in 45°rotation left: 38 ± 9 kg Extension in 45°rotation right: 39 ± 10 kg PTF/PTE ratio: 0.5 **Baseline (SD) senior players**: Flexion: 44 ± 12 kg Extension: 71 ± 9 kg Lateral left: 59 ± 11 kg Lateral right: 61 ± 11 kg Flexion in 45° rotation left: 40 ± 8 kg Flexion in 45° rotation right: 41 ± 11 kg Extension in 45°rotation left: 66 ± 9 kg Extension in 45°rotation right: 68 ± 11 kg PTF/PTE ratio: 0.6 **Key findings**: Senior players were significantly stronger than age-grade players in all neck strength measures.
Dempsey et al. [12]	10 professional players.	**Test**: Peak isometric **Equipment**: Load cell and head harness **Type**: NR **Position**: lying, neck neutral **Direction**: Extension, flexion, lateral left and right flexion **Protocol**: Peak of 3 RM x each direction holds and rest period of 60 seconds	**Peak isometric strength** **Baseline mean (SD)** Flexion: 293.8 ± 65.1 N Extension: 222 ± 49.3 N Lateral left: 221.9 ± 38.8 N Lateral right: 216.6 ± 43.2 N **Key findings**: Positive correlations were found between neck strength flexion, extension, and angular and linear accelerations in a simulated tackling situation.

(Continued)

Table 2. (Continued).

Study	Participants	Strength assessment	Outcomes
Geary et al. [41]	25 amateur players.	**Test**: Peak isometric **Equipment**: Handheld dynamometer, load cell, and head harness **Type**: Break test **Position**: Seated, head neutral **Direction**: Extension, flexion, lateral left and right flexion **Protocol**: Mean of 3 RM x each direction holds and rest period of 60 seconds	**Peak isometric strength** **Baseline (SD) forwards**: Flexion: 357.1 ± 51.6 N Extension: 637.1 ± 75.1 N Lateral left: 581.1 ± 105.4 N Lateral right: 576.4 ± 79.4 N Total: 2151.9 ± 231.1 N **Baseline (SD) backs**: Flexion: 322.2 ± 53.6 N Extension: 537.8 ± 82.2 N Lateral left: 471.3 ± 73.5 N Lateral right: 482.7 ± 93.7 N Total: 1814.2 ± 211.2 N **Key findings**: Forwards significantly stronger in extension vs backs, as well as in total isometric neck strength.
Geary et al. [43]	15 professional and 10 semiprofessional players.	**Test**: Peak isometric **Equipment**: Handheld dynamometer and head harness **Type**: Break test **Position**: Seated, head neutral **Direction**: Extension, flexion, lateral left and right flexion **Protocol**: Peak of 3 RM x each direction holds and rest period of 60 seconds	**Peak isometric strength pre and post 5-week neck strengthening program** **Pre (SD)/Post (SD)** Flexion: 334.4 ± 39.3/396 ± 75.5 N Extension: 606.1 ± 97.3/733.8 ± 127.1 N Lateral left: 555.5 ± 88.3/657.1 ± 122.9 N Lateral right: 570 ± 106.5/668 N ± 142.1 N **Key findings**: A 5-week neck strengthening program significantly increased sagittal (flexion and extension) and frontal (lateral right and left) plane isometric measures.
Hamilton et al. [33]	382 schoolchildren players.	**Test**: Peak isometric extension strength **Equipment**: Customized neck device with a load cell **Type**: Break test **Position**: Seated, head neutral **Direction**: Extension **Protocol**: Mean of 3 RM x each direction and rest period of 30 seconds	**Peak isometric extension strength** **Baseline (SD) by age**: 12 y: 18 ± 3.1 kg 13 y: 21 ± 3.9 kg 14 y: 25 ± 5.7 kg 15 y: 28 ± 6.0 kg 16 y: 30 ± 6.0 kg 17 y: 32 ± 6.3 kg 18 y: 34 ± 8.1 kg **Key findings**: Peak isometric neck extension strength increased with age from 18 kg at 12 y to 34 kg at 18 y.

(*Continued*)

Table 2. (Continued).

Study	Participants	Strength assessment	Outcomes
Hamilton, Gatherer [42]	27 professional players.	**Test**: Peak isometric **Equipment**: Customized neck device with a load cell **Type**: Break test **Position**: Seated, head neutral **Direction**: Extension, flexion, lateral left and right flexion, Left and right rotation **Protocol**: Mean of 3 RM x each direction and rest period of 30 seconds	**Peak isometric strength** Baseline (SD) forwards: Flexion: 32 ± 5.6 kg Extension: 44.9 ± 7.1 kg Left lateral flexion 42.9 ± 7.7 kg Right lateral flexion: 43.1 ± 7.5 kg Rotation left: 37.5 ± 6.9 kg Rotation right: 38.5 ± 5.5 kg Baseline (± SD) backs: Flexion: 28.5 ± 3.9 kg Extension: 39.5 ± 5.2 kg Lateral left: 35 ± 4.5 kg Lateral right: 35 ± 4.5 kg Flexion with left rotation: 33 ± 3.3 kg Flexion with right rotation: 33.4 ± 3 kg All players PTF/PTE ratio: 0.7 **Key findings**: Forwards were significantly stronger than backs in all directions, except flexion.
Hamilton et al. [34]	30 senior school-aged and 22 male adult senior school-aged front-row players.	**Test**: Peak isometric **Equipment**: Customized neck device with a load cell **Type**: Break test **Position**: Seated, head neutral **Direction**: Extension, flexion, lateral left and right flexion, Left and right rotation **Protocol**: The mean 3 RM x each direction holds and rest period of 60 seconds	**Peak isometric strength** **Baseline [95% CI] under 19 y**: Flexion: 22.5 [20.4 to 24.72] kg Extension: 41.7 [39.36 to 44.18] kg Lateral left: 32.2 [30.04 to 34.45] kg Lateral right: 31.8 [29.66 to 24.01] kg **Baseline [95% CI] adults**: Flexion: 25.4 [22.94 to 27.86] kg Extension: 53.7 [48.42 to 58.99] kg Lateral left: 40.5 [36.36 to 44.71] kg Lateral right: 42.4 [39.24 to 45.73] kg **Key findings**: Adults were significantly stronger than the under-19 group in all directions, except in flexion.
Konrath, Appleby [40]	40 professional players.	**Test**: Peak isometric **Equipment**: Customized neck device with a load cell and velcro head strap **Type**: Make test **Position**: Supine and prone and head horizontal to the floor **Direction**: Extension and flexion **Protocol**: The peak of 3 RM x each direction with 5 sec duration and rest period of 60 seconds	**Peak isometric strength** **Forwards**: Flexion: 295.2 N Extension: 328 N PTF/PTE ratio: 0.92 **Backs**: Flexion: 244 N Extension: 229 N PTF/PTE ratio: 1.28 **Key findings**: Forwards were significantly stronger in flexion and extension vs backs. Forwards had significantly lower isometric flexion to extension ratios than backs.

(*Continued*)

Table 2. (Continued).

Study	Participants	Strength assessment	Outcomes
Maconi et al. [39]	23 amateur players and 11 controls	**Test**: Peak isometric **Equipment**: Customized ergometer load cell **Type**: Flexion of the head against an unmovable support **Position**: Seated, neck neutral **Direction**: Extension, flexion, lateral left and right flexion and left and right rotation **Protocol**: The peak of 3 RM x each direction of 3 sec and rest period of 30 seconds	**Peak isometric strength pre and post 12-week neck strengthening program** **Pre (SD)/Post (SD)** Flexion: 135 ± 47/202 ± 44 N Extension: 164 ± 37/214 ± 41 N Lateral left: 137.5 ± 29.7/141.6 ± 35 N [no significant increase post training] Lateral Right: 144.2 ± 30.5/146.1 ± 31.8 N [no significant increase post training] Flexion with left rotation: 130 ± 31/165 ± 31 N Flexion with right rotation: 129 ± 31/154 ± 22 N **Key findings**: Flexion, extension, flexion with left and right rotation neck strength measures increased significantly after a 12-week training program. There were *no significant changes* in right and left flexion with training.
Naish et al. [35]	27 professional players	**Test**: Peak isometric **Equipment**: Customized load cell device, head harness, and immovable metal frame **Type**: Make test **Position**: Seated, head neutral **Direction**: Extension, flexion, lateral left and right flexion **Protocol**: The peak of 3 RM x each direction with 5 sec duration and rest period of 30 seconds	**Peak isometric strength pre and post neck strengthening program at week 5** **Pre (SD)/Post (SD)** Flexion: 277.6 ± 63.0/288 ± 64.1 N Extension: 367.7 ± 47.9/372.4 ± 50.9 N Lateral left: 363.2 ± 53.9/372.2 ± 50.6 N Lateral right: 376.4 ± 44.7/383.6 ± 51.9 N **Key findings**: An intervention of neck strengthening did not significantly affect strength values at week 5.
Olivier, Du Toit [38]	189 professional players	**Test**: Peak isokinetic torque **Equipment**: Isokinetic dynamometer **Type**: Isokinetic test **Position**: Seated, head neutral **Direction**: Flexion, extension, lateral left and right flexion **Protocol**: The peak of 3 RM x each direction and NR rest period	**Peak isokinetic strength** **Baseline [95% CI] front row forwards**: Flexion: 42.6 [39.76, 45.54] Nm Extension: 65.6 [62.12, 69.0] Nm Lateral left: 64.8 [60.65, 67.51] Nm Lateral right: 65.1 [61.08, 69.16] Nm **Baseline [95% CI] backs**: Flexion: 33.5 [32.26, 34.76] Nm Extension: 46.1 [44.38, 47.86] Nm Lateral left: 50.4 [48.25, 52.55] Nm Lateral right: 50 [48.21, 51.81] Nm **Difference of peak torque relative to body weight** PTF/BW PTE/BW Front row 0.38 [0.36, 0.40] 0.59 [0.56,0.62] Second row 0.4 [0.36,0.44] 0.57 [0.52,0.62] Back row 0.41[0.38, 0.44] 0.58 [0.54,0.62] Backline 0.4 [0.38, 0.42] 0.55[0.53,0.57] All players PTF/PTE: 70% [68.40–71.6] **Key findings**: Among positions the difference of peak torque relative to body weight was small. Extension of front row forwards significantly greater than any other player. Front row forwards were significantly stronger than backs in all peak torque measures. Peak torque ratio: Front row forwards demonstrated PTF/PTE ratios 65% lower than any other position.

(*Continued*)

Table 2. (Continued).

Study	Participants	Strength assessment	Outcomes
Salmon et al. [36]	41 amateur players.	**Test**: Peak isometric **Equipment**: Load cell and fixed-frame dynamometer **Type**: Bracing against the bench **Position**: Contact posture (tackle/scrummaging) **Direction**: Extension, flexion, lateral left and right flexion **Protocol**: 1 RM x each direction, held by 5s and rest period of 60 seconds	**Peak isometric strength pre and post 20-week Rugby Union season** **Pre (SD)/Post (SD) forwards**: Flexion: 238.8 ± 149.4/245.7 ± 125.80 N Extension: 326.6 ± 116.9/367 ± 116.73 N Lateral left: 195 ± 97.9/234.5 ± 93.31 N Lateral right: 221.5 ± 128.7/233.9 ± 90.05 N **Pre (SD)/Post (SD) backs**: Flexion 161.8 ± 51.3/175.9 ± 57.7 N Extension 253.4 ± 74.09/276 ± 60.5 N Lateral left: 169.3 ± 64.59/196.7 ± 63.46 N Lateral right: 182.2 ± 73.19/190.8 ± 48.41 N **Key findings**: Forwards exhibited higher peak values at baseline in all directions vs backs. After a 20-week in-season follow-up, neck strength in significantly improved in forwards in extension 16%, flexion 19%, left 35% and right 27% lateral flexion and backs in extension 10%, flexion 21%, and left lateral flexion in 27%. Forwards demonstrated significant improvements (35.3–59.1 N) in all directions post-season compared to controls.
Snodgrass et al. [37]	142 semiprofessional players.	**Test**: Peak isometric **Equipment**: Handheld dynamometer **Type**: Push against a manually applied force **Position**: Seated, neck neutral **Direction**: Extension, flexion, lateral left and right flexion and left and right flexion and extension with rotation **Protocol**: The mean of 3 RM x each direction NR rest period	**Peak isometric strength** Baseline (± SD) no history of neck injury: Flexion: 17.9 ± 3.5 kg Extension: 23.2 ± 2.7 kg Lateral left: 18 ± 3.6 kg Lateral right: 17.3 ± 3.6 kg Flexion with left rotation: 14.5 ± 2.2 kg Flexion with right rotation: 15.3 ± 2.7 kg Baseline (± SD) history of neck injury: Flexion: 18.2 ± 3.7 kg Extension: 22.6 ± 19.0, kg Lateral left: 18.1 ± 3.8 kg Lateral right: 17.5 ± 4.0 kg Flexion with left rotation: 14.7 ± 2.2 kg Flexion with right rotation: 15.8 ± 3.1 kg **Key findings**: No significant difference was observed in strength between players with and without a history of neck injuries.

Notes. **Values are means ± standard deviation, means [95% confidence intervals], and minimum – maximum ranges.**
Abbreviations: BW, bodyweight; CI, confidence interval; PTF, peak torque flexion.; PTE, peak torque extension; RM repetition maximal; N, Newton; Nm, Newton-meter; NR, No report; SD, standard deviation.

Figure 2. Illustration of 'break test' to assess the neck extension muscles.

scrummaging positions [36], and one study recorded the neck strength lying on a bench in a supine or prone position [40].

3.4.3 Outcomes

In five studies, neck strength was evaluated by playing position and compared between forwards and backs [36,38,-38,40–42]. In all studies, forwards were stronger than backs, but not in all directions across studies. For instance, Geary et al. [41] showed that amateur forwards were significantly stronger in extension than backs, but not in flexion or bilateral side flexion, whereas Olivier, Du Toit [38] found significantly stronger necks in forwards compared to backs in flexion, extension, and bilateral side flexion. Konrath, Appleby [40] reported significantly stronger necks in extension and flexion for forwards than backs, with larger neck girth and longer necks with greater cross-sectional area and muscle mass for forwards in both studies. Of note, Salmon et al. [36] highlighted that peak force in all directions significantly correlated with neck girth in amateur players, with greater increase in neck strength measures over a season in amateur forwards than backs despite forwards being stronger at baseline.

3.4.4 Normative values

In relation to peak isometric strength by level of competition, Davies et al. [32] showed greater values in extension, flexion, left lateral, and right lateral directions when comparing senior to junior school-aged players. Hamilton et al. [33] indicated differences in peak isometric strength in extension from 12 to 18 years. In amateur players, Geary et al. [41] indicated greater values in extension, flexion, and bilateral side flexion compared to the results by Salmon et al. [36] and Maconi et al. [39]

Flexion-to-extension strength ratios in Rugby Union were, on average, from 0.65 Olivier, Du Toit [38] to 0.7 Hamilton, Gatherer [42]. Forwards exhibited a significantly lower ratio than backs [38,40], indicating that forwards have greater extension strength relative to flexion strength. Results from Davies et al. [32] highlighted that age-grade players also had lower flexion-to-extension ratio than senior players, with lesser neck flexor strength (41%) compared to senior players, with no difference between positions.

Three studies evaluated neck strength differences between age groups and indicated that neck strength increases with age from school children to professional players [32–34]. In the study by Hamilton et al. [34], adult amateur players demonstrated significantly stronger neck strength in all directions except flexion compared to under-19s level players. In school-aged players, extension neck strength (the only direction assessed) was significantly greater in 18 compared to 12-year-old players [33]. Likewise, Davies et al. [32] reported that senior players were significantly stronger than younger age-grade players in all directions (flexion, extension, bilateral side flexion, and bilateral side flexion and extension with rotation measures).

Dempsey et al. [12] measured neck flexion and extension in ten professional players, as well as peak angular and linear accelerations using three-dimensional cameras. The test consisted of a tackle situation, and the attacking player was tracked with body markers and the contact with the defender was analyzed. These authors found a significant reduction in medial and lateral angular and linear accelerations of the head in players with stronger flexion and extension neck strength [44].

3.5 Neck strengthening programs

Four of the included studies implemented a neck-strengthening program [31,35,39,43] (Table 3). The stated goals of the studies included increasing neck strength [31,35,43], resilience to fatigue, and range of motion [31]; reducing neck soreness [39] and neck injuries [35]; and identifying neck imbalances as a potential risk factor for injuries [31]. All four training programs implemented isometric routines, with one study also implementing concentric exercises [39]. In the two studies involving professional players, one used rigid cables [35] and the other manual resistance [43] for neck strengthening; although the studies were performed at the same level of competition and implemented similar training protocols (two to three sets of 3 or 4 reps of neck holds of 3 to 10 s in four directions twice a week), differences between outcomes are likely due to the difference in timing of the strength test, strength test measures, and training loads. The other two studies performed training exercises using elastic cords with variable resistance loads in school-aged [31] and amateur players [39]. All four studies implemented neck flexion, extension, and bilateral flexion exercises; with one study incorporating right and left rotation [31]. These exercises were executed two to three times per week, usually three to four sets of four to twelve repetitions per session. The program duration varied from five to twelve weeks.

After implementing a 5-week strengthening training program, Geary et al. [43] found significant increases in neck strength in flexion (18%), extension (20%), and left (18%) and right (17%) lateral flexion. Maconi et al. [39] found greater gains in strength in neck flexion (50%), extension (30%), and bilateral rotation (left 27%, right 19%) following 12 weeks of strengthening, but not in lateral flexion. In contrast, Naish et al. [35] found no significant improvements in strength after a 26-week strengthening training period when measured at week five of the program, with no further assessment performed thereafter. Similarly, Barrett et al. [31] reported

Table 3. Neck training protocols and results.

Study	Participants	Training program	Protocol	Outcomes
Barrett et al. [31]	34 senior school-aged players (17 test players and 17 controls)	6-week duration Isometric holds with a head harness and custom variable resistance elastic cords. The control trained and played as normal.	**Type**: Isometric **Frequency**: 3 x per week **Sets and reps**: 4 sets x 6 reps **Load**: 50% MVC	**Mean change (%) intervention/control**: Flexion: 15.7/14.7% Extension: 21.7/13.2% **Mean change (raw units) intervention/control**: Flexion: 3.1/2.7 kg Extension: 6.9/4.4 kg **Key findings**: A 6-week neck strengthening program did not significantly increase neck strength in any direction compared to controls.
Geary et al. [43]	15 professional and 10 control semiprofessional players	5-week duration Isometric holds in flexion, extension, and left and right lateral flexion against a manual resistance.	**Type**: Isometric **Frequency**: 2 x per week. **Sets and reps**: 1 set x 3 reps **Load**: 10 s holds against manual resistance	**Mean increases [95% CI]**: Flexion: 61.6 [33.1, 90.03] N Extension: 127.6 [68.2, 187.0] N Left lateral flexion: 101.5 [46.4, 156.6] N Right lateral flexion: 98 [47.6, 148.3] N **Key findings**: A 5-week neck strengthening program significantly increased sagittal anc frontal isometric measures.
Maconi et al. [39]	23 amateur male players and 11 control	12-week duration Isometric and concentric strengthening using elastic bands.	**Type**: Isometric **Frequency**: 3 x per week **Sets and reps**: 3 sets x 10 reps **Load**: 10 s holds at 70% MVC **Type**: Concentric **Frequency**: 3 x per week **Sets and reps**: 3 sets x 8 reps	**Pre (SD)/Post (SD)**: Flexion: 135 ± 47/202 ± 44 N Extension: 164 ± 37/214 ± 41 N Flexion with left rotation: 130 ± 31/165 ± 31 N Flexion with right rotation: 129 ± 31/154 ± 22 N Right lateral flexion: 144.2 ± 30/146.1 ± 31 N Left lateral flexion: 137.5 ± 29.7/141.6 ± 35.0 N **Key findings**: A 12-week neck strengthening program significantly increased all neck strength measures, except for left and right lateral flexion.
Naish et al. [35]	27 professional players	26-week duration Isometric cable holds in flexion, extension, and left and right lateral flexion.	**Preseason**: Weeks 1–13 **Type**: Isometric **Frequency**: 2 x per week **Sets and reps**: 2–3 sets x 4–12 reps **Load**: 70%-100% 1RM **Maintenance phase**: Weeks 14–26 **Type**: Isometric **Frequency**: 1–2 x per week. **Sets and reps**: 2–3 sets of 3–4 reps. **Load**: 3 s holds %MVC NR	**Pre (SD)/Post (SD)** Flexion: 277.6 N ± 63/288 N ± 64.1 Extension: 367.7 N ± 47.9/372.4 N ± 50.9 Lateral left: 363.2 N ± 53.9/372.2 N ± 50.6 Lateral right: 376.4 N ± 44.7/383.6 N ± 51.9 **Key findings**: A 26-week neck strengthening program did not significantly improve neck strength measures after 5 weeks.

Notes. Values are means ± standard deviation, means [95% confidence intervals], and minimum – maximum ranges.
Abbreviations: CI, confidence interval; MVC, maximal voluntary contraction; N, Newton; NR, not report; RM, maximal repetition; SD, standard deviation.

Table 4. Neck strength and injuries.

Study	Participants	Duration	Neck strength measure and/or training program	Outcomes
Naish et al. [35]	27 professional Super Rugby Union players.	26-week training program	26-week training program Isometric cable holds in flexion, extension, and left and right lateral flexion. Preseason: weeks 1–13 **Type**: Isometric **Frequency**: 2 x per week **Sets and reps**: 2–3 sets x 4–12 reps **Load**: 70%-100% 1RM Maintenance phase: weeks 14–26 **Type**: Isometric **Frequency**: 1–2 x per week. **Sets and reps**: 2–3 sets of 3–4 reps. **Load**: 3 s holds	**2-season neck injury report**: **First season (no neck training program)**: Players injured: 8 Number of injuries: 12 Training injuries: 1 Match injuries: 11 **Second season (with neck training program)**: Players injured: 6 Number of injuries: 6 Training injuries: 4 Matches injuries: 2 **Key findings**: Significant reduction in match neck injuries, not in peak strength values after a neck strengthening program.
Snodgrass et al. [37]	142 semiprofessional players.	Pre-season	Pre-season assessment of neck strength, anthropometrics, proprioception, and range of motion. Neck injuries monitored during a competitive Rugby Union season.	**Characteristics of the 11 neck injuries**: **Position**: Front row: 5 (45%) Back row: 5 (45%) Wing: 1 (10%) **Phase of play**: Tackle: 7 (64%) Scrum: 1 (9%) Ruck: 2 (18%) Maul: 1 (9%) **Concussion**: Yes: 4(36%) No: 6 (55%) ***missing data** **Previous neck injury**: Yes: 7 (63%) No: 4 (36%) **Key findings**: Older and more experience players had more history of previous neck injuries.

Abbreviations: RM, maximal repetition.

that a 6-week training program did not significantly increase neck strength in any direction.

3.6 Neck strength measures, training programs, and injuries

Two of the studies reviewed considered the relationship between neck strength measures, neck strength training programs, and injuries in Rugby Union [35,37] (see Table 4). Naish et al. [35] performed a 26-week isometric neck-strengthening program in professional players across two competition seasons. In the second season, a neck strengthening program was introduced (13-week strengthening period followed by a 13-week maintenance) and compared injury reports to the previous season. The results indicated that the athletes had a significant reduction in neck injuries during matches played within the neck strengthening program. In their retrospective analysis, there was a significant reduction in match neck injuries from eleven to two after the intervention program.

The other longitudinal study that aimed to understand the association between physical characteristics and incidence of neck pain and injuries by Snodgrass et al. [37] evaluated 142 semiprofessional players. The neck assessment included measurements relating to neck strength, anthropometrics, proprioception, and range of motion. No significant difference was found in neck strength when comparing players with or without a history of neck injury. On the other hand, a greater number of previous neck injuries were observed with increasing age and playing experience. In-season neck injuries were associated with a reduced range of motion in left and right lateral flexion.

4. Discussion

4.1 Neck strength measures in Rugby Union

In Rugby Union, neck strength has been measured in a number of studies with the intention of determining differences between age groups, positions, and injury prevalence [12,31–43]. We examined the scientific literature addressing neck strength in Rugby Union with a focus on neck strength assessment protocols training programs and relationships with injuries. The studies included in this review were implemented with male players; therefore, we advise against the generalization of findings to female players due to – amongst other reasons – the previously reported physiological differences between sexes [45]. Furthermore, pooling results across studies to make strong inferences is challenging given the various testing procedures, equipment, and units used.

Isometric neck strength was assessed in nearly all studies, except in one where isokinetic strength was examined [38]. Overall, the 'break test' displayed greater neck strength values compared to the other methods of testing although no direction comparisons between testing methods have been undertaken, and the outcome of these tests showed strength variations based on player characteristics, positions, and level of competition. Adopting a standardized method of assessment of neck strength to compare outcomes across studies is of upmost importance. Indeed, there is a lack of consistency between studies, and no dynamic and eccentric testing procedures. As such, important physical properties (i.e. stiffness) of the neck musculature are not currently being examined with respect to their association to neck, head, or concussion injury risk in Rugby Union [46].

4.1.1 Methodological discussion

Salmon et al. [36] assessed amateur players with a fixed-frame dynamometer in a rugby specific position (similar body position to player running into contact or scrum position) and found stronger necks in all directions for forwards compared to backs at baseline. At the conclusion of a playing season, both forwards and backs (except in right lateral flexion) exhibited greater neck strength, with the improvement being somewhat unexpected for the backs given their lesser contact demands and associated neck loading. In contrast, Geary et al. [41] assessed neck strength in a seated position in a 'break test' fashion and found greater extension strength in forwards than backs, and not in any other direction. This difference in strength outcomes between positions could be attributable to the rugby specific position used by Salmon et al. [36] with the isolation of the neck muscles and the improved neuromuscular recruitment assumed in the scrummaging posture. Furthermore, it could be that this rugby specific position was more familiar for forwards given their scrummaging on-field role, with the test position being unfamiliar for backs. From these studies, the considerable variation in test methods is clear; therefore comparing studies to build up a picture of neck strength in players and to get a definitive relationship between neck strength and injury is challenging with the current literature.

4.1.2 Position effects in neck strength

Variables such as greater body mass [36,38,40–42], larger neck girths [36,38,40], and longer necks [36,40] were associated with stronger necks in forwards compared to backs. In professional players, greater body mass was associated with larger cross-sectional neck areas and stronger necks [42]. At this level, forwards from Geary et al. [43] displayed the highest isometric strength values in this review. The test was performed in a 'break test' manner, with forwards being stronger than backs in all four directions. To date, there is no consensus regarding what strength values at this or at any level of competition should be targeted and sufficient to minimize risk of injury. Indeed, levels of neck strength require further investigation to assist coaches and players to understand what is required to prevent injury and/or decrease injury severity. We strongly suggest that recommendations be prescribed regarding neck strength in younger rugby athletes given the 'in-game' stressors such as scrum, ruck, maul and collision and the rising numbers of head injuries observed.

4.1.3 Neck strength ratios

With regard to the ratio between flexion and extension, forwards appear to have a significantly lower ratio compared to backs [38,40], with greater extension strength measures compared to flexion. These findings are probably due to the neck extension forces exerted by forwards to keep the neck stable during scrummaging. In relation to age, younger players showed lower flexion to extension ratios compared to senior players [32]. These discrepancies in neck musculature are a potential risk factor for neck injuries, where a flexion to extension ratio imbalance having been associated with higher head angular and linear accelerations in other cohorts [47]. Promoting strength symmetry between muscles is a strategy used in practice in attempts to mitigate injury risk in other anatomical parts of the body (e.g. knee) [48]. The neck is not except as symmetry in muscle strength between flexors and extensors is crucial in neck stabilization [49].

4.2 Neck strengthening training programs

In the studies reviewed, four studies implemented neck strengthening programs in Rugby Union players. Two studies reported a significant increase in neck strength of the players post intervention [39,43], and two reported no improvements [31,35]. In a longer 12-week intervention that added concentric exercises, Maconi et al. [39] found a significant increase in strength in all directions except in bilateral side flexion. This research group also noted improvements in coactivation of neck muscles, motor recruitment, and muscle firing rate patterns of neck musculature using electromyography.

The American College of Sports Medicine (ACSM) guidelines for exercise prescription [50] recommend for resistance strength training the following routine: frequency of 2 to 3 times per week, with 2 to 4 sets of 8 to 12 repetitions at a load of 60% to 70% for intermediate and >80% for experienced participants to improve strength and power. Based on these parameters, the most comprehensive training strategies were implemented by Geary et al. [43] and Naish et al. [35] using isometrics, and Maconi et al. [39] using isometrics and concentric exercises. Barrett et al. [31] performed lower training intensities and repetitions than the ACSM recommendations, using 50% of maximal voluntary isometric contractions and 6 repetitions. This exercise prescription might have not induced enough stimulus to produce improvement in strength.

As mentioned previously, most protocols undertaken in rugby were performed with isometric exercises without dynamic, neuromuscular, or eccentric training routines. Lisman et al. [51] implemented an 8-week isometric resistance training for the neck muscles in collegiate NFL players. The intervention was effective in increasing left lateral flexion (7%) and extension strength (10%), but did not affect tackling head accelerations or activation of neck stabilizers during tackling. These results hence suggest that isometric neck strength alone may be insufficient to reduce incidence and severity of head injuries and that training stabilizer muscles, and that incorporating neck stabilization training modalities could be important. This proposition is supported by results from Schmidt et al. [52] who demonstrated that stronger and larger necks were not protective of head injuries in NFL players, whereas stiffer and more responsive neck musculatures to cervical perturbations were protective. Modeling studies substantiate that strengthening strategies in American football and other contact sports should include eccentric training and preparation for impact exercises to reduce head injury metrics [53]. Despite very different rules and regulations regarding mandated protective equipment between American Football and Rugby Union, these studies overall highlight the importance of diverse neck training strategies in decreasing the severity of impacts. Future research in rugby should seek to implement neuromuscular, eccentric, and anticipation for impact training to determine their relevance and effectiveness in the context of concussions in rugby.

4.3 Neck strength measures, training programs, and injuries

Injury risk factors, including neck asymmetries, previous injuries, as well as deficits in range of motion and proprioception, have not been linked to neck and head injuries in Rugby Union players [54]. Despite the introduction of a new tackle rule, the incidence of concussions in professional players continue to increase [11,55]. It would seem that improving neck strength should be a priority in any injury prevention and performance program in Rugby Union. Neck strength values can assist in the preparation and screening of rugby players at every level, i.e. targeting specific preseason training strategies; as well as providing a clinical tool to aid the rehabilitation of cervical injuries or return to play protocols. Few studies have examined the relationship between neck strength values, neck strengthening exercises, and the incidence of neck and head injuries [35,37].

Naish et al. [35] presented a paradoxical result, wherein the decrease in the number of neck match injuries was not associated with changes in neck strength values after a strengthening program. The researchers attributed this result to neurological changes in neck proprioception, greater stabilization of deep cervical flexors, and improvements in muscle coactivation due to the training program. A limitation could exist in the neck strength evaluation, which was only measured at week five of the 26-week program, with no further assessments undertaken. As such, it is uncertain whether neck strength changes occurred after the initial 5-week period and the extent to which they influenced the prevalence of neck injuries.

None of the studies in the current review evaluated the association between neck strength or strengthening programs and the incidence of concussion injuries. However, Dempsey et al. [12] found players with stronger necks in flexion and extension had a significant reduction in medial and lateral angular and linear head accelerations. The pre-activation of the neck flexor and extensor muscles before a collision has been shown to significantly decrease the peak linear velocity and deaccelerating of the head [14,15]. As such, there is the potential for neck strength to reduce concussion risk in Rugby Union. However, the systematic review by Le Flao et al. [56] found no clear relationship between neck strength and head/neck accelerations and their influence on concussion injuries, and a review of the literature by Hrysomallis [57] found inconsistent outcomes that increasing isometric neck strength reduce head accelerations and therefore a better head stabilization with impact anticipation strategies.

5. Conclusion

In Rugby Union, neck strength has been measured through different playing positions and levels of competition; however, there is no consensus regarding a standardized method to assess neck strength in Rugby Union. All studies have been completed in a male population, with an obvious gap pertaining to the assessment of neck strength in female athletes. Nonetheless, senior elite male players were stronger than younger-aged players, which could be due to their immature musculature and/or lesser training experience. Forwards were stronger in extension than any other directions assessed, and when compared to backs, were generally stronger and possessed larger necks and greater cross-sectional areas.

Implementation of isometric exercise routines in professional players has been reported to improve neck strength in all directions. Whilst the training programs across levels showed different outcomes, establishing an evidence-based strengthening routine with different exercise modalities (i.e. isometric, eccentric, and concentric) is essential. Moving forward, work should be undertaken to further standardize and develop guidelines regarding strength test protocols and benchmark values, as well as training protocols across age groups and performance levels.

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Declaration of interest

None to declare.

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Appendix A2. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review

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REVIEW

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Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: a systematic review

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ABSTRACT

Background: Hamstring strain injuries are one of the most common injuries in Rugby Union, representing up to 15% of all injuries sustained. We aimed to systematically review and summarize the scientific literature that addressed hamstring strain injury incidence, risk factors, injury prevention or strengthening strategies, and strength or asymmetry measures in Rugby Union.

Methods: We conducted a systematic search to locate published peer-reviewed articles from PubMed, SPORTDiscus™, Web of Science®, and Scopus® e-databases. Studies included were original research conducted in Rugby Union that evaluated hamstring strength, hamstring strengthening interventions, and/or hamstring injury outcomes. Included studies were quality assessed using the Newcastle-Ottawa Scale.

Results: Twenty-four studies met inclusion and altogether involved 2866 participants. Isokinetic testing was the most common method used to quantify hamstring strength and imbalances in Rugby Union; with data indicating that professionals are stronger than amateurs, and forwards are stronger than backs. Regarding risk factors, we identified playing position, fatigue, previous injuries, between leg strength imbalances, lack of readiness to return to play post injury, and game actions (i.e. running). There is evidence to support the use of Nordic eccentric strength measures to inform practice, with strength and imbalances useful in predicting injuries. Strengthening programs with Nordic exercises significantly increased hamstring strength, increased muscle thickness, and decreased imbalance ratios in female and male players. A significant reduction in injury incidence and severity in professional players has been observed in players performing routines incorporating progressive Nordic exercises.

Conclusion: The etiology of hamstring strain injuries is multifactorial, with playing position, fatigue, previous injuries, leg imbalances, lack of readiness to return to play, and running actions identified as contributing factors across levels. Combining strategies to prevent hamstring injuries and recurrences, and to inform return to play, is likely worthwhile and should include Nordic strength assessment and Nordic exercises.

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1. Introduction

Hamstring strain injuries are one of the most common injuries in Rugby Union and represent 6 to 15% of all sustained injuries [1]. With respect to the epidemiology of hamstring injuries, acute hamstring strains have the highest recurrence rate of any muscle injury [2]. A previous hamstring injury is a paramount risk factor to sustaining another hamstring injury [3] and the elevated risk is proposed to be due to residual neuromuscular inhibition, strength deficits, altered muscle tendon morphology, and modified contractile mechanics [2].

The 2019 Rugby World Cup injury surveillance data revealed lower limb injuries accounted for almost 50% of all players absence days [4]. Hamstring strains were the second most common match injury after concussion, with hamstring injuries representing 9.8% of all match injuries and causing 467 missed days. The England Rugby Football Union reported that hamstring strains were their most common injury during training and the second most common injury during match play with 6.4 injuries per 1000 hours [5]. Moreover, the Welsh injury surveillance report from 2012 to 2016 recorded an increase in posterior thigh injury from 6.7 to 7.7 per 1000 hours, as well as 155.7 to 172.6 days lost during that time frame [6]. Hamstring strains are also of considerable concern at a younger school-age level, representing 21% of all injuries [7] and comprising 23% of all training time-loss in male amateur players.

Regarding prevention of sport-related injuries, a multifactorial approach is required and should involve the monitoring of intrinsic and extrinsic factors [8,9]. For instance, asymmetries in strength between muscle groups and limbs are commonly assessed and used as screening methods in sports [10,11]. Strength imbalances between quadriceps and hamstrings have been linked to a four to five times greater risk of hamstring strain in football players, with an asymmetry in hamstring strengths between sides of 10–15% also considered to represent a risk for hamstring strains [12]. These imbalances appear more evident at slower angular velocities, and

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decrease at higher velocities [13]. Hamstring strength deficits and imbalances have been targeted with Nordic eccentric strengthening exercises, and a reduction of 51% in hamstring injury incidence across team sports was reported in a literature review and metanalysis of 8,459 athletes [14], including in Rugby Union [1].

Training and playing load variables, such as the number of high-speed running events, have been associated with hamstring injury occurrence in team sports and investigated mainly in football [15,16]. Although hamstring injuries often occur during the eccentric phase of running or kicking in rugby, similar to other team sports, severe hamstring strains can also occur because of specific-game related events in rugby, such as during tackles and competing for the ball on the ground [17]. In the tackling position, the hamstring is stretched fully, and the addition of a collision can further stretch the muscle, leading to a tendinous-junction tear. This mechanism of injury may be responsible for the increasing severity of hamstring injuries seen in Rugby Union in recent years [5], which is dissimilar to hamstring mechanisms in other sports. Thus, rugby demonstrates unique susceptibility and risk factors that require position-specific injury profiling to better target physical preparation and injury prevention strategies [18]. Given that player availability correlates with team success [19], research that targets injury prevention also has performance implications.

To prevent such injuries, it is important to identify how individual characteristics and game dynamics relate to contact and non-contact injury incidence. Therefore, we sought to critically examine and summarize the existing scientific literature on the topic of hamstring strain injuries in Rugby Union specifically. In particular, we aimed to systematically review and summarize the scientific literature that addressed hamstring strain injury incidence, risk factors, injury prevention and strengthening strategies, and strength or asymmetry measures in Rugby Union.

2. Materials and methods

2.1. Information sources and search strategy

We conducted a systematic review of the literature following the Preferred Reporting Items for Systematic Reviews and Metanalysis guidelines [20]. One author (CC) and one reviewer (CC) performed a systematic search on September 4th, 2020 to locate published peer-reviewed articles from four electronic databases: PubMed, SciVerse Scopus, SPORTDiscus™, and Web of Science®. The search strategy consisted of the following keywords and Boolean operators entered in the main search bar of each e-database: 'hamstring AND rugby.' The exact resulting search syntax in PubMed was: ('hamstring muscles'[MeSH Terms] OR ('hamstring'[All Fields] AND 'muscles'[All Fields]) OR 'hamstring muscles'[All Fields] OR 'hamstring'[All Fields] OR 'hamstrings'[All Fields]) AND ('football'[MeSH Terms] OR 'football'[All Fields] OR 'rugby'[All Fields]), SciVerse Scopus was: TITLE-ABS-KEY(hamstring AND rugby), SPORTDiscus™ was: Boolean/Phrase: (hamstring AND rugby), and Web of Science® was: TOPIC: (hamstring AND rugby).

2.2. Inclusion and exclusion criteria

Articles were included when they were original, peer-reviewed research studies written in the English language, involved Rugby Union players, and included one or several of the following hamstring-related information: hamstring injury incidence, risk factors, strengthening or injury prevention programmes, and/or hamstring strength or asymmetry measures in Rugby Union players, regardless of sex, age and level of competition. Articles were excluded if these were not in the English language or did not involve Rugby Union players.

2.3. Screening process

Duplicates from the initial database search were removed first. Subsequently, two reviewers (CC, KHL) independently screened all remaining titles, abstracts, and full texts sequentially for inclusion. The study selection process was replicated for articles that were located through other sources (e.g. Google Scholar) and reference lists of included full-text articles. The two reviewers met to discuss any disagreements during the screening process and agreed on the articles to be included.

2.4. Quality assessment

Two reviewers (CC, IH) independently assessed the methodological quality of included studies (n = 24) using the Newcastle – Ottawa Scale (NOS) [21]. The reliability of the NOS for case-control and cohort studies has fair to good inter-rater reliability and validity [22]. This tool was used as it is recommended by the Cochrane Collaboration [23], is a suitable alternative to other available tools to assess risk of bias [24], and could be used across the included studies. The NOS for case control and cohort studies was used across studies for ease of implementation and interpretation. Prior to assessment, the two reviewers met to discuss and familiarize themselves with the scales. All identifiable information (i.e. authors, affiliations, countries, and sources of publication) were removed from articles to reduce likelihood of assessment bias. Disagreements in the scores were resolved by discussion between the two reviewers, and consensus scores are presented in this article.

The tool uses a 'star system,' wherein more stars indicate a superior methodological quality and lower risk of bias. The NOS awards a maximum of 10 stars: five stars for selection (representativeness of the sample, sample size, non-respondents, and ascertainment of the exposure), two stars for comparability, and three stars for outcome (assessment of outcome and statistical test). Reviewers agreed that for the statistical test item, the highest star rating would be allocated for the reporting of confidence intervals, quartiles, or limits of agreement. The methodological quality of studies was divided into three groups based on the number of stars awarded: *weak* (0 to 3 stars), *moderate* (4 to 6 stars), and *strong* (7 to 10 stars) [25]. The design of each study was classified as cohort studies, case series, cases and controls, or randomized controlled trial.

2.5. Data extraction and synthesis

The first author (CC) extracted data from the selected full-text articles using a data extraction template customized to suit this review, and the last author (KHL) verified the data extracted. For each study, study design, participant information, level of competition, location of the study, study characteristics, assessment methods, and outcome data specific to hamstrings were extracted. Data were grouped and extracted under main themes of interest: (1) hamstring injury incidence and risk factors; (2) hamstring strengthening and injury prevention programmes; and (3) hamstring strength or asymmetry assessment methods and measures. Data were managed and analyzed using Microsoft® Office Excel 2016 (Redmond, Washington). Conducting a meta-analyses on data was not considered given the aims of this review to summarize the existing literature, the high degree of heterogeneity of the data in the included studies, and the inappropriateness of pooling results from studies with different study designs, injury definitions, and outcome measures.

3. Results

3.1. Included studies

The flow diagram from the search strategy and screening process is shown Figure 1. Twenty-four studies met the eligibility criteria.

3.2. Study characteristics

The main characteristics of the 24 studies that met inclusion are presented in Table 1. Based on Newcastle-Ottawa Scale NOS, most studies were of *moderate* quality (n = 13, 54%) [26–36]. Ten articles were of *strong* quality (40%) [1,37–45], and one study was defined as *weak* quality (6%) [46].

3.3. Participants

The 24 studies that met inclusion comprised of 2866 participants, male players were involved in 21 studies [1,27–45,47], one study involved female players [26], and two studies included both males and females [46,48]. Eleven articles were conducted with professional players [1,27,33,36–39,41,43–45], ten with amateur players [26,28–32,34,42,46–49], two with semiprofessional players [40,42], and not enough information about the level of competition was available in one study [35]. The articles were designed as cohort studies in

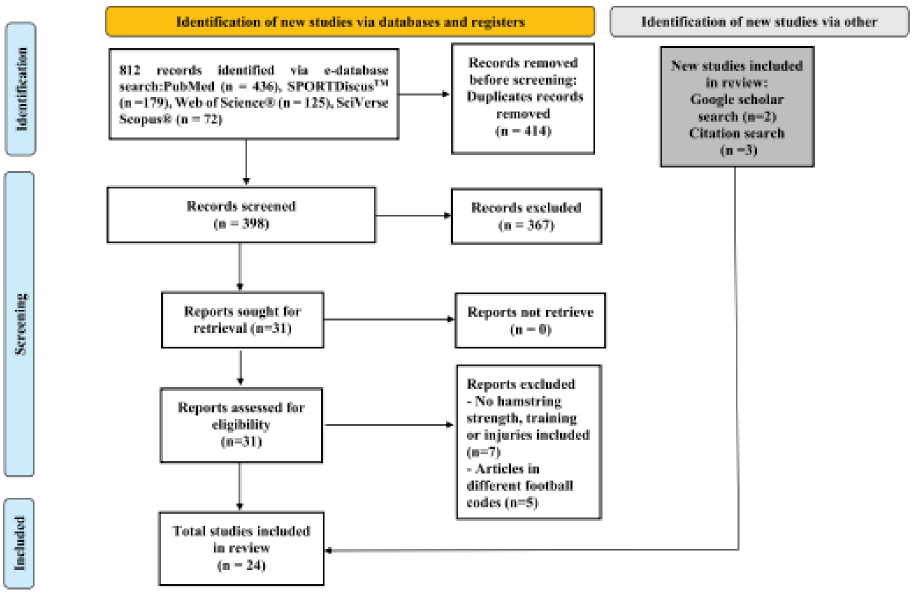

Figure 1. Preferred reporting items for systematic reviews and meta-analyses flow chart.

Table 1. Characteristics of the 24 included studies.

Study	NOS rating*	Player characteristics	Study designLocation	Study aims	Key study characteristics
Abdelfettah et al. [47]	Moderate5 stars	10 male amateur playersAge: 26.4 ± 5.1 yMass: 83.2 ± 15.3 kgHeight: 177.9 ± 8.3 cm	Cohort(cross-sectional) Morocco	Compare the strength of the knee flexors and extensors between soccer and rugby players and the level of strength by playing positions	Duration: 1 seasonInjuries: NoIntervention: No
Anastasi, Hamzeh [26]	Moderate5 stars	24 female amateur players (13 test players and 11 controls)Age: 25.2 ± 5.3 yMass: 69.5 ± 10.9 kgHeight: 166 ± 5.0 cm	Case controlUnited Kingdom	Evaluate the effect of hamstring eccentric program on leg strength imbalance and maximal vertical jump height	Duration: 1 seasonInjuries: NoIntervention: Yes
Beyer et al. [31]	Moderate4 stars	25 male amateur players.Age: 20.7 ± 2 yMass: 86.8 ± 15.4 kgHeight: 179 ± 8.0 cm	Case series (laboratory investigation)USA	Compare isotonic versus isometric strength measures between players with < 2 years and ≥ 2 years of experience	Duration: 1 seasonInjuries: NoIntervention: No
Bourne et al. [37]	Strong8 stars	178 male players (75 professionals and 103 semiprofessionals subdivided in 65 sub-elite and 38 under 19s)Age: 22.6 ± 3.8 yMass: 96.5 ± 13.1 kgHeight: 185.0 ± 6.8 cm	Cohort (prospective)Australia	Determine the thresholds of hamstring strength imbalance in eccentric Nordic exercises and association with hamstring injuries	Duration: 1 seasonInjuries: YesIntervention: No
Brooks et al. [38]	Strong9 stars	546 male professional playersAge: 25.3 ± 4.1 yMass: 100.0 ± 12.1 kgHeight: 185.1 ± 7.4 cm	Cohort (prospective)United Kingdom	Study match injuries in professional players and define incidence, etiology, and severity	Duration: 2 seasonsInjuries: YesIntervention: No
Brooks et al. [39]	Strong9 stars	502 male professional playersAge: 25.3 ± 4.1 yMass: 100 ± 12.1 kgHeight: 185.1 ± 7.4 cm	Cohort (prospective)United Kingdom	Study training injuries in professional players and define incidence, etiology, and severity	Duration: 2 seasonsInjuries: YesIntervention: No
Brooks et al. [1]	Strong9 stars	546 male professional playersAge: 25.3 ± 4.1 yMass: 100 ± 12.1 kgHeight: 185.1 ± 7.4 cm	Cohort (prospective)United Kingdom	Describe incidence, risk factors, and severity of hamstring injuries and the impact of hamstring strengthening and stretching exercises on injury incidence and severity	Duration: 2 seasonsInjuries: YesIntervention: No
Brooks, Kemp [43]	Strong7 stars	899 male professional playersAge: 25.3 ± 4.1 yMass: 100 ± 12.1 kgHeight: 185.1 ± 7.4 cm	Cohort (prospective)United Kingdom	Examine match injury profile of professional players by playing positions	Duration: 2 seasonsInjuries: YesIntervention: No
Brown et al. [28]	Moderate4 stars	25 male professional playersAge: 25 ± 3 yMass: 103 ± 12 kgHeight: 186 ± 7.0 cm	Cohort(cross-sectional)New Zealand	Determine lower-limb strength profiles and compare isokinetic knee and hip strength of professional players	Duration: 1 seasonInjuries: NoIntervention: No
Brown et al. [30]	Moderate4 stars	30 male amateur players(15 forwards and 15 backs)**Forwards**Age: 20 ± 1 yMass: 103 ± 11 kgHeight: 190 ± 1.0 cm**Backs**Age: 24 ± 4 yearsMass: 90 ± 8 kgHeight: 180 ± 0.0 cm	Cohort(cross-sectional)New Zealand	Determine lower-limb strength profile and compare isokinetic measures between limbs and positions	Duration: 1 seasonInjuries: NoIntervention: No
Deighan et al. [29]	Moderate4 stars	11 male amateur playersAge: 19.3 ± 0.8 yMass: 92.8 ± 12.6 kgHeight: 182.2 ± 8.0 cm	Cohort(cross sectional repeated measure laboratory test)United Kingdom	Determine differences in peak torque and strength ratios between positions (seated and supine) and examine the relation of position with joint velocity	Duration: 1 seasonInjuries: NoIntervention: No
Dobbs et al. [46]	Weak2 stars	19 amateur players (11 females and 8 males)**Males**Age: 22.0 ± 2.6 yMass: 80.3 ± 11.1 kgHeight: 172.7 ± 6.1 cm**Females**Age: 24.7 ± 3.7 yMass: 74 ± 18.1 kgHeight: 164 ± 5.2 cm	Cohort(cross-sectional)USA	Measure H:Q and DCR in male and female amateur players and assess differences in muscle strength and imbalance	Duration: 1 seasonInjuries: NoIntervention: No
Fanan et al. [32]	Moderate5 stars	54 male amateur playersAge: 21 ± 2 yMass: 88.1 ± 10.7 kgHeight: 183 ± 5.2 cm	Cohort (prospective)Ireland	Determine hamstring injuries incidence, and severity	Duration: 1 seasonInjuries: YesIntervention: No

(*Continued*)

Table 1. (Continued).

Study	NOS rating*	Player characteristics	Study designLocation	Study aims	Key study characteristics
Kenneally-Dabrowski et al. [45]	Strong7 stars	74 male professional playersAge: NRMass: NRHeight: NR	Cohort (retrospective) Australia	Describe hamstring injuries (severity, grade, and location) and the relationship with game demands	Duration: 5 seasonInjuries: YesIntervention: No
Kenneally-Dabrowski et al. [44]	Strong7 stars	10 male professional playersAge: 27.3 ± 3.2 yMass: 100.9 ± 13.1 kgHeight:193 ± 9.0 cm	Cohort (prospective)Australia	Analysis of the relationship between overground high-speed running mechanics and hamstring injury	Duration: 1 seasonInjuries: YesIntervention: No
Mendiguchia et al. [33]	Moderate4 stars	1 male professional playerAge: 23 yMass: 94 kgHeight: 187 cm	Case series(laboratory investigation)New Zealand	Determine the changes in sprinting mechanics in relation to hamstring injuries	Duration: 1 seasonInjuries: NoIntervention: No
Mondin et al. [36]	Moderate4 stars	10 male professional players and 14 healthy controlsAge: 23.1 ± 2.5 yMass: 88.4 ± 8.5 kgHeight: 180.9 ± 8.2 cm	Cohort(repeated-measures reliability)United Kingdom and Italy	Measure hamstring strength with a sphygmomanometer test and the correspondence with an isokinetic dynamometry test.	Duration: 1 seasonInjuries: NoIntervention: No
Reid et al. [27]	Moderate6 stars	8 male professional playersAge: 27.9 ± 4.8 yMass: 99.1 ± 9.9 kgHeight: 185 ± 8.0 cm	Case seriesIreland	Demonstrate the application of GPStechnology in the management of return to play	Duration: 1 seasonInjuries: NoIntervention: No
Roberts et al. [42]	Strong7 stars	189 male community playersGroup A: semiprofessionalGroup B: amateurGroup C: recreationalAge: NRMass: NRHeight: NR	Cohort (prospective)United Kingdom	Establish injury incidence and severity in community rugby and assess differences between levels	Duration: 3 seasonInjuries: YesIntervention: No
Severo-Silveira et al. [41]	Strong8 stars	21 male professional players(11 in the Constant group and 10 in the Progressive group)**Constant group**Age: 27.2 ± 3.4 yMass: 90.1 ± 14.3 kgHeight: 175 ± 0.1 cm**Progressive group**Age: 25.2 ± 3.3 yMass: 88.6 ± 12.8 kgHeight: 176 ± 0.1 cm	Randomized control trialBrazil and Australia	Study the effect of 2 different Nordic hamstring training programs (constant versus progressive) on multiple risk factors for hamstring strain injury	Duration: 1 seasonInjuries: NoIntervention: Yes
Turl, George [40]	Strong7 stars	28 male semiprofessional (14 tested players and 14 controls)Age: 29 ± 3 yWeight: 88 ± 12 kgHeight: 181 ± 1.0 cm	Cases and controls (cross sectional)United Kingdom	Existence of adverse neural tension in players with grade I hamstring injuries	Duration: 1 seasonInjuries: YesIntervention: No
Upton et al. [35]	Moderate5 stars	44 male NR level playersAge: 23 ± 3 yWeight: NRHeight: NR	Cohort (prospective)South Africa	Determine if the use of thermal pants reduce the risk of hamstring injuries.	Duration: 1 seasonInjuries: YesIntervention: Yes
Yamada, Mastumoto [34]	Moderate5 stars	21 male amateur playersAge: 21.3 ± 0.3 yWeight: 71.8 ± 6.3 kgHeight: 172.2 ± 4.1 cm	Cohort(laboratory investigation)Japan	Determine the relationship between motor imagery and hamstring injuries.	Duration: 1 seasonInjuries: YesIntervention: No
Yeomans et al. [48]	Moderate6 stars	137 amateur players (13 males and 24 females)**Males**Age: 22.7 ± 3.9 yWeight: Forwards 102.8 ± 10.9; Backs 85.4 ± 7.9 kgHeight: Forwards 180.5 ± 23.6; Backs 179.5 ± 4.8 cm**Females**Age: 25.6 ± 4.9 yWeight: Forwards 87.3 ± 14.1; Backs 69.5 ± 11.3 kgHeight: Forwards 169.8 ± 3.8; Backs 165.9 ± 7.1 cm	Cohort (prospective)Ireland	Determine risk factors associate to injuries.	Duration: 1 seasonInjuries: YesIntervention: No

Values are means ± standard deviations.
Abbreviations: DCR, isokinetic dynamic control ratio; H:Q, isokinetic hamstring quadriceps ratio; GPS, global positioning system; NOS, Newcastle-Ottawa Scale; NR, not reported.
* Weak: 0 to 3 stars; moderate: 4 to 6 stars; strong: 7 to 10 stars.

18 cases (75%) [1,28,30,32,34,35,37–39,42–48], case series in three (13%) [27,31,33], case–controls in two (8%) [26,40], and a randomized control trial (4%) [41]. Studies were conducted in the United Kingdom (n = 9) [1,26,29,36,38–40,42,43], Australia (n = 4) [37,41,44,45], New Zealand (n = 3) [28,30,33], Ireland (n = 3) [27,32,48], USA (n = 2) [31,46], Morocco (n = 1) [47], Japan (n = 1) [34], and South Africa (n = 1) [35] (Table 1).

3.4. Hamstring injuries: incidence and risk factors

3.4.1. Professional level

Hamstring strain injuries caused the greatest number of days of absence diagnosed in backs and was ranked third in forwards after shoulder and lumbar disc injuries [39]. In a two-part study involving professional players across two seasons, Part One monitored match injuries and Part Two monitored training injuries. In the first part, the incidence of hamstring strain injuries of backs were nearly three times greater than forwards [38]. Additionally, hamstring injuries were the most severe diagnosed injury in the backs and resulted in 17 days of absence. The lower limb was the most common anatomical site injured, with hamstring strains being the second most common injury in backs after thigh hematomas. Running was the most frequent mechanism of hamstring injury in game. In contrast to matches, forwards and backs had a similar incidence and mechanism of hamstring injuries during training [39], with more incidence of injuries during the preseason, with running again being the most common mechanism of injury, see Table 2.

Retrospective data analysis across five seasons in professional players indicated that 6% of all injuries were to the hamstring, with most hamstring injuries occurring during training and preseason [45]. Hamstring injuries occurred more whilst running, with similar incidence between forwards and backs. The median days lost for hamstring injury was 26 days, and most of the injuries were moderate (60%), or severe (37%). The running mechanics of 10 professional players were analyzed. Injured players had greater ipsilateral thoracic lateral flexion, absorbed greater power at the knee, and had greater hip extension moment [44].

Brooks, Kemp [43] examined player injuries by playing position. Regarding severity of hamstring injuries, fly halves were the most affected players, followed by centers, wings, and the blind side flankers who presented with the most severe hamstring injuries whilst running. Data regarding hamstring injuries were also collected when implementing different hamstring training programs [1]. The incidence was similar between dominant and non-dominant legs. Overall, the most severe hamstring injuries happened during kicking. During matches, hamstring injuries were most frequent and severe in the last 20 minutes, and substitute players had twice as many injuries as starting players; however, both starters and substitutes had similar rates of recurrence.

Another study on hamstring strain injuries in professional players found that backs were the most affected players, with 21 days of absence overall [37]. The majority (45%) of injuries were recurrences from the past season and 24% recurred in the same season. Most of the injuries involved the biceps femoris and occurred while running. Comparing the players with a recurrent injury, players with a previous hamstring injury in the last 12 months had 4.1 times higher risk of suffering a recurrent injury compared with players with no history of hamstring injury. Imbalances between limbs of more than 15% increased the risk of having a hamstring injury by 2.4 times; moreover, imbalances of more than 20% increased this figure to 3.4 times.

Regarding return to play after injuries, a five-week program to return to play with GPS technology was designed [27], and the recommendation to return to play after a hamstring injury was based on the ability to reach a running speed and intensity similar to pre-injury. The rehabilitation therapy recommended focusing on achieving maximum speed and long distances; involving cutting, passing, kicking, grappling, tackle drills, and wrestling; and achieving full training activities before returning to play. In one case study, a professional male Rugby Union player demonstrated an 'abnormal' force-velocity profile during a 40-m sprint that resulted in an acute hamstring strain. The injurious sprint was characterized by an increase in horizontal force production compared to velocity when contrasted to his previous sprints and force-velocity profiles of his uninjured teammates [33].

3.4.2. Semi-professional, amateur, and school level

A community-level investigation across three seasons identified that hamstring strain injuries occupied the fifth place in terms of total injuries [42]. Running was the most frequent action of the game to produce hamstring injuries, and backs had a higher incidence than forwards. Hamstring injuries more frequently occurred in the first quarter of the game. At the amateur level, a prospective study with 65 players involving questionnaires found that 21% of all match and 30% of all training injuries were hamstring strain injuries [32].

With regards to the risk factors for hamstring injuries, three investigations have been conducted; the first followed semi-professional players with grade I hamstring strain injuries [40]. Their protocol comprised of two parts, one flexibility test and a slump test (validated for neural tension). In the group with a previous hamstring injury, 57% of the players had a positive slump test, whereas no positives were found in the control group. The results suggested that adverse neural tension should be assessed as a risk factor of hamstring injury and could be considered in return to play practices.

A prospective analysis of the relationship between motor imagery capacity of senior players (the ability to mentally perceive a rotated object) and hamstring injuries was undertaken [34]. Motor function was assessed with isokinetic hamstring quadriceps (H:Q) ratio, straight-leg raise angle, and a vertical jump test on one leg. Six players had symptoms of hamstring injuries (7 legs). The injured group (occurred in non-contact actions) had longer reaction times for the 0° dorsal and −90° plantar views compared to the non-injured group (delay in 2.48 seconds) based motor imagery capacity test, with none of the motor function tests associated with injury. The third study in this area provided the option to players with previous hamstring injuries to wear or not wear thermal pants in training and matches during a season [35]. The

Table 2. Hamstring injury studies involving Rugby Union players.

Study	Participants	Incidence	Severity	Training	Playing matches	Intervention/Test	Outcome
Brooks et al. [38]	546 professional players	**All**: 5.6 injuries/1000 player-hours**Forwards**: 3 injuries/1000 player-hours**Backs**: 8.6 injuries/1000 player-hours	**All**: 17 days of absence**Forwards**: 15 days of absence**Backs**: 1176 total days of absence18 days of absence151 days absence/1000 hours	0%	100%	No	Hamstring injuries were the second most common injury. Hamstring injuries were the most severe injury.
Brooks et al. [39]	502 professional players	**All**: 0.30 injuries /1000 player-hours**Forwards**: 0.28 injuries /1000 player-hours **Backs**: 0.32 injuries/1000 player-hours	**All**: 17 days absence**Forwards**: 478 total days. 15 days of absence. 4.3 days absence/1000 hours**Backs**: 502 total days. 19 days of absence. 6 days absence/1000 hours	100%	0%	No	The most common injury mechanism for forwards andbacks was running.
Brooks et al. [1]	546 professional players	**All**: 164 injuries (94 match and 70 training injuries)122 players (22%) at least one injury.-5.6 injuries/1000 player-hours-Each of the 12 teams 7.5 hamstring injuries (5.8% new and 1.7% recurrent)**New**: 127 injuries**Recurrent**: 37 injuries24% match20% training	**All**: 2707 total days lost. 17 days lost per injuryEach of the 12 teams 123 days absence (81 days for new and 42 days for a recurrent injury).**New**: 1775 total days. 14 [12–16] days lost per injury**Recurrent**: 932 total days. 25 [17–33] days lost per injury	70 injuries42%	94 injuries58%	Stretching, strengthening, and Nordic eccentric exercises	The group performing Nordic exercises had a lower incidence of hamstring injuries compared to the group performing strengthening exercises
Brooks, Kemp [43]	899 professional players	**All**: 164 injuries5.6 injuries/1000 player-hours	**Blind side flankers**: 99 days absence per 1000 player-hours**Fly halves**: 241 days absence per 1000 player-hours**Centers**: 173 days absence per 1000 player-hours**Wingers**: 157 days absence per 1000 player-hours**Full backs**: 161 days absence per 1000 player-hours	**NR**	**NR**	**NR**	Absence due to thigh injuries was high for most backs and a consequence of the faster running speed. While absence due to hamstring muscle injuries was high in wingers, it was the absence due to thigh hematomas that was most significant.
Bourne et al. [37]	178 professional players	**All**: 20 injuries**Forwards**: 40% **Backs**: 60%**New**: 55% **Recurrent**:45%	21 days lost average	**NR**	**NR**	**Nordic eccentric test**:Injured players: Injured limb 355 N and for the uninjured limb 410 N imbalance 17.37% Non-injured: the raw average strength was 367 N with 10% imbalance.	80% affected the biceps femoris as the primary site of injury, 85% resulted from high-speed running. Previous hamstring strain injury and limb imbalance was associated with an increased risk of future hamstring injury in Rugby Union
Farnan et al. [32]	54 amateur players	**All**: 13.1 injuries /1000 player-hours	**NR**	12 /1000 player-hours	7.9 /1000 player-hours	No	Severe injuries were not common at the amateur level. The injury risk was like the professional level.

(Continued)

Table 2. (Continued).

Study	Participants	Incidence	Severity	Training	Playing matches	Intervention/Test	Outcome
Kenneally-Dabrowski et al. [45]	74 professional players	**All**: 6% = 30 injured players**Forwards**: 47% **Backs**: 53%**New**: 93% **Recurrent**: 7% at days 157 and 166	Median of days lost: 26 daysIn average 207 days were lost per season. **SeveritySlight** (0–1 day): 0%**Minimal** (2–3 days): 0% **Mild** (4–7 days): 3% **Moderate** (7–28 days): 68% **Severe** (more than 28 days): 37%**Career ending**: 0%	11 injuries**Preseason**0**Early season**4 (36%)**Late season**6 (55%)**Off-season**1 (9%)	19 injuries**Preseason**9 (47%)**Early season**3 (16%)**Late season**6 (31%)**Off-season**1 (5%)	**MRI injury test Grade II** 80% **Grade III** 20%	The incidence of injuries in the late season was almost double that of early season injuries (12 and 7 injuries, respectively).
Kenneally-Dabrowski et al. [44]	10 professional players	**All**: 4 injured players	**NR**	**NR**	**NR**	**Biomechanical analysis**Hamstring injuries classification OSICS diagnosis codes: TMHX (Hamstring strain), TMHS (Hamstring strain – semimembranosus/ tendinous strain, grade 1–2), TMHB (Hamstring strain – biceps femoris strain, grade 1–2) and TMHR (Grade 3 hamstring strain).	Compared to uninjured athletes recurrent injured athletes demonstrated a tendency for greater thoracic lateral flexion, greater hip extension moments and greater knee power absorption during running.
Mendiguchia et al. [33]	1 professional player	1 hamstring strain injury	**NR**	**NR**	**NR**	**Test**: Instantaneous sprint velocity**Protocol**: The test comprised of ten 40 m sprints on 30 s running cycle, and the speed was recorded with a sport radar.	**Injured player** Change in force and velocity relationship (from – 0.76 to – 0.92; **+21.1%**) associated with an increase in force (from 7.6 N/kg to 8.7 N/kg, **+14%**) and a minor decrease in velocity (from 10.1 m/s to 9.5 m/s, – **6%**).
Reid et al. [27]	8 professional players	**NR**	**NR**	**NR**	**NR**	**RTP StrategiesPhase I and II** (0–6 days)Return to run with no pain and medium intensities**Phase III and IV** (7–12 days)High intensity running and agility, return to sprinting and skills**Phase V**(13–17 days)Full team training, skills, and contact	**RTP ProgramPhase I and IIAD**: 0.6–5 m/ sprint**Distance**2500–5500 m**Phase III and IVAD**: 0.6–5 m/ sprint**Distance**3500–4700 m**Phase VAD**: 0.6–5 m/s**Distance**4000–4500 m
Roberts et al. [42]	189 community players	**All**: 1.4 [1.2, 1.7] injuries/1000 player-hours**Backs**: 1.4 [1.1, 1.8]injuries/1000 player-hours**Forwards**: 0.5 [0.3,0.7] injuries/1000 player-hours	**All**: 5.9 mean weeks missed (4.6 to 6.4)41 days lost	**First quarter**1.9 [1.4,2.5] injuries/1000 player-hours**Third quarter** 1.1 [0.7,1.6] injuries/1000 player-hours	**NR**	No	Hamstring strains are the most common non-contact injury. Backs had higher incidence than forwards. Running actions accounted for 10% of all injuries and of those 54% were hamstring strain injuries

(*Continued*)

Table 2. (Continued).

Study	Participants	Incidence	Severity	Training	Playing matches	Intervention/Test	Outcome
Turl, George [40]	28 semiprofessional players(14 tested players and 14 controls)	**All**: 14 injured players	**NR**	**NR**	**NR**	**Slump test**: In a seated position, with the knees and hips at 90 degrees, the player had to slump forward with the chin flexed to the chest. Pressure is applied to the thoracic spine while extending the ipsilateral leg.	A positive slump test reproduced radicular symptoms 57% positive in test group, 0% in control group.
Upton et al. [35]	44 players NR level players	**All**: 3 users vs 57 non-users **Recurrent**: 42%	275 matches hours832 training hours	55%	45%	Thermal pants	Significant reduction in hamstring injury incidence wearing thermal pants sometimes: 3 injuries/ 1000 hours playing wearing thermal pants vs 57 injuries/1000 hours playing without thermal pants.
Yamada, Mastumoto [34]	21 amateur players	**All**: 6 injured players	**NR**	0%	100%	**H:Q 60°/s**Injured 0.63 ± 0.03 Non injured 0.60 ± 0.10**H:Q 180°/s**Injured 0.91 ± 0.57 Non injured 0.64 ± 0.13**DCR 60°** Injured 0.74 ± 0.13 Non injured 0.70 ± 0.13**DCR 180°**Injured 1.07 ± 0.59 Non injured 0.79 ± 0.16	Motor imagery capacity, and the time to identify the foot picture was defined as the reaction time (ms). Motor imagery influences the development of hamstring strain.
Yeomans et al. [48]	137 amateur players	**All**: Hamstring muscle strains 9%	**NR**	**NR**	**NR**	**Test**: Hamstring flexibility (higher score more flexibility)**Protocol:Straight leg raise test** Hamstring board scores**Males**: Forwards: 78.6° ± 8.1Backs: 80.9°± 5.3**Females**: Forwards: 73.3° ± 11.3Backs: 78.9° ± 10.1	**NR** results regarding hamstrings straight leg raise measures and injuries

Abbreviations: AD, average distance; N Newton; NR, not reported; RTP, return to play.
Values are means ± standard deviation, means [95% confidence intervals], and minimum – maximum range.

incidence of injuries was significantly lower in players who chose to wear thermal pants.

3.5. Hamstring strength and asymmetry assessment: methods and measures

3.5.1. Overview

All methods and outcome measures used to assess hamstring strength are summarized in Table 3. Isokinetic testing is considered the 'gold standard' method to measure hamstring and quadriceps strength [50], with most of the studies assessing strength in rugby using isokinetic methods [26,29–31,41,46,47]. All of these isokinetic studies were conducted at 60°/s, with a subset also using 180°/s [29,31,47] and the one of poor methodological quality assessing at 35°/s [46]. Concentric hamstring strength was examined across all isokinetic studies, with five subjects considering eccentrics [29–31,41,46]. Nine studies measured the hamstring to quadriceps ratio (H:Q) [26,28–31,34,36,41,46,47] and five included dynamic control ratio (DCR) [29–31,41,46]. The H:Q is conventionally measured concentrically and used to quantify strength and imbalance between muscles and limbs. The dynamic control ratio is considered more functional, calculated as the *eccentric* hamstrings to concentric quadriceps strength ratio. There were no H:Q and DCR thresholds specifically established for Rugby Union players in the literature here reviewed. The Rugby Union literature cited thresholds from track and field that recommended H:Q values exceed 0.6 and DCR of 1.0 or above [51]. Other forms of hamstring strength testing methods used in rugby included eccentric [37], isometric [46], isotonic [31], and sphygmomanometer [36].

3.5.2. Protocols

3.5.2.1. Isokinetic strength tests. Concentric hamstring strength at 60°/s ranged from 89 to 252 Nm in amateur to professional players across positions and genders, and at 180°/s ranged from 71 to 121 Nm in male amateurs (no data for professionals or females). Eccentric hamstring strength across at 60°/s from ~135 to 220 Nm, and 209 to 220 Nm at 180°/s in male amateurs (no data for professionals or females). Key findings were that professionals were stronger than academy [30], forwards were stronger than backs [28,47]. In amateur players, experience had little effect on hamstring values [31] and effect of leg dominance was inconsistent across studies [28,30,47].

In amateur players, H:Q values ranged from 0.45 to 0.56, with no difference based on years of experience [31] or playing position [30]. Professional players displayed H:Q values of 0.52 to 0.68 [28,41], with again no difference between playing positions [28], but the potential to increase with progressive Nordic eccentric training [41]. Concerning DCR values in amateur players, ratios ranged from 0.64 to 1.17, and was significant greater in experienced players [31], but not affected by playing position or limb dominance [30]. DCR in professionals ranged from 0.74 to 0.81 [41], and was greater subsequent progressive Nordic eccentric hamstring training. Two studies undertook isokinetic knee strength assessment in amateur female athletes [26,46], with one of these being of poor methodological quality. These studies identified that non-dominant limb H:Q (0.81) and DCR values were significantly greater than the dominant limb (0.74).

Deighan et al. [29] examined how conducting testing in seated vs supine influenced isokinetic knee extensor and flexor strength. The DCR at 180°/s and mean peak torque values seated were significantly greater than supine. Furthermore, knee extensors were stronger than flexors, and eccentric produced superior values than concentric. The study highlighted the significance of testing eccentric isokinetic strength with a hip flexion angle of approximately 10° to determine imbalances and to screen for risk of injuries. Analysis in amateur players with both isometric and isokinetic strength tests in experienced and inexperienced player indicated experienced players had greater DCR at 60°/s values [31]. No significant differences were observed between players in DCR and H:Q at 180°/s velocity, which the authors attributed to an adaptation to the high sprint demands of Rugby Union. At the same level of competition, Deighan et al. [29] found similar H:Q 60°/s, but lower DCR values when compared to the results by Beyer et al. [31]

3.5.2.2 Eccentric strength test with Nordic exercises. Preseason Nordic hamstring eccentric testing performed with a load cell device [37], see Figure 2, indicated that weaker players (bilateral average < 267.9 N) were at a similar risk of sustaining a hamstring injury than stronger players. Forwards were stronger than backs. Injured players demonstrated an imbalance between limbs of 17.4% that was significantly greater than injury-free players who displayed an imbalance of ≤10%.

3.6. Hamstring strengthening programs

During two seasons, 12 professional male teams followed a training program with stretching and strengthening exercises in one of three groups: 1) strengthening, 2) strengthening and stretching, and 3) strengthening, stretching, and Nordic exercises [1], see Table 4. The group performing Nordic exercises had a lower incidence of hamstring injuries compared to the group performing strengthening exercises alone. Although no significant differences were found in severity, there were less absence days in the Nordic exercise group. Second row players displayed the lowest incidence and severity of hamstring injuries.

In another study, two Nordic exercise 8-week training programs were examined: progressive and constant workload [41]. Along with the Nordic exercises, ultrasonography of the biceps femoris long head was performed. Both Nordic exercises strategies significantly increased the muscle thickness and length, without pennation angle changes. The progressive routine significantly increased the strength values by 7 to 8%, H:Q from 0.53 to 0.57, and DCR from 0.76 to 0.81; but not the constant workload group.

Intervention strategies with Nordic exercises have also been implemented in female rugby players [26]. Following a 10-week Nordic hamstring training intervention, isokinetic strength at 60°/s improved 11–13%. Also of interest was that, following the training period, a significant reduction in

Table 3. Hamstring strength measures and imbalances.

Study	Strength assessment protocols	Hamstring Measures	Bilateral strength imbalances and values (H:Q, DCR, Newtons, etc)	Key findings
Abdelfettah et al. [47]	**Male amateur playersTest**: Isokinetic (concentric) **Equipment**: Cybex Norm isokinetic dynamometer**Protocol**: Peak 1RM at 60 and 180°/s for series of successive movements of 5 and 30 repetitions.	**Dominant limbConcentric hamstring 60°/s**Backs 101.5 ± 10.4 NmForwards 133.1 ± 30.4 Nm**Concentric hamstring 180°/s**Backs 70.7 ± 8.9 NmForwards 91 ± 21.3 Nm**Non dominant limbConcentric hamstring 60°/s**Backs 98 ± 21.8 NmForwards 130.5 ± 35 Nm**Concentric hamstring 180°/s**Backs 72.7 ± 15.6 NmForwards 83.7 ± 14.2 Nm	**Average value of the H:Q ratio in percentagesH:Q 60°/sDominant limb**56.4 ± 9.5%**Non dominant limb**53.9 ± 10.2%**H:Q 180°/sDominant limb**56.1 ± 10.25%**Non dominant limb**56 ± 6.6%	Peak torque values in extension of the non-dominant limb were higher in forwards than backs.
Anastasi, Hamzeh [26]	**Female amateur playersTest**: Isokinetic (concentric)**Equipment**: Cybex Norm isokinetic dynamometer**Protocol**: Peak during pre- and post-training in both legs at 60°/s	**Dominant limbPre-intervention** 89.2 ± 19.9 Nm**Post intervention**102.2 ± 21.2 Nm**Non dominant limbPre-intervention**93.15 ± 20.0 Nm**Post intervention**104.23 ± 18.8 Nm	**Bilateral strength imbalances in percentagePre-training**10.4 ± 3.5%**Post-training**4.7 ± 2.2%	Intervention group had a significant decrease in the percentage of bilateral strength imbalances.
Beyer et al. [31]	**Male amateur playersTest**: Isokinetic (concentric, eccentric). Isotonic test (squatting).**Equipment**: Biodex Medical System isokinetic dynamometer**Protocol**: 10 experienced players (≥ 2 years) and 14 inexperience players (< 2 years).**Isokinetic**: Peak of 3 RM measured at 60°/s and 180°/s**Isotonic**: 1 RM squat	**Dominant legConcentric hamstring 60°/s**Inexperienced 114.3 ± 4.8 NmExperienced 119.3 ± 5.8 Nm**Concentric hamstring 180°/s**Inexperienced 91.9 ± 3.9 NmExperienced 92.8 ± 4.7 Nm**Eccentric hamstring 60°/s**Inexperienced 207.3 ± 8.2 NmExperienced 225.8 ± 9.9 Nm**Eccentric hamstring 180°/s**Inexperienced 208.8 ± 9.6 NmExperienced 220.4 ± 11.4 Nm**Squat 1RM**Inexperienced 132.4 ± 9.5 kgExperienced 143.9 ± 11.8 kg	**H:Q 60°/s**Inexperienced 0.45 ± 0.02Experienced 0.50 ± 0.02**H:Q 180°/s**Inexperienced 0.47 ± 0.02Experienced 0.50 ± 0.03**DCR 60°/s**Inexperienced 0.81 ± 0.04Experienced 0.95 ± 0.05**DCR 180°/s**Inexperienced 1.07 ± 0.05Experienced 1.17 ± 0.06	Experience group had a significantly greater DCR 60°/s than the inexperienced group. No significant differences in mass, age, eccentric hamstring strength values at H:Q 60°/s, 180°/s, or DCR 180°/s between groups.
Bourne et al. [37]	**Male professional playersTest**: Nordic eccentrics**Equipment**: Nordic board with custom-made uniaxial load cells**Protocol**: Peak of 3RM of bilateral Nordic exercises	**Professional**366.9 ± 76.9 N**semiprofessional(sub-elite)**387.9 ± 96.3 N**(under 19)** 342.8 ± 81.5 N**Combined: Forwards**388.5 ± 95.5 N**Backs**353.1 ± 74.9 N	**Bilateral strength imbalancesInjured**17.3 ± 16.1%**Uninjured**10.0 ± 9.8%	No significant difference was found between professional and semiprofessional players; whilst among semiprofessionals, sub-elites were significantly stronger than under 19s. Relative to body mass, these values significantly differed from professional to semiprofessional players, the sub-elite and the under 19s were significantly stronger than the former players, whilst among sub-elite and under 19 players no significant difference was found. Forwards were stronger than backs; but relative to body weight, no significant differences were found.
Brown et al. [28]	**Male professional playersTest**: Isokinetic (concentric)**Equipment**: Humac Norm dynamometer**Protocol**: Average peak torque from 4 RM measured at 60°/s during seated knee-extension/flexion and supine hip-extension /flexion at 60°/s.	**Leg ExtensionForwards**Dominant 281 ± 45 NmNon-dominant 268 ± 44 Nm**Backs**Dominant 244 ± 29 NmNon-dominant 247 ± 38 Nm**Leg FlexionForwards**Dominant 184 ± 27 NmNon-dominant 180 ± 20 Nm**Backs**Dominant 157 ± 27 NmNon-dominant 156 ± 27 Nm	**H:QForwards**Dominant 0.66 ± 0.09Non-dominant 0.68 ± 0.10**Backs**Dominant 0.64 ± 0.10Non-dominant 0.64 ± 0.08	In two rugby codes, forwards were taller and heavier than backs. Professional Rugby Union forwards had significantly larger peak torque during knee flexion in both dominant and non-dominant limbs compared to professional rugby league forwards and Rugby Union backs.

(Continued)

Table 3. (Continued).

Study	Strength assessment protocols	Hamstring Measures	Bilateral strength imbalances and values (H:Q, DCR, Newtons, etc)	Key findings
Brown et al. [30]	**Male amateur players** **Test**: Isokinetic (concentric and eccentric) **Equipment**: HumacNorm dynamometer **Protocol**: 1 RM with the dominant and nondominant limb in sitting and in a supine position at 60°/s. Dominant limb was defined as the limb that the player preferred to kick the ball or could kick the ball the farthest	**Leg Extension Concentric** **Forwards** Dominant 252 ± 62 Nm Non-dominant 228 ± 38 Nm **Backs** Dominant 225 ± 38 Nm Non-dominant 214 ± 53 Nm **Leg Flexion Concentric** **Forwards** Dominant 129 ± 25 Nm Non-dominant 124 ± 19 Nm **Backs** Dominant 115 ± 14 Nm Non-dominant 118 ± 28 Nm **Leg Flexion Eccentric** **Backs** Dominant 148 Nm Non-dominant 125 Nm **Forwards** Dominant 155 Nm Non-dominant 145 Nm	**H:Q** **Forwards** Dominant 0.52 Non-dominant 0.55 **Backs** Dominant 0.52 Non-dominant 0.56 **DCR** **Forwards** Dominant 0.65 Non-dominant 0.64 **Backs** Dominant 0.65 Non-dominant 0.66	Professionals were stronger in all the peak torque measures compared to academy players.In forwards, the dominant limb was stronger than the non-dominant limb.The average H:Q ratio was less than 0.6 and the DCR was more than 0.6. In the isokinetic eccentric knee strength test, results showed forwards were stronger in the dominant leg compared to the non-dominant leg. Backs had similar strength torque values in both legs in flexion, however the dominant leg was stronger in extension. No differences between positions and limbs were found. Isokinetic concentric hip strength in forwards were similar between dominant and non-dominant legs. Forwards displayed greater values in the dominant leg during flexion compared to backs.
Deighan et al. [29]	**Male amateur players** **Test**: Isokinetic (Concentric) **Equipment**: Biodex System 3 dynamometer **Protocol**: 1RM isokinetic seated. For supine, participants were placed lying on their backs at 60 and 180°/s.	**Seated peak torque** **Hamstring concentric** 60°/s: 144 ± 26 Nm 180°/s: 121 ± 16 Nm **Hamstring eccentric** 60°/s: 179 ± 45 Nm 180°/s: 186 ± 60 Nm **Supine peak torque** **Hamstring concentric** 60°/s: 123 ± 19 Nm 180°/s: 109 ± 18 Nm **Hamstring eccentric** 60°/s: 147 ± 20 Nm 180°/s: 138 ± 30 Nm	**H:Q** **Seated** 60°/s: 0.53 ± 0.07 180°/s: 0.56 ± 0.07 **Supine** 60°/s: 0.47 ± 0.06 180°/s: 0.51 ± 0.09 **DCR** **Seated** 60°/s: 0.66 ± 0.09 180°/s: 0.86 ± 0.23 **Supine** 60°/s: 0.58 ± 0.07 180°/s: 0.68 ± 0.15	In a seated position, concentric peak torque was greater compared to supine eccentric. The H:Q in the seated position showed no significant difference compared supine.
Dobbs et al. [46]	**Female and male amateur players** **Test**: Isokinetic (concentric and eccentric) and isometric (leg pull) **Equipment**: Biodex Pro 4 dynamometer **Protocol**: **Isokinetic tests**: Average of 3RM at 60°/s; 1RM isometric quadriceps strength at 60°/s, and 1RM isometric hamstring strength at 35°/s **Isometric**: Bilateral and unilateral leg isometric mid-thigh pull. 3RM for both legs, and 2RM for a single leg were recorded on force plates.Dominant limb was defined as the preferred leg to kick a ball.	**NR**	**H:Q** **Non-dominant limb**: 0.81 ± 0.13 **Dominant limb**: 0.74 ± 0.14 **DCR** 0.81 ± 0.14	The non-dominant limb H:Q ratio was significantly greater than the dominant leg whilst the DCR was significantly greater than the simple H:Q

(*Continued*)

Table 3. (Continued).

Study	Strength assessment protocols	Hamstring Measures	Bilateral strength imbalances and values (H:Q, DCR, Newtons, etc)	Key findings
Mondin et al. [36]	**Male professional playersTest**: Sphygmomanometer measures of maximal isometric strength. Isokinetic dynamometry (concentric) strength.**Equipment**: Humac Norm dynamometer and an adapted sphygmomanometer**Protocol:Isokinetic tests**: Peak of 3RM at 60°/s.**The sphygmomanometer test**: Subjects in supine with knees flexed at 30° or 90° and heel of one leg on the cuff, and opposite leg resting on the floor and extended. 3RM isometric strength of hamstring at 30° and 90° were recorded.	**NR**	ICC (95% CI):**Quadriceps 90° right** 0.64 (−0.28–0.91)**Quadriceps 90° left** 0.81 (0.21–0.95) **Hamstrings 90° right** 0.83 (0.30–0.96) **Hamstrings 90° left** 0.87 (0.45–0.97) **Hamstrings 30° right** 0.92 (0.69–0.98) **Hamstrings 30° left** 0.87 (0.45–0.97)87	A positive correlation in 90° of knee flexion between sphygmomanometer and isokinetic tests was found, as well as hamstring strength at 90° and 30° of knee flexion for both measures. No relation in strength asymmetry between legs or tests at 30° or 90° when testing the efficacy of the sphygmomanometer compared to the isokinetic test. No correlation in hamstring to quadriceps ratio at 90° between test for dominant and non-dominant leg.The group found reliability and validity measuring hamstring strength with the adapted sphygmomanometer test, although the test was not valid or reliable assessing bilateral or hamstrings to quadriceps asymmetries.
Severo-Silveira et al. [41]	**Male professional playersTest**: Isokinetic (concentric and eccentric)**Equipment**: ultrasound assessment B-mode ultrasonography and Biodex Pro 4 dynamometer**Protocol**: Peak of 3RM of flexion-extension at 60°/s	**Pre-interventionQuadriceps concentric**Constant group: 275.5 ± 27.1 NmProgressive group: 278 ± 48.8 Nm**Hamstrings concentric**Constant group: 142.2 ± 19.6 NmProgressive group: 146.6 ± 24.3 Nm**Hamstrings eccentric**Constant group 204.5 ± 43.3 NmProgressive group 211.1 ± 31.8 Nm	**Pre-interventionH:Q**Constant group: 0.52 ± 0.05Progressive group: 0.53 ± 0.07**DCR**Constant group: 0.74 ± 0.14Progressive group: 0.76 ± 0.06	After the training intervention only the progressive group had an increased in hamstring concentric and eccentric peak torques, H:Q and DCR.

Values are means ± standard deviations.
Abbreviations: DCR, isokinetic dynamic control ratio; H:Q, isokinetic hamstring quadriceps ratio; Nm, Nanometer; NR, not reported; RM, repetition maximum.

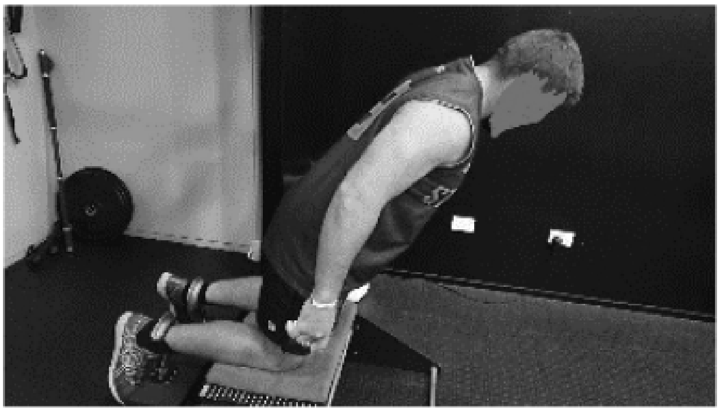

Figure 2. Illustration of a Nordic hamstring exercise.

bilateral strength imbalance from 10.3% to 4.6% was observed. Table 4.

4. Discussion

4.1. Hamstring injury incidence and risk factors

We aimed to examine the scientific literature specific to Rugby Union and hamstring with focus on injury incidence, risk factors, injury prevention and strengthening strategies, and strength and asymmetry measures. The overall incidence of hamstring injuries during matches in professional players [38] was four times greater than community and amateur players [32,42]. Across levels, backs suffered more hamstring injuries than forwards [1,37,42] due to their greater running actions. The hamstring severity in community players was approximately 2 to 2.5 times higher than professionals [1,37] suggestively due to lack of appropriate warm-up and hamstring training interventions in these cohorts [42].

In professional players, 23 to 45% of hamstring injuries were recurrences from either the current or previous season [1,37], with a previous hamstring strain associated with a 4.1 times increased risk of recurrence [37]. The highest injury recurrence occurred in the first month of returning to play [1], suggesting that return to play was too quick and/or rehabilitation and reconditioning insufficient to meet the load demands. Similarly, 18% of the injuries have been found to recur in the first twelve days after returning to play and at the same site of the previous injury [35]. Of concern is that recurrences had more days lost (25 days) compared to new injuries (17 days) [1]. These studies altogether indicate that there is insufficient preparation before returning to training and playing after a hamstring injury, with a previous hamstring strain being a considerable risk factor. These findings align with a meta-analysis indicating that previous hamstring injury was a significant risk factor, in addition to other injuries (Anterior Cruciate Ligament, calf, and knee) for hamstring injuries [3]. Bourne et al. [37] highlighted the significant relationship between leg imbalances in eccentric strength and a previous hamstring strain injury in Rugby Union players, and concluded that players with a previous injury had an increased risk of sustaining another injury if they returned to play with pronounced strength imbalances between legs. In contrast, when isokinetic testing was included as a tool to return to play, van Dyk et al. [52] found no value in this strength measure as a criterion for return to play after a hamstring injury in football players. Whatever the tool used, rugby players should be monitored in their return to play progression and assessed periodically for imbalances, especially if they have sustained a previous hamstring injury.

Running was the most common action of the game to produce a hamstring strain injury across levels, accounting for 68 to 85% of all injuries in professionals [1,37,45] and 54% in amateur [42]. There was somewhat conflicting evidence in terms of when in the game injuries were more likely to occur. In professionals, the majority of the injuries in backs occurred in the last part of each half, but incidences were greater later in the game in forwards [1]. In contrast, hamstring injuries occurred more frequently in the first quarter in community players [42]. These contrasting results suggest insufficient warm-up or game preparation at lower levels of competition as a potential contributor to injury rates, whereas fatigue may be a greater contributor at higher levels. This proposition relating to warm-up strategies is indirectly supported by findings of a significant decrease in hamstring injuries when previously injured players wore warm pants during training and matches [35].

Running training and high speed exposures have been postulated as an effective tool to reduce hamstring injuries [53]. One of the recommendations by Buckthorpe et al. [15] for preventing hamstring injuries involved incorporating high speed-running routines at least twice a week at 95% of maximum speed. Analysis of a player with a hamstring injury identified impaired sprint accelerations with a decrease in horizontal force production, potentially due to weak hamstring or gluteal muscles, before the injury and after return

Table 4. Hamstring training protocols and results.

Study	Participants	Duration and exercises	Protocol	Outcome
Brooks et al. [1]	492 professional males	**1st group (n = 148)StrengtheningProportion of weeks**:87% of weeks strengthening**2nd group (n = 148) Strengthening and stretchingProportion of weeks**:77% of weeks strengthening and 87% of weeks stretching**3rd group (n = 200)Proportion of weeks**:44% of weeks strengthening, 87% of weeks stretching, and 65% of weeks Nordic exercises	**1st group strengthening**Sessions per week: 1.2 ± 0.2Sets per session: 3.6 ± 0.4Reps per set: 8.2 ± 2.5**2nd group strengthening and stretchingStrengthening**Sessions per week: 1.8 ± 0.4Sets per session: 3.3 ± 0.3Reps per set: 7.5 ± 1.0**Stretching**Sessions per week: 2.6 ± 0.4Sets per session: 2.8 ± 0.3Reps per set: 2.5 ± 9.0**3rd group strengthening stretching and Nordic exercisesStrengthening**Sessions per week: 1.3 ± 0.3Sets per session: 3.0 ± 0.4Reps per set: 7.5 ± 2.1**Stretching**Sessions per week: 1.8 ± 0.2Sets per session: 2.6 ± 0.4Reps per set: 28 ± 20**Nordic exercises**Sessions per week: 1.3 ± 0.5Sets per session: 2.8 ± 0 .7Reps per set6.7 ± 1.5	The group performing Nordic exercises had a lower incidence of hamstring injuries compared to the group performing strengthening exercises.The incidence of injuries in matches and training was not significantly different between the group performing Nordic exercises (0.39 injuries per 1000 hours player) and the group with stretching and strengthening exercises (0.59 injuries per 1000 hours player).
Anastasi, Hamzeh [26]	24 females amateur (11 tested players, 11 control players)	10 weeksNordic exercises performed in couples of players, 3 times per week	**Program**Weeks 1–2: 3 sets x 6 repsWeeks 3–4: 3 sets x 7 repsWeeks 5–7: 3 sets x 8 repsWeeks 8 – 10: 3 sets x 10 reps	The 10-week training program significantly decreased the bilateral strength imbalances from: 10.38 ± 3.53% to 4.69 ± 2.18%.The Nordic exercise group displayed a significant change in the mean maximal vertical jump height from 31.22 to 35.93 cm
Severo-Silveira et al. [41]	21 male professionals	8 weeksNordic exercises	**Training Constant [Progressive]**Week 1: 2 sets x 6 reps [2 sets x 6 reps]Week 2: 3 sets x 6 reps [3 sets x 6 reps]Week 3: 3 sets x6 reps [3 sets x 8 reps]Week 4: 3 sets x 6 reps [3 sets x 10 reps]Week 5: 3 sets x 6 reps [4 sets x 8–10 reps]Week 6: 3 sets X 6 reps [4 sets x 8– 10 reps]Week 7: 3 sets X 6 reps [4 sets x 10 reps]Week 8: 3 sets X 6 reps [4 sets x 10 reps]	An 8-week training program significantly increased hamstring strength values by 7–8%, and H:Q from 0.53 to 0.57 and DCR from 0.76 to 0.81 in the progressive training group only.

Values are means ± standard deviation.
Abbreviations: DCR, dynamic ratio; HQ Hamstring to quadriceps ratio

Table 5. Summary of the risk of bias assessment of the reviewed studies (Modified Newcastle – Ottawa Quality score).

	SELECTION				COMPARABILITY	OUTCOME		TOTAL
	1	**1**	**3**	**4**	**1**	**1**	**2**	
Anastasi, Hamzeh [26]	b	b	c	a	b	d	a	5
Beyer et al. [31]	b	b	ca	a	b	d	b	4
Bourne et al. [37]	b	b	c	a	a,b	b	a	8
Brooks et al. [38]	a	b	a	a	a,b	b	a	9
Brooks et al. [39]	a	b	a	a	a,b	b	a	9
Brooks et al. [1]	a	b	c	a	b	b	a	9
Brooks, Kemp [43]	a	b	c	a	b	b	a	7
Brown et al. [28]	b	b	c	b	a,b	d	B	4
Brown et al. [30]	b	b	c	b	a,b	d	b	4
Deighan et al. [29]	b	b	c	b	b	d	a	4
[46]	c	b	c	b	b	D	b	2
Faman et al. [32]	b	b	a	b	b	c	a	5
Kenneally-Dabrowski et al. [45]	a	b	c	a	b	b	a	7
Kenneally-Dabrowski et al. [44]	b	b	c	a	a,b	b	b	7
Mendiguchia et al. [33]	c	b	c	a	a,b	d	b	4
Mondin et al. [36]	c	b	c	a	b	d	a	4
Reid et al. [27]	c	b	c	a	a,b	b	b	6
Roberts et al. [42]	a	b	c	a	b	b	a	7
Severo-Silveira et al. [41]	b	b	a	a	b	a	a	8
Turl, George [40]	b	b	c	a	a,b	a	b	7
Upton et al. [35]	b	b	c	b	a,b	c	b	5
Yamada, Mastumoto [34]	b	b	c	b	b	b	b	5

Methodology quality assessment score based on Newcastle-Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0–3 stars), moderate (4–6 stars), and strong (7–10 stars).

to play [33]. The authors highlighted the importance of running activities for preventing hamstring injuries, and suggested sprint time measurement to detect deficits during the initial acceleration phase. Magnetic resonant imaging of hamstring injuries in professional players showed the biceps femoris long head fascicle was the most injured muscle (73%), and that this injury occurred most frequently in running actions (77%) [45]. In contrast to football players who sustained more Proximal Myofascial junction intramuscular injuries [54], the Distal Myofascial junction site was more common in Rugby Union players, re-emphasizing the importance of Nordic exercises to target this portion of the muscle [55].

4.2. Hamstring strength

Playing level and position in rugby have previously been associated with different attributes and demands, including body composition, speed, strength, power, and repeated sprint performance [56]. The isokinetic measures here reviewed support these findings overall, with professionals being stronger than amateurs and forwards being stronger than backs [28,30]. The differences between playing positions and levels likely relates to the match demands of forwards requiring greater leg strength (i.e. tackling, scrummaging, rucking, mauling, and pick-and-goes) than backs, and strength increasing with years of experience and the greater demands at higher levels.

From the literature reviewed, no H:Q and DCR thresholds from isokinetic testing have been established as optimal or protective of injury for Rugby Union. In track and field, H:Q values exceeding 0.6 [51] and DCR values of 1.0 or above are considered normal [57] and recommended for reducing the risk of hamstring injuries [51]. H:Q values below 0.6 have been shown to increase hamstring injuries 17-fold in sprinters [10]. Across the Rugby Union literature reviewed, H:Q values were typically lower than 0.6 [30,31,42], although reported to surpass 0.6 in professional players [28]. Similarly, DCR were often below 1.0 [28,31,41], even in professionals. Addressing these imbalances could potentially reduce the relatively high incidence of hamstring strains in Rugby Union. That said, van Dyk et al. [58] found no relationship between H:Q isokinetic strength ratios in injured and uninjured football players. Furthermore, the systematic review and meta-analysis for hamstring strain injury risk factors by Freckleton, Pizzari [3] did not find evidence that any isokinetic ratio, at any speed or type of contraction, was associated with the risk of hamstring injuries. Therefore, it remains uncertain whether improving these ratios would actually reduce hamstring incidence in rugby.

In amateur female players, an increase in strength was found, as well as a reduction in imbalance between limbs, after a Nordic exercise intervention [26]. A systematic review by Hewett et al. [59] found no significant difference between females and males in isokinetic H:Q values at slow velocities; although males had significantly greater H:Q values at higher angular velocities (from 30 to 360°/s). The reduced capacity of females to control the knee joint at high velocities might increase their risk to sustain a hamstring injury during high speed running [60]. These results suggest that assessing H:Q values at higher angular velocities might be more clinically-relevant in the context of Rugby Union and hamstring injuries, and should be used preferentially by clinicians in the context of assessing injury risk.

Nordic eccentric strength assessments are proposed as a more feasible, physiological, and functional test than isokinetic. Forces generated during Nordic exercises are similar to those observed during sprinting [61]. However, only one study measured Nordic eccentric values in Rugby Union. Bourne et al. [37] detected significantly weaker limbs in injured than uninjured limb, as well as greater imbalances between legs in injured than uninjured players. Imbalances of more than 15% and 20% between legs increased the risk of hamstring injuries by 2.4 and 3.4 times, respectively. A review by Kalkhoven et al. [62] found that during all the phases of sprinting, the hamstring muscles are active (from the stance phase to the swing phase). The 'hamstring muscle slack,' a term which suggests the hamstring act isometrically in the late swing of sprinting, does not occur. These authors concluded that the hamstring contracts in an eccentric fashion in the late swing phase, such that an eccentric test may be a more appropriate way to measure hamstring strength and capability. This interpretation of the kinematics of sprinting may also suggest that eccentric exercises are a better way to train hamstring function. That said, authors of a systematic review and meta-analysis of different devices measuring hamstring eccentric strength in different sports with the Nordbord device cautioned when assessing hamstring peak strength and imbalances to estimate hamstring injury risks [63]. This caution was due to the Nordic hamstring test not eliciting the same demands as running, and therefore, it should be used as the sole tool to assess injury risk in-season neuromuscular status [63].

4.3. *Hamstring strengthening programs*

Rugby Union players that followed a Nordic eccentric exercise program exhibited significantly improved hamstring strength [26,41], decreased bilateral strength imbalances [26], and reduced hamstring injury incidence and severity (i.e. less days absent from training and matches) [1]. Interventions also improved H:Q and DCR values, as well as an increased the biceps femoris long head fascicle length and thickness. As a short fascicle length has been shown to increase the risk of hamstring injuries, and longer fascicles identified as a protective factor of hamstring strain injuries in older football players with previous hamstring injuries [64], the progressive Nordic program in Rugby Union can promote beneficial morphological adaptations. Giakoumis [65] suggested a number of possible mechanisms underpinning the beneficial effects of Nordic exercises in athletes other than semitendinosus and biceps femoris fascicle lengthening, including hypertrophy of these muscles and synergistic role of the semitendinosus in sprinting activities. Compared to other exercises, eccentrics elicit greater electromyographic activity, increases in strength, and muscle adaptations [65]. Therefore, although cautioned against being used as a sole screening measure [63], the integration of Nordic exercises appear of benefit to Rugby Union and are recommended. The intervention programs in Rugby Union with beneficial effects followed similar training strategies over the course of 8 to 10 weeks, and can be recommended to practitioners. These programs involved eccentric hamstring training 2 to 3 times a week, completing 3 to 4 sets of 6 to 10 repetitions.

5. Conclusion

Current literature is lacking to support the evidence-based use of isokinetic strength, H:Q, and DCR measures to inform injury prevention and return to play strategies for hamstring injuries in Rugby Union. Nordic eccentric strength assessment has been shown to be a better physiological and functional test, with differences in strength and imbalances predicting new and recurrent injuries. Strengthening programs with Nordic exercises significantly increased hamstring strength measures, decreased imbalance ratios, and reduced injury incidence and severity. The etiology of hamstring injuries is multifactorial, with playing position, fatigue, previous injuries, leg imbalances, lack of readiness to return to play, and running actions identified as contributing factors across levels. Combining strategies to prevent hamstring injuries and recurrences, and to inform return to play, is likely worthwhile and should include Nordic strength assessment and Nordic exercises. It has been proposed that high-speed running and warm-up routines may be important in the prevention of hamstring injuries, although strong evidence for these suggestions is lacking.

Disclosure statement

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Appendix

Quality assessment tool

NEWCASTLE – OTTAWA QUALITY ASSESSMENT SCALE

Selection: (Maximum 5 stars)

(1) Representativeness of the sample:
  a. Truly representative of the average in the target population. * (all subjects or random sampling
  b. Somewhat representative of the average in the target population. * (nonrandom sampling)
  c. Selected group of users.
  d. No description of the sampling strategy.

(2) Sample size:
  a. Justified and satisfactory. *
  b. Not justified.

(3) Non-respondents: Rate between participants asked to participate and participants actually participated
  a. Comparability between respondents and non-respondents characteristics is established, and the response rate is satisfactory. * Rate more than 60%
  b. The response rate is unsatisfactory, or the comparability between respondents and non-respondents is unsatisfactory.
  c. No description of the response rate or the characteristics of the responders and the non-responders.

(4) Ascertainment of the exposure (risk factor):
  a. Validated measurement tool. **
  b. Non-validated measurement tool, but the tool is available or described.*
  c. No description of the measurement tool.

Comparability: (Maximum 2 stars)

(1) The subjects in different outcome groups are comparable, based on the study design or analysis. Confounding factors are controlled.
  a. The study controls for the most important factor (select one). * Age
  b. The study control for any additional factor. * Weight, height

Outcome: (Maximum 3 stars)

(1) Assessment of the outcome:
  a. Independent blind assessment. **
  b. Record linkage. **
  c. Self report. *
  d. No description.

(2) Statistical test:
  a. The statistical test used to analyze the data is clearly described and appropriate, and the measurement of the association is presented, including confidence intervals and the probability level (p value). *
  b. The statistical test is not appropriate, not described or incomplete.

Appendix A3. Reliability of repeated isometric neck strength in Rugby Union players using a load cell device.

sensors

MDPI

Article

Reliability of Repeated Isometric Neck Strength in Rugby Union Players Using a Load Cell Device

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Abstract: Concussion is the most common injury in professional Rugby Union (RU) players, with increasing incidence and severity each year. Strengthening the neck is an intervention used to decrease concussion incidence and severity, which can only be proven effective if strength neck measures are reliable. We conducted a repeated-measures reliability study with 23 male RU players. Neck strength was assessed seated in a 'make' test fashion in flexion, extension, and bilateral-side flexion. Flexion-to-extension and left-to-right side ratios were also computed. Three testing sessions were undertaken over three consecutive weeks. Intrasession and intersession reliabilities were assessed using typical errors, coefficient of variations (CV), and intraclass correlation coefficients (ICC). Intrasession reliability demonstrated good-to-excellent relative (ICC > 0.75) and good absolute (CV ≤ 20%) reliability in all directions (ICC = 0.86–0.95, CV = 6.4–8.8%), whereas intersession reliability showed fair relative (ICC: 0.40 to 0.75) and acceptable absolute (CV ≤ 20%) reliability for mean and maximal values (ICC = 0.51–0.69, CV = 14.5–19.8%). Intrasession reliability for flexion-to-extension ratio was good (relative, ICC = 0.86) and acceptable (absolute, CV = 11.5%) and was fair (relative, ICC = 0.75) and acceptable (absolute, CV = 11.5%) for left-to-right ratio. Intersession ratios from mean and maximal values were fair (relative, ICC = 0.52–0.55) but not always acceptable (absolute, CV = 16.8–24%). Assessing isometric neck strength with a head harness and a cable with a load cell device seated in semi-professional RU players is feasible and demonstrates good-to-excellent intrasession and fair intersession reliability. We provide data from RU players to inform practice and assist standardisation of testing methods.

Keywords: concussion; football; muscle testing; stability; test-retest

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1. Introduction

Concussion is consistently ranked as the most common injury in professional male English Rugby Union players (21%), with increasing incidence and severity from 2002 to 2019 [1]. Considering the medical impact of concussion in Rugby Union, various strategies are being implemented and trialled to reduce the incidence and severity of these injuries. Given that the tackler is the player with the largest incidence of concussion, World Rugby introduced a series of evidence-based initiatives to lessen concussion rates and severity and improve player welfare [2]. These initiatives include improving the tackling technique, reducing the height of the tackle, and changing the speed of the tackle, which presumably have contributed to the 12% reduction in concussions at the 2019 Rugby World Cup compared to the 2015 tournament [3]. In Rugby Union, the average momentum when tackling another player is above 320 kg·m/s, and this elicits high levels of muscle activation at the neck and shoulder, particularly in previously injured players [4]. While rule changes have been identified as one strategy to address concussion in Rugby Union [3], neck strength has also been identified as a modifiable risk factor [5,6]. Training and return to sport protocols highlight the clinical and rehabilitative value of neck strength in neck and head injuries [7,8]. Furthermore, flexion-to-extension and left-to-right lateral flexion imbalances in neck strength are potential risk factors for neck injuries, wherein flexion-to-extension imbalances have been associated with higher head angular and linear accelerations in other cohorts than Rugby Union [9]. These ratios are often assessed in Rugby Union, with a review summarising greater strength values in extension compared to flexion [10], with forwards possessing a significantly lower ratio (0.56) compared to backs (0.61) [11]. Considering bilateral lateral flexion ratios, left to right ratio values range from 0.98 in backs and 1.00 in forwards across the literature [11].

Currently, variations exist in neck strength assessment methods, benchmark values, and exercise prescription in Rugby Union [10]. The most common test used to assess neck strength in Rugby Union is the 'break' test, which measures peak isometric neck strength when resisting against an incrementally applied load [10]. Although the break test is the most common method used in Rugby Union, clinicians have expressed concerns regarding the 'aggressiveness' of this method and the potential to injure players during testing [12]. The resistance is applied to evoke a maximal muscle contraction in flexion, extension, and bilateral lateral flexion directions using a head harness attached to a cable and dynamometer or load cell until the initiation of the movement (i.e., positional failure) [11,13–17]. Previous reliability studies with this neck strength assessment method demonstrate good-to-excellent intrarater and interrater reliability (intraclass correlation coefficient (ICC) 0.80–0.92) when implemented in seated or lying positions [11,18].

An alternative to the 'break' test is to use the 'make' test, which is performed using a head harness attached to a load cell device to a fixed frame or tested against a manual resistance in seated or lying positions with the participant exerting maximal strength against the load cell or handheld dynamometer [7,19,20]. The reliability of make test isometric neck strength measures from a load cell in healthy individuals was excellent between-day (ICC 0.94–0.98) performed in sitting position [21]. In semi-professional Rugby Union players, the make test intrasession reliability assessed using a fixed-mounted handheld dynamometer was good for flexion, extension, and bilateral lateral flexion (ICC 0.77–0.92), as well as when tested against a manual resistance in these four directions (ICC 0.77–0.90) [22]. However, intersession reliability for the neck test in Rugby Union has not been examined. The lack of data on the between-day reliability of the make test in Rugby Union might explain research showing no significant changes in make test neck strength measures during a 26-week neck strengthening programme in Rugby Union despite a significant decrease in neck match-injuries [7].

It is of upmost importance that clinicians use reliable methods when assessing individuals to inform their clinical practice. It is also essential that normative data for neck strength values be available for male Rugby Union players to inform management of this unique cohort, particularly in rehabilitation and return to play. In Rugby Union, there are no studies examining the reliability of an isometric make test using a rigid cable with load cell in a seated position set-up or information on the between day reliability on the make test. Therefore, we aimed to examine the reliability of make test isometric neck strength measures in Rugby Union players using a load cell device.

2. Materials and Methods

2.1. Study Design

A repeated-measures reliability study was conducted targeting semi-professional male Rugby Union players. Based on methods described to establish minimum sample size requirements for reliability studies [23], a minimum of around 20 participants was needed when setting the acceptable reliability level at $\rho0 = 0.40$ (i.e., fair reliability threshold) and desired reliability level at $\rho1 > 0.75$ (i.e., good reliability threshold) with an $\alpha = 0.05$ and $\beta = 0.20$ knowing that players were assessed on three occasions.

2.2. Participants

Twenty-three semi-professional male Rugby Union players (mean ± standard deviation (SD), age 22.3 ± 3.2 year, height 184 ± 7.5 cm, and body mass 100 ± 11 kg) agreed to participate in this study that took place during their regular season. Inclusion criteria required participants to be free of neck pain, cervical injury, or illness in the last month as to not compromise maximal isometric neck strength. All participants were informed of the purpose, benefits, and risks of participation through written and oral description, and they gave their written informed consent to participate. The study protocol was approved by the University of Waikato Human Research Ethics Committee (HREC(Health) 2019#74) and adhered to the latest Declaration of Helsinki.

2.3. Instrumentation

Tests were conducted using a SOUFEI digital portable load cell (SF-912 Soufei Electronic Technology Co., Ltd., Jiangyin, China) of 100 g accuracy with the capacity set to 50 kg. The load cell was connected via Bluetooth to an iPad Model A1566 device, and data were recorded at 20 Hz. Participants were seated in a standard fixed gym seat bench for testing.

2.4. Procedures

This study assessed the neck strength in a make test fashion in four different directions: flexion, extension, and right and left lateral flexion. Each player completed three testing sessions over three consecutive weeks, one week apart. Before the experimental procedure, all participants completed a warm-up protocol of three submaximal isometric repetitions in each direction tested.

For the experimental procedure, we followed procedures similar to those reported elsewhere [24] and implemented in professional Rugby Union players [7]. Participants were seated on the standard gym bench with the head and neck in a neutral position. A seat belt secured the trunk to minimise movement, and two balance air pads were placed under the feet to prevent further movement and contributions from the lower limbs. A head harness was placed around the forehead for flexion, occiput for extension, and temporal bones for lateral flexion. The harness was attached to a load cell apparatus via a rigid cable attached to a fixed metal frame (Figure 1). For data collection, participants completed three maximal effort repetitions in each of the four directions tested, with 30-s rest between contractions, and 60-s rest between directions. The order of testing was randomized between participants and held constant between testing occasions. The instructions provided before the make test was to "pull as hard as you can with 100% strength and hold for 5 s". The peak strength in kilograms was recorded for each isometric contraction and used as the main outcome measure.

2.5. Statistical Analysis

Data are described using means ± SD. The normal distribution of variables was assessed with Shapiro–Wilks's and d'Agostino–Pearson tests. Data were log-transformed for reliability analysis to reduce bias arising from non-uniformity of error when appropriate. The three repetitions completed during the first session were used to examine the intrasession reliability for each direction. For intersession reliability, analysis of both mean and maximal values was undertaken for each direction. The intersession reliability reflects the stability of measures as it defines the day-to-day variability in measures, which typically needs more than one-day between measures in sport measures [25]. The reliability of intrasession and intersession measurements was assessed using intraclass correlation coefficient (ICC), coefficient of variation (CV), typical error (TE), and mean change (Δ), and these were calculated with their SD or 95% confidence limits [lower, upper] using a customised statistical Excel spreadsheets [26] in Microsoft Excel for Office MSO (Version 2111 Build 16.0.14701.20254). Relative reliability was interpreted as poor, fair, good, and excellent when corresponding ICCs were <0.40, 0.40 to 0.75, >0.75 to 0.90, and >0.90 [27].

Absolute reliability was considered good and acceptable when corresponding CVs were ≤10% and ≤20% [28,29].

Figure 1. Illustration of the isometric make neck strength test experimental setup for extension.

Trials and repetitions were assessed for systematic error (i.e., learning effects) using a one-way repeated measures analysis of variance (RM ANOVA) using STATA. The Duncan method was applied in post hoc testing. Statistical significance level was set at $p \leq 0.05$ for all analysis. If the assumption of sphericity was violated, the adjusted *p*-values were reported.

3. Results

Descriptive and reliability statistics related to intrasession isometric neck strength values and ratios are shown in Table 1. Those related to intersession mean values are displayed in Table 2, and intersession maximal values are reported in Table 3.

3.1. Extension

Isometric neck extension demonstrated good intrasession reliability (ICC = 0.86, TE = 2.5 kg, and CV = 8.8%), fair intersession reliability for mean values (ICC = 0.51, TE = 4.5 kg, and CV = 15.9%), and fair intersession reliability for maximal values (ICC = 0.54, TE = 4.9 kg, and CV = 15.1%). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.732$).

3.2. Flexion

Isometric neck flexion demonstrated excellent intrasession reliability (ICC = 0.91, TE = 1.6 kg, and CV = 6.7%), fair intersession reliability for mean values (ICC = 0.60, TE = 3.3 kg, and CV = 14.5%), and fair intersession reliability for maximal values (ICC = 0.58, TE = 3.3 kg, and CV = 14.5%). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.053$).

3.3. Left Lateral Flexion

Isometric neck left lateral flexion demonstrated excellent intrasession reliability (ICC = 0.95, TE = 1.6 kg, and CV = 6.4%), fair intersession reliability for mean values (ICC = 0.56, TE = 3.9 kg, and CV = 18.1), and fair intersession reliability for maximal values (ICC = 0.63, TE = 4.0 kg, and CV = 18.6%). There was no systematic bias for intrasession and mean intersession analyses based on the RM ANOVAs ($p \geq 0.058$). However, bias was detected for intersession reliability analysis of maximal values (p = 0.044). Post hoc testing revealed a significant difference between Trial 3 and 1 (p = 0.031), and Trial 3 and 2 (p = 0.033), with lower values at the third session.

Table 1. Descriptive and reliability statistics related to intrasession isometric neck strength values. Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for the four different directions examined.

	Isometric Strength (Raw Units)			Δ Isometric Strength (Raw Units)			Reliability Statistics			
	T1	T2	T3	T1–T2	T2–T3	T1–T3	ICC [95% CI]	TE (kg) [95% CI]	CV (%) [95% CI]	p-Value [a]
Extension (kg)	31.9 (5.6)	32.3 (6.4)	31.4 (7.5)	0.5 (3.4)	−0.9 (3.4)	−0.5 (3.4)	0.86 [0.75–0.93]	2.5 [2.0–3.0]	8.8 [7.1–11.7]	0.538
Flexion (kg)	23.9 (4.7)	25.8 (5.9)	25.7 (5.6)	0.2 (2.1)	0.1 (2.5)	−0.3 (2.0)	0.91 [0.84–0.95]	1.6 [1.3–1.9]	6.7 [5.6–8.5]	0.809
Left lateral flexion (kg)	25.4 (5.9)	25.6 (6.4)	25.6 (6.3)	0.2 (2.1)	−0.1 (2.5)	−0.2 (2.1)	0.95 [0.90–0.97]	1.6 [1.4–1.9]	6.4 [5.6–8.5]	0.873
Right lateral flexion (kg)	26.1 (5.3)	25.8 (5.9)	25.7 (5.6)	−0.4 (2.0)	−0.1 (2.7)	0.4 (3.3)	0.88 [0.78–0.94]	1.9 [1.7–2.3]	7.9 [6.5–10.7]	0.734
Flexion/extension ratio	0.77 (0.20)	0.77 (0.21)	0.82 (0.31)	0.0 (0.3)	0.1 (0.2)	0.1 (0.3)	0.86 [0.69–0.91]	0.13 [0.11–0.15]	11.5 [9.6–11.5]	0.363
Left/right ratio	0.98 (0.15)	1.00 (0.13)	1.00 (0.16)	0.1 (0.2)	0.0 (0.3)	0.1 (0.2)	0.75 [0.58–0.87]	0.08 [0.07–0.10]	8.2 [6.9–10.7]	0.617

[a] p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

Table 2. Descriptive and reliability statistics related to intersession isometric neck strength (mean of three trials). Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for the four different directions examined.

	Isometric Strength (Raw Units)			Δ Isometric Strength (Raw Units)			Reliability Statistics			
	T1	T2	T3	T1–T2	T2–T3	T1–T3	ICC [95% CI]	TE (kg) [95% CI]	CV (%) [95% CI]	p-Value [a]
Extension (kg)	32.0 (6.0)	31.7 (6.4)	31.2 (6.7)	0.1 (8.2)	−0.4 (3.2)	0.7 (8.4)	0.51 [0.26–0.73]	4.5 [3.6–6.3]	15.9 [12.6–22.6]	0.732
Flexion (kg)	24.0 (4.8)	23.5 (5.7)	22.1 (4.3)	−0.7 (4.3)	−2.5 (4.9)	3.1 (5.1)	0.60 [0.35–0.77]	3.3 [2.8–4.1]	14.5 [12.0–19.5]	0.053
Left lateral flexion (kg)	25.5 (6.1)	24.9 (4.1)	22.8 (6.4)	0.1 (5.5)	−2.0 (5.3)	2.1 (6.1)	0.56 [0.32–0.75]	3.9 [3.4–5.0]	18.1 [14.9–24.4]	0.058
Right lateral flexion (kg)	25.7 (5.5)	25.6 (6.6)	24.2 (8.2)	0.6 (8.0)	−1.4 (4.6)	1.1 (8.2)	0.53 [0.27–0.73]	5.0 [4.3–6.3]	19.8 [16.3–26.9]	0.431
Flexion/extension ratio	0.78 (0.27)	0.77 (0.28)	0.74 (0.13)	0.0 (0.3)	−0.1 (0.2)	0.1 (0.3)	0.55 [0.29–0.74]	0.82 [0.70–1.02]	24.0 [19.7–32.7]	0.649
Left/right ratio	1.00 (0.27)	1.01 (0.28)	0.96 (1.37)	0.0 (0.3)	−0.1 (0.2)	−0.1 (0.2)	0.52 [0.23–0.76]	0.94 [0.8–1.16]	18.8 [0.2–0.8]	0.646

[a] p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error.

Table 3. Descriptive and reliability statistics related to intersession isometric neck strength (maximal value from three trials). Values include mean, standard deviation, and 95% confidence intervals [upper, lower] for the four different directions examined.

	Isometric Strength (Raw Units)			Δ Isometric Strength (Raw Units)			Reliability Statistics			
	T1	T2	T3	T1–T2	T2–T3	T1–T3	ICC [95% CI]	TE (kg) [95% CI]	CV (%) [95% CI]	p-Value [a]
Extension (kg)	33.6 (6.3)	33.4 (6.2)	33.1 (6.8)	0.4 (8.1)	−0.1 (3.6)	0 (8.4)	0.54 [0.25–0.76]	4.9 [4.0–6.2]	15.1 [12.0–21.5]	0.849
Flexion (kg)	25.3 (5.2)	25.1 (5.9)	23.4 (4.7)	-0.5 (4.6)	−2.8 (5.4)	3.3 (5.4)	0.58 [0.33–0.76]	3.6 [3.0–4.8]	14.5 [12.0–19.5]	0.055
Left lateral flexion (kg)	26.8 (6.3)	26.8 (4.7)	24.2 (6.4)	0.4 (5.6)	−2.4 (5.6)	1.6 (5.9)	0.69 [0.43–0.85]	4.0 [3.4–4.8]	18.6 [14.9–26.0]	0.044 *
Right lateral flexion (kg)	27.6 (5.4)	26.0 (4.5)	25.0 (7.1)	-0.9 (5.1)	−0.8 (5.5)	2.4 (4.9)	0.60 [0.35–0.77]	3.6 [3.12–4.53]	16.9 [13.9–22.8]	0.097
Flexion/extension ratio	0.74 (0.21)	0.73 (0.25)	0.70 (0.20)	0.0 (0.3)	−0.1 (0.2)	0.1 (0.2)	0.53 [0.27–0.77]	0.77 [0.66–0.95]	20.7 [17.0–28.1]	0.547
Left/right ratio	0.97 (0.14)	1.04 (0.16)	0.97 (0.11)	0.1 (0.2)	−0.1 (0.2)	0.0 (0.2)	0.53 [0.26–0.73]	0.89 [0.76–1.08]	16.8 [13.5–24.0]	0.162

* $p < 0.05$. [a] p-value from repeated measures analysis of variance. CI: Confidence interval, CV: coefficient of variation, ICC: intraclass correlation coefficient, SD: standard deviation, change, T1: trial 1, T2: trial 2, T3, trial 3, TE: Typical error. Repeated measures analysis of variance significance set at $p < 0.05$.

3.4. Right Lateral Flexion

Isometric neck right lateral flexion demonstrated excellent intrasession reliability (ICC = 0.88, TE = 1.9 kg, and CV = 7.9%), fair intersession reliability for mean values (ICC = 0.53, TE = 5.0 kg, and CV = 19.8%), and fair intersession reliability for maximal values (ICC = 0.59, TE = 5.0 kg, and CV = 19.8%). There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.431$).

3.5. Flexion-to-Extension and Lateral Left-to-Right Ratios

Intrasession flexion-to-extension ratio values ranged from 0.77 to 0.81 with excellent reliability (ICC = 0.86, TE = 0.13, and CV = 11.5%). Intrasession lateral left-to-right ratio values ranged from 0.97 to 0.99 with fair reliability (ICC = 0.75, TE = 0.08, and CV = 8.2%). Intersession mean flexion-to-extension ratios demonstrated fair reliability (ICC = 0.55, TE = 0.82, and CV = 24%) as did lateral left-to-right ratios (ICC = 0.52, TE = 0.94, and CV = 18.8%). Intersession reliability for maximal flexion-to-extension (ICC = 0.53, TE = 0.77, and CV = 20.7%) and lateral left-to-right (ICC = 0.53, TE = 0.89, and CV: 16.8%) ratios were fair. There was no systematic bias across reliability analyses based on the RM ANOVAs ($p \geq 0.649$).

4. Discussion

We examined the reliability of make test isometric neck strength measures in male Rugby Union players using a load cell device in extension, flexion, and left and right lateral flexion. Reliability of flexion-to-extension and left-to-right lateral flexion ratios were also examined. Intrasession reliability was good to excellent (ICC = 0.85–0.95), whereas intersession reliability–which here reflects the stability in measures–was fair for both mean and maximal values (ICC = 0.51–0.69). Similar make test isometric methods have been used to assess Rugby Union players, but reliability was not assessed [7], providing new insight, particularly with regards to intersession reliability and stability of measures.

Our intrasession reliability results coincide with previous studies in semi-professional Rugby Union players using different devices, wherein intrasession reliability of make test isometric neck strength measures using a fixed-mounted handheld dynamometer was good to excellent for extension, flexion, and bilateral lateral flexion (ICC = 0.77–0.92), as well as when tested against a manual resistance in these four directions (ICC = 0.77–0.90) [22]. When the reliability was assessed in a break test fashion with a handheld dynamometer in a seated position in academy Rugby Union players, intrasession reliability was good but did not reach excellent across directions (ICC = 0.80–0.85) [11]. Regarding values of absolute reliability, intrasession reliability was good with CV $\leq$ 10%, and intersession reliability for mean and maximal values were acceptable with CV $\leq$ 20%. When tested using a computerized dynamometer in a seated position, no significant intrasession or intersession differences were detected in non-Rugby Union cohorts, with strong correlations between measures for intrasession (r 0.951–0.989) and intersession (r 0.731–0.969). The CV were <15% when assessed in a neutral neck position and reached 26% in 10° of neck extension, suggesting that both intrasession and intersession assessments were reliable [30]. Our results indicate that the current method to test neck strength in Rugby Union within the same session is good, and we here provide new information regarding intersession reliability and stability of measures. When tested a week apart, reliability can be considered acceptable. The intersession reliability was the weakest for extension, which aligns with findings on flexion and extension intersession isometric neck strength assessed using a scrum device in university school Rugby Union players [31]. The lower reliability in extension was thought to be due to variations in technique and body positioning between sessions [31]. It would seem that using a head harness and cable with a load cell device in a seated position in Rugby Union players is also subject to variations in position between sessions, which could explain the superior intrasession than intersession reliability outcomes.

To our knowledge, this is the first study examining the reliability of an isometric neck strength test in a make test manner using a rigid cable, a head harness with load cell device, in a seated position in Rugby Union players. Our study found neck strength values in semi-professional Rugby Union players range from 22 to 33 kg in all directions. These maximal isometric neck strength values are similar to those observed with amateur players assessed in a contact position using a load cell or fixed-frame dynamometer [32]. Our ranges were, however, greater than those from isometric neck strength values assessed in a cohort of semi-professional Rugby Union players tested using a mounted handheld dynamometer and a make test approach (range 17.3–23.5 kg) [22]. The difference potentially reflects the superior procedural methods of the load cell with harness and cable set-up than the handheld dynamometer set-up due to the testing interaction between the participant and examiner in the latter method [22]. When professional players were assessed in a similar fashion to ours, specifically in a seated position with a customized load cell device, a head harness, and an immovable metal frame in a make test fashion, the maximal strength values were greater than those reported here (i.e., 29–39 kg) [7]. Several studies have attempted to identify normative neck strength values in Rugby Union players with different methods of testing [10]; however, there is no agreement on the strength testing method to be used or requisite strength levels [10]. The results of the present study provide data on isometric neck strength for semi-professional male Rugby Union players in flexion, extension, and left and right lateral flexion, as well as flexion-to-extension and left-to-right lateral flexion ratios using a reproducible set-up. In addition, our study indicates that reliability is good-to-excellent intrasession and fair intersession when players are tested in-season.

Extension-to-flexion ratios ranged from 0.74 and 0.82 with good intrasession reliability, and left-to-right lateral flexion ratios were around 0.97 to 1.01 with fair intrasession reliability. Intersession reliability was fair for both ratios. Our results are similar to those reported elsewhere in semi-professional Rugby Union players with flexion-to-extension ratios of 0.75 to 0.76 and bilateral lateral flexion ratios of 0.96 to 1.0 in a make test fashion with a load cell device via cable in a seated position [7,11]. Noteworthy is that these ratios are marginally greater than those presented elsewhere using different methods of testing (isokinetic and break test), wherein flexion-to-extension ratios in Rugby Union ranged, on average, from 0.65 to 0.7 [14,33]. Results of previous studies at different levels of competition have shown greater absolute values in extension compared to flexion in Rugby Union players [34–36], with younger players possessing lower strength ratios compared to senior players [17], and forwards exhibiting lower ratios than backs [19,33]. These imbalances in neck musculature are a potential risk factor for neck injuries, where flexion-to-extension ratio imbalances have been associated with higher head angular and linear accelerations in other cohorts [37]. Promoting strength symmetry between muscles is a strategy used in practice to mitigate injury risk in other anatomical parts of the body (e.g., knee) [38] and should be explored further as a mean to mitigate concussion and neck injury risk in Rugby Union.

5. Conclusions

Assessing isometric neck strength with a head harness and a cable with a load cell device in a seated position in semi-professional Rugby Union players is feasible and demonstrates good-to-excellent intrasession and fair intersession relative reliability. Absolute reliability is good intrasession (CV $\leq$ 10%) and acceptable intersession (CV $\leq$ 20%). Although the load cell approach appears less reliable than using a handheld dynamometer based on reliability values reported in the literature, the load cell approach can be reliably used to assess isometric neck strength in extension, flexion, and bilateral lateral flexion, as well as to derive flexion-to-extension and left-to-right lateral flexion ratios in male Rugby Union players. A direct comparison of reliability data from the same cohort using both the handheld dynamometer and cable load cell approach is needed to confirm that one method is more reliable than the other. We provide data from Rugby Union players to inform practice and assist standardisation of testing methods. Further experimentation with the load cell device to improve intersession reliability and stability of measures in neck isometric testing is recommended. Intersession reliability might be improved using three-axial load cells, ensuring an initial familiarisation session and further attention to individualised and repeatable neck positions.

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Appendix B. Conference presentations arising from this thesis

Appendix B1. Neck strength in Rugby Union players: A systematic review of the literature

Poster Presentations

51. Acute effects of blue light on motor control and cognition in older adults

Beaven, C.M.[1], Hébert-Losier, K.[1], Uiga, L.[1]

[1]*Te Huataki Waiora School of Health, University of Waikato.*

Introduction: Falls are a major economic burden and risk factor for mortality in older adults. Over half of all ACC claims by people 65+ are a consequence of falling, costing an estimated ~$1,700 million in 2010. Blue light interventions can improve cognitive function and performance in fine motor tasks, but the potential impact on motor function with relevance to falling is unknown. **Methods**: Sixteen older adults [age 74 ± 8.1 y (65 to 82)] participated in four counter-balanced sessions with light delivered visually [Luminette®: (placebo/blue-enriched)] and/or aurally [Human Charger®: (on/off)] for 12 minutes. Motor function was assessed using the OptojumpNext® (Microgate, Italy) where participants were asked to lift and plant their right leg from a double-leg stanceas quickly as possible in response to an unexpected visual cue. Cognitive function was assessed using computer-based executive function test (Eriksen Flanker Task; PEBL V2.1). Both tests were assessed before and after the light intervention. **Results**: Motor function was significantly enhanced ($p = 0.03$) with a large effect size ($d = 1.13$) in the visual blue-light relative to the placebo condition. No effects of the light intervention occurred in measures of cognitive function. **Discussion**: The brief light intervention was capable of altering measures with potential relevance to fall risk in older adults. Specifically, the ability to rapidly respond and re-plant the foot following a disturbance could decrease the likelihood of falling. **Take home message**: Novel light interventions may provide a potential countermeasure to decrease the financial and human costs of falls.

52. Effects of traditional Chinese meridian massage combined with soymilk supplementation on post-exercise recovery

Chan, C.H.[1], Yang, C.C.[2], Yu, C.J.[1,2], Kuo, Y.C.[2], Tsao, Y.C.[2], Liao, Y.H.[2]

[1]*Institute of Sports Sciences, University of Taipei, Taipei City, Taiwan*
[2]*Department of Exercise and Health Science, National Taipei University of Nursing and Health Sciences, Taipei City, Taiwan*

Introduction: This study investigated the combined effects of Chinese meridian massage (CMM) and soymilk supplementation on muscle damage and post-exercise recovery. **Method**: Nine healthy young adults (6M/3F; age: 24.3 ± 0.5 yrs old) completed two trials in a counter-balanced order: 1) CMM + placebo (CMM/P), and 2) CMM + soymilk (CMM/S). On Day 1, participants performed a 1st 5-km time trial (TT) and continued for a further 15-km self-paced cycling after a 30-s break (20 km total). The CMM (15 min) was performed 45 min post-exercise. The first and second doses of soymilk/placebo (300 ml/dose) were provided immediately and 60 min after the 20-km cycling. On Day 2, participants performed a 2nd 5-km TT to assess the recovery. We periodically measured heart rate, systemic oxygen saturation (SpO_2), blood creatine kinase (CK) and uric acid (UA), TT performance, and work completed. **Results**: There were no differences in heart rate or SpO_2 during exercise and recovery between trials. 5-km TT performance and work output was unaltered between trials. However, the exercise-induced increases in circulating CK and UA were significantly lower in CMM/S than in CMM/P ($p<0.05$). **Discussion**: We demonstrate that provision of soymilk to Chinese meridian massage after strenuous exercise effectively suppressed endurance exercise-induced muscle damage, reflected by the lower responses in circulating CK and UA, but this does not promote the recovery of exercise. **Take home message**: The addition of soymilk to Chinese meridian massage may be effective to decrease endurance exercise-induced muscle damage.

53. Neck strength in Rugby Union players: A literature review

Chavarro-Nieto, C.D.[1], Beaven, C.M.[1], Gill, N.D.[1,2], Hébert-Losier, K.[1]

[1]*University of Waikato*
[2]*New Zealand Rugby*

Introduction: Concussion is the most prevalent injury in professional Rugby Union. Neck strengthening is one strategy of potential protective value for concussion. We aimed to examine the scientific literature addressing neck strength in Rugby Union with a focus on the potential role of neck strength on injury incidence. **Method**: The first author (CC) performed a systematic search in June, 2019, to locate published peer-reviewed articles from four electronic databases. Studies included were original research conducted with Rugby Union that evaluated neck strength, neck-strengthening interventions, and/or head or neck injury outcomes. Studies were not excluded based on sex, age, level of competition, or study design. **Results**: 106 articles were identified using the search strategy, with 14 articles meeting inclusion. These articles tested 1066 male players (average: 76 participants per study), with 7 (50%) studies in professional, 4 (28.5%) schoolchildren, 2 (14.2%) semi-professional, and 2 (14.2%) amateur. Studies were cross-sectional (46%), retrospective (30%), or prospective (23%). Four studies (29%) included neck-strengthening interventions. **Discussion**: Forwards were significantly stronger than backs in all neck strength measures and were stronger in extension than any other movement direction. Professional senior players were stronger in all strength measures than any other age or level of competition ($p<0.05$). Isometric exercise routines in semi-professional and professional players were shown to improve neck strength in all directions. In Rugby Union, strengthening the neck effectively reduced neck match-related injuries. **Take Home Message:** It is important to implement evidence-based neck training strategies to minimise neck and head injury risk in Rugby Union.

54. The working conditions of performance analysts in Oceania

Dickey, L.[1], Ramsey, C.[1], Humphrey, R.[1], Middlemas, S.[1]

[1]*Institute of Sport, Exercise and Health, Otago Polytechnic*

Introduction: Performance analysis (PA) has become an essential tool in the sports industry. Current PA research has been completed mainly looking at the application and effectiveness in different sport settings. Despite the continued growth of research on PA there is little known about the working condition of the analysts. Working conditions studies are completed to gain an understanding of the work environment and identify ways to better support practitioners. This research aims to explore the working conditions of the performance analysts. **Method:** An online survey distributed to performance analysts in Oceania collected data on PA demographics, job type, renumeration and job satisfaction. Data analysis involved descriptive statistics, a T-test and a Mann Whitney U. **Results:** The 65 performance analysts in this study are predominantly 25-34-year-old males on $62,000 per annum, with six years of experience. The majority of the participants held a Bachelor's degree or higher qualification and frequently travelled and worked above their agreed hours unpaid. **Discussion:** The work demands of a performance analyst could lead to burnout as found in other industries where employees were stressed and working long hours. **Take home message:** Work demands should be managed before they become a bigger issue with burnout and poor retention of employees a possibility, like in the coaching industry.

55. Beat the heat: The effectiveness of a practical, cold water arm immersion protocol during a simulated rugby sevens protocol.

Fenemor, S.P.[1,2,3], Walsh, K.[1], Davie, C.[1], Wharemate, J.[1], van der Laan, M.[1], Carson, D.[1], Olsen, J.[1], Beaven, C.M.[1]

[1]*University of Waikato*
[2]*High Performance Sport New Zealand*
[3]*New Zealand Rugby*

Background: The environmental conditions at the Tokyo 2020 Olympics are likely to decrease performance factors associated with rugby sevens. The efficacy of many cooling strategies has been well described, however, practical strategies such as pre- and per-cooling using cold-water immersion of the arms (CWI) has received little consideration. **Methods:** Nine recreationally trained athletes (4 male) completed two Wattbike™ repeated-sprint interventions using a cross-over design in a heated laboratory environment (~30-32 °C, ~50-65% rH). The protocol was designed to replicate the physiological demands of rugby sevens. Tympanic temperature (T_{TYMP}), peak power (PP), and thermal comfort was collected before, during, and after each intervention. Participants either performed CWAI with arms submerged to the elbow in ice water for 60 seconds both after the warm up and during half-time, or a passive control. **Results:** CWI enhanced PP immediately post half-time by 96 W ($p=0.01$, Cohen's $d=0.61$), with no significant differences in PP at any other time point. CWI decreased T_{TYMP} at all time points after half-time ($p<0.05$; $d=1.07$ to 1.19). Thermal comfort was significantly improved immediately post each immersion ($p<0.05$). **Discussion:** Given that the CWI intervention was transiently effective in enhancing PP and thermal comfort, and decreasing T_{TYMP}, it may provide a practical pre- &/or per-cooling strategy for athletes competing in hot environments. Effective cooling may also positively impact subsequent rugby sevens performance by mitigating the increase in T_{TYMP}. **Take home message:** A cold-water arm immersion protocol can improve performance, T_{TYMP}, and perceptual measures when completing repeated efforts in the heat.

56. Comparative running demands of under 18, under 21 and senior regional field hockey tournaments

van der Merwe, F.H.[1], Platt, T.[1]

[1]*Waikato Institute of Technology (WINTEC)*

Introduction: The purpose of this study was to quantify match play running demands of field hockey players in relation to playing level and position. **Methods:** Distance covered was measured on 30 regional field hockey players (under 18, under 21 and senior) during 18 open and age-group national competition tournament games. Total distance (TD), high-intensity running (HIR; distance ≥15km.hr), low-intensity running (LIR; distance ≤14.9km.hr), high-intensity acceleration (HI-ACC; acceleration ≥3m.s^{-2}) and high-intensity deceleration (HI-DEC; deceleration ≥3m.s^{-2}) were assessed global positioning system (GPS) technology. Data was analysed using analysis of variance (ANOVA) and post hoc Bonferroni correction ($p \leq 0.05$). **Results:** Under 18 strikers (1839.79 ± 456.85) and midfielders (1501.56 ± 559.42) showcased significantly higher HIR distance than the under 21 strikers (1211.08 ± 458.49) and midfielders (1064.00 ± 432.69) respectively. Senior midfielders (5961.55 ± 964.05) covered significantly higher LIR distance in comparison to both under 18 (5046.91 ± 852.14) and 21 midfielders (5126.83 ± 376.24), more HI-ACC efforts (194.61 ± 31.11) than under 21 midfielders (164.94 ± 21.64) and more HI-DEC efforts (73.12 ± 18.45) than under 18 midfielders (55.21 ± 13.42). Under 18 strikers showcased significantly less HI-ACC efforts (137.88 ± 19.17) than senior (168.11 ± 25.16) and under 21 strikers (173.25 ± 18.29) and less HI-DEC efforts (61.21 ± 12.17) than the under 21 strikers (82.50 ± 21.01). Senior defenders had significantly more HI-ACC efforts (169.35 ± 38.56) than under 18 defenders (140.45 ± 33.39). **Take home message:** These results show that the different playing levels and positions in field hockey are sufficiently different to warrant specialized, position-specific, conditioning training as part of an informed long-term athletic development plan.

Neck strength in Rugby Union players: a literature review

[1]Chavarro-Nieto, C.D. [1]Beaven, C.M; [1,2]Gill, N.D; [1]Hébert-Losier, K.

[1]University of Waikato; [2]New Zealand Rugby.

Introduction

Concussion is the most prevalent injury in professional Rugby Union. Neck strengthening is one strategy of potential protective value for concussion. We aimed to examine the scientific literature addressing neck strength in Rugby Union with a focus on the potential role of neck strength on injury incidence.

Methods

We carried out a systematic review of the literature. The first author (CC) performed a systematic search in June, 2019, to locate published peer-reviewed articles from Pubmed, SPORTdiscus Web of Science, and Scopus databases. Studies included were original research conducted with Rugby Union players that evaluated neck strength, neck-strengthening interventions, and/or head or neck injury outcomes. Studies were not excluded based on sex, age, level of competition, or study design.

Results

106 articles were identified using the search strategy, with 14 articles meeting inclusion. These articles tested 1066 male players (average: 76 participants per study), with seven (50%) studies in professional, four (28.5%) schoolchildren, two (14.2%) semi-professional, and two (14.2%) amateur players. Studies were cross-sectional (46%), retrospective (30%), or prospective (23%). Four studies (29%) included neck-strengthening interventions.

Conclusions

Forwards were significantly stronger than backs in most of the neck strength measures and were stronger in extension than any other movement direction. Professional senior players were stronger in all strength measures than any other age or level of competition ($p<0.05$). Isometric exercise routines in semi-professional and professional players were shown to improve neck strength in all directions. In Rugby Union, strengthening the neck effectively reduced neck match-related injuries.

Appendix B2. Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review.

access to deep water appears to increase the likelihood of infants engaging in drowning incidents.

6. Hamstrings injury incidence, risk factors, and prevention in rugby union players: A literature review

[1]Chavarro-Nieto, C.D.; [1]Beaven, C.M; [1,2]Gill, N.D; [1]Hébert-Losier, K.

[1]*Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, University of Waikato, New Zealand*
[2]*New Zealand Rugby, Wellington, New Zealand.*

Introduction: Hamstring strain injuries are one of the most common injuries in Rugby Union, representing up to 15% of all injuries sustained. Acute hamstring strains have the highest recurrence rate of any muscle injury. **Methods**: We conducted a systematic search of the literature in September 2020 to locate published peer-reviewed articles from PubMed, SPORTDiscus™, Web of Science®, and Scopus® e-databases. Studies included were original research conducted in Rugby Union that evaluated hamstring strength, hamstring strengthening interventions, and/or hamstring injury outcomes. **Results**: Twenty-four studies met inclusion. Twenty-one studies (87%) included male players; one, female players (4%); and two, both males and females (8%). Isokinetic testing was the most common method used to quantify hamstring strength and imbalances in Rugby Union; with data indicating that professionals are stronger than amateurs, and forwards are stronger than backs. There is, however, a lack of evidence supporting the utility of isokinetic-based measures to inform injury prevention and return-to-play decisions in practical settings. There is stronger scientific evidence to support the use of Nordic eccentric strength measures to inform practice, with eccentric strength measures and imbalances predicting new and recurrent injuries in Rugby Union. **Discussion**: The aetiology of hamstring strain injuries is multifactorial, with age, playing position, fatigue, previous injuries, running actions, strength imbalances, and lack of readiness to play identified as potential risk factors. As such, return-to-play and injury prevention programs should seek to combine multiple strategies. These strategies should include Nordic strength assessment and exercises, high-speed running routines, biomechanical assessment, and adequate warm-up routines. **Take home message**: Strengthening programs with Nordic exercises significantly increased hamstring strength measures and decreased imbalance ratios in male and female Rugby Union players. These programs and measures were associated with a significant reduction in hamstring injury incidence and severity in professional players, warranting their integration in practice.

7. Assessing the effectiveness of an online exercise program for Cerebral Palsy patients using 'Physitrack': A randomised controlled trial protocol

[1]Kelly, L.; [1]Ramsey, C.; [1]Humphrey, R.

[1]*Otago Polytechnic*

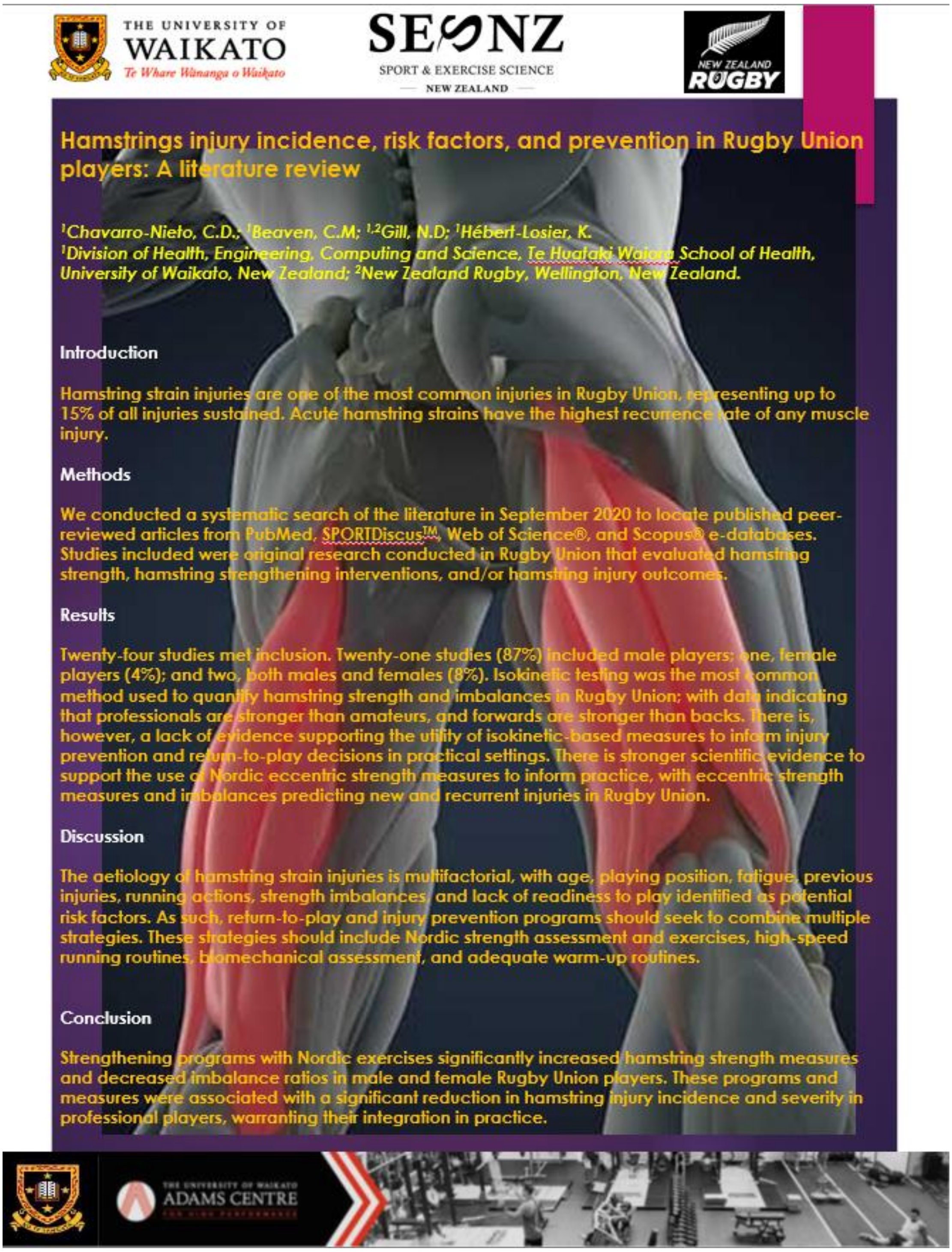
Introduction: Cerebral Palsy (CP) children often receive exercise programs to assist in rehabilitation. Adherence to exercise programs is a necessary component to achieve exercise goals but can be challenging. With the severity of CP, the accessibility of technology show successful integrations in the field of rehabilitation. **Method**: This thesis evaluates the current literature for online exercise applications used with the CP population. It uses it to develop a Randomized Controlled Trial (RCT) protocol, which determines an online application's effectiveness for use with CP. The literature review searches and reviews three main areas: 1) exercises for CP, 2) online applications, and 3) Gross Motor Function Classification System. Data were analysed to determine the frequency, intensity, type, and duration of training that improves Gross Motor Function Measure (GMFM) outcomes among CP patients. **Results**: Eleven studies informed the training program and outcome measures in the RCT protocol. Exercises modalities performed by the experimental and control groups included; cardiovascular, musculoskeletal, and cardiovascular + musculoskeletal. The experimental group's primary outcome was against the control group, GMFM-88E, Visual Pain Analog Scale, grip strength, and caregiver adherence. The secondary outcome measure is cardiovascular versus musculoskeletal versus cardiovascular + musculoskeletal subgroups. **Discussion**: There is a lack of evidence supporting online applications, indicating a need for more research. There are various studies on the use of games through technology, such as virtual reality. Still, few studies evaluate applications used primarily for demonstrating exercises for replication into the real environment (as opposed to the virtual environment). This thesis could help with future directions in online applications for CP patients. **Take home message**: Please find a way to make exercise/physical activity cost-effective and engage for CP patients and their caregivers for a higher rate of motivation and adherence. This advice will help make exercise rehabilitation more accessible, and a healthier routine adheres.

8. Cerebral metabolism appears elevated in hyperthermic individuals while completing cognitive tasks during exercise

[1]Ashworth E.T.; [2]Cotter J.D.; [1] Kilding A.E.

[1]*Auckland University of Technology*
[2]*University of Otago*

Introduction: Cognition can be impaired during exercise in the heat, which could contribute to military casualties. To our knowledge, the independent role of elevated core temperature during exercise has not been determined. The aim of the current study was to evaluate effects of elevated core temperature on cognition during physically-encumbering, heated exercise, and to determine whether the perceptual cooling effects of menthol can preserve any deficit in cognitive performance. **Method**: Eight participants completed three trials in randomised order: One normothermic (CON) and two with elevated (38.5°C) core temperature, induced by prior immersion in neutral versus hot water. In the CON trial and one hot trial (HOT) a water



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Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A literature review

[1]Chavarro-Nieto, C.D.; [1]Beaven, C.M; [1,2]Gill, N.D; [1]Hébert-Losier, K.
[1]Division of Health, Engineering, Computing and Science, Te Huataki Waiora School of Health, University of Waikato, New Zealand; [2]New Zealand Rugby, Wellington, New Zealand.

Introduction

Hamstring strain injuries are one of the most common injuries in Rugby Union, representing up to 15% of all injuries sustained. Acute hamstring strains have the highest recurrence rate of any muscle injury.

Methods

We conducted a systematic search of the literature in September 2020 to locate published peer-reviewed articles from PubMed, SPORTDiscus™, Web of Science®, and Scopus® e-databases. Studies included were original research conducted in Rugby Union that evaluated hamstring strength, hamstring strengthening interventions, and/or hamstring injury outcomes.

Results

Twenty-four studies met inclusion. Twenty-one studies (87%) included male players; one, female players (4%); and two, both males and females (8%). Isokinetic testing was the most common method used to quantify hamstring strength and imbalances in Rugby Union; with data indicating that professionals are stronger than amateurs, and forwards are stronger than backs. There is, however, a lack of evidence supporting the utility of isokinetic-based measures to inform injury prevention and return-to-play decisions in practical settings. There is stronger scientific evidence to support the use of Nordic eccentric strength measures to inform practice, with eccentric strength measures and imbalances predicting new and recurrent injuries in Rugby Union.

Discussion

The aetiology of hamstring strain injuries is multifactorial, with age, playing position, fatigue, previous injuries, running actions, strength imbalances, and lack of readiness to play identified as potential risk factors. As such, return-to-play and injury prevention programs should seek to combine multiple strategies. These strategies should include Nordic strength assessment and exercises, high-speed running routines, biomechanical assessment, and adequate warm-up routines.

Conclusion

Strengthening programs with Nordic exercises significantly increased hamstring strength measures and decreased imbalance ratios in male and female Rugby Union players. These programs and measures were associated with a significant reduction in hamstring injury incidence and severity in professional players, warranting their integration in practice.

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Appendix C. Appendices for Chapter 2:

Appendix C1 Summary of the study designs, levels of evidence, and quality scores of the studies reviewed (n = 10). The number of stars (*) allocated for each quality assessment item is provided.
Quality assessment tool

MODIFIED NEWCASTLE - OTTAWA QUALITY ASSESSMENT SCALE

Selection: (Maximum 5 stars)
1) Representativeness of the sample:
 a) Truly representative of the average in the target population. * (all subjects or random sampling
 b) Somewhat representative of the average in the target population. * (non-random sampling)
 c) Selected group of users.
 d) No description of the sampling strategy.
2) Sample size:
 a) Justified and satisfactory. *
 b) Not justified.
3) Non-respondents**:** Rate between participants asked to participate and participants actually participated
 a) Comparability between respondents and non-respondents' characteristics is established, and the response rate is satisfactory. * Rate more than 60%
 b) The response rate is unsatisfactory, or the comparability between respondents and non-respondents is unsatisfactory.
 c) No description of the response rate or the characteristics of the responders and the non-responders.
4) Ascertainment of the exposure (risk factor):
 a) Validated measurement tool. **
 b) Non-validated measurement tool, but the tool is available or described.*
 c) No description of the measurement tool.

Comparability: (Maximum 2 stars)
1) The subjects in different outcome groups are comparable, based on the study design or analysis. Confounding factors are controlled.
 a) The study controls for the most important factor (select one). * Age
 b) The study control for any additional factor. * Weight, height

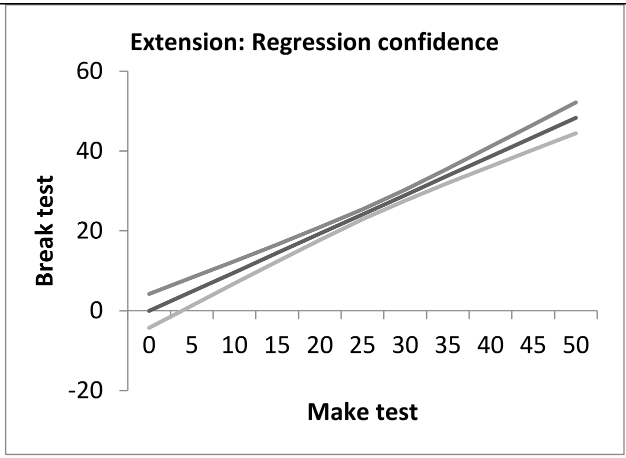
Outcome: (Maximum 3 stars)
1) Assessment of the outcome:
 a) Independent blind assessment. **
 b) Record linkage. **
 c) Self report. *
 d) No description.
2) Statistical test:
 a) The statistical test used to analyze the data is clearly described and appropriate, and the measurement of the association is presented, including confidence intervals and the probability level (p value). *

	Selection				Comparability	Outcome		Total
	1	**2**	**3**	**4**	**1**	**1**	**2**	
Barrett et al. (2015)	b*	b	a*	a**	a,b**	d	b	**6***
Davies et al. (2016)	a*	b	a*	a**	a,b**	d	b	**6***
Dempsey et al. (2015)	c	b	c	a**	a,b**	d	b	**4***
Geary et al. (2013)	b*	a*	c	a**	a,b**	d	a*	**7***
Geary et al. (2014)	b*	b	c	a**	non	d	b	**3***
D. F. Hamilton et al. (2012)	b*	b	c	a**	a,b**	d	a*	**6***
D. F. Hamilton and Gatherer (2014a)	c	b	a*	a**	a,b**	a**	b	**7***
D. F. Hamilton et al. (2014a)	a*	b	c	a**	a,b**	d	a*	**6***
Konrath and Appleby (2012)	c	b	c	a**	a,b**	d	b	**4***
Maconi et al. (2016)	b*	b	c	b*	a,b**	d	a*	**5***
(Naish et al., 2013a)	a*	b	a*	a**	a,b**	d	b	**6***
Olivier and Du Toit (2008)	b*	b	c	b*	a,b**	d	a*	**5***
Salmon et al. (2018)	a*	b	b	a**	a,b**	d	a*	**6***
Snodgrass et al. (2018)	b*	b	c	a**	a,b**	d	a*	**6***

Appendix C2. Summary of the risk of bias assessment of the reviewed studies (Modified Newcastle - Ottawa Quality score).

Methodology quality assessment score based on Newcastle-Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars).

Appendix D. Appendices for Chapter 3:


Extension: Regression confidence
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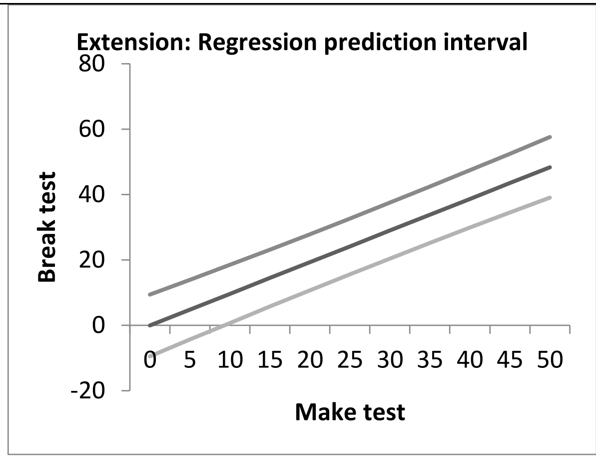
Extension: Regression prediction interval
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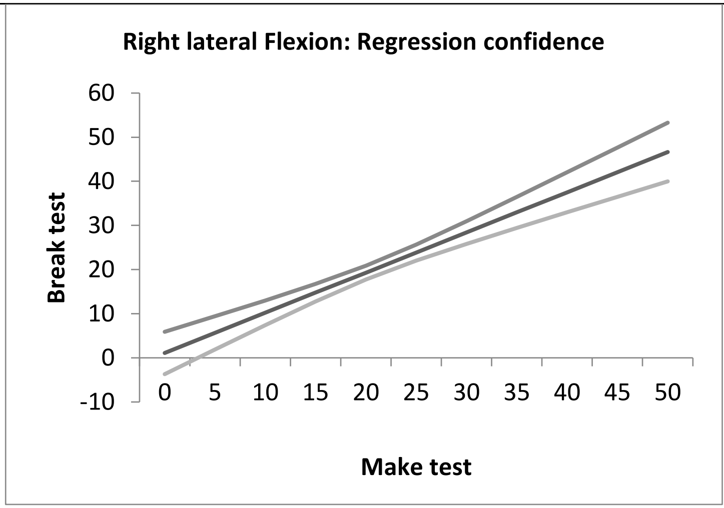
Right lateral Flexion: Regression confidence
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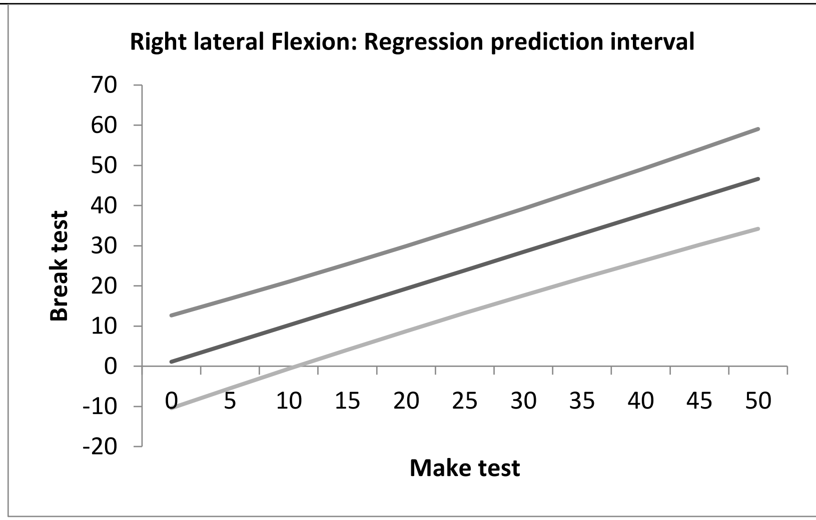
Right lateral Flexion: Regression prediction interval
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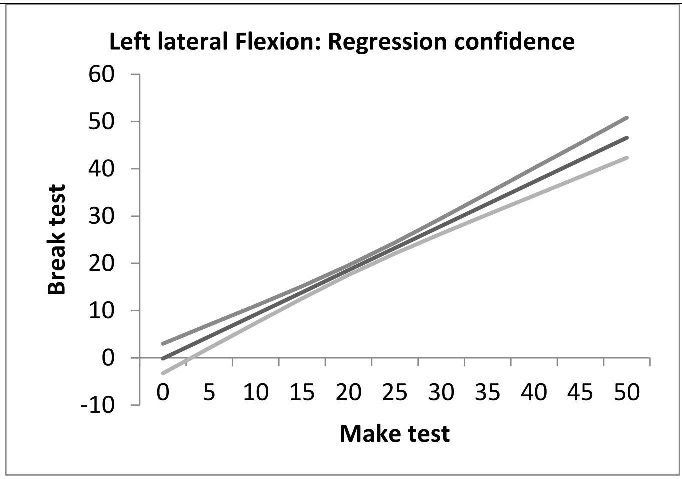
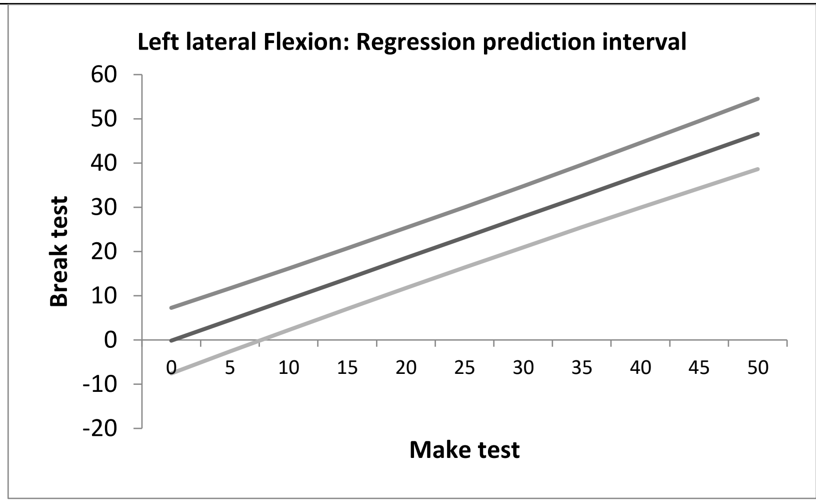




Appendix D1. Illustration of flexion, extension, and right and left lateral flexion Left: Scatter diagram with regression confidence interval between flexion make vs break test. Right: Scatter diagram with regression prediction interval between flexion make vs break tests.

Appendix E. Appendices for Chapter 5:

Appendix E1 Summary of the study designs, levels of evidence, and quality scores of the studies reviewed (n = 10). The number of stars (*) allocated for each quality assessment item is provided.

Quality assessment tool

NEWCASTLE - OTTAWA QUALITY ASSESSMENT SCALE

Selection: (Maximum 5 stars)

1) Representativeness of the sample:

    a) Truly representative of the average in the target population. * (all subjects or random sampling

    b) Somewhat representative of the average in the target population. * (non-random sampling)

    c) Selected group of users.

    d) No description of the sampling strategy.

2) Sample size:

    a) Justified and satisfactory. *

    b) Not justified.

3) Non-respondents**:** Rate between participants asked to participate and participants actually participated

    a) Comparability between respondents and non-respondents characteristics is established, and the response rate is satisfactory. * Rate more than 60%

    b) The response rate is unsatisfactory, or the comparability between respondents and non-respondents is unsatisfactory.

    c) No description of the response rate or the characteristics of the responders and the non-responders.

4) Ascertainment of the exposure (risk factor):

    a) Validated measurement tool. **

    b) Non-validated measurement tool, but the tool is available or described.*

    c) No description of the measurement tool.

Comparability: (Maximum 2 stars)

1) The subjects in different outcome groups are comparable, based on the study design or analysis. Confounding factors are controlled.

    a) The study controls for the most important factor (select one). * Age

    b) The study control for any additional factor. * Weight , height

Outcome: (Maximum 3 stars)

1) Assessment of the outcome:

    a) Independent blind assessment. **

    b) Record linkage. **

    c) Self report. *

    d) No description.

2) Statistical test:

a) The statistical test used to analyze the data is clearly described and appropriate, and the measurement of the association is presented, including confidence intervals and the probability level (p value). *

b) The statistical test is not appropriate, not described or incomplete.

Appendix E2. Summary of the risk of bias assessment of the reviewed studies (Modified Newcastle - Ottawa Quality score).

	SELECTION				COMPARABILITY	OUTCOME		TOTAL
	1	**1**	**3**	**4**	**1**	**1**	**2**	
Anastasi and Hamzeh (2011)	b	b	c	a	b	d	a	5
Beyer et al. (2016)	b	b	ca	a	b	d	b	4
M. N. Bourne et al. (2015b)	b	b	c	a	a,b	b	a	8
Brooks et al. (2005a)	a	b	a	a	a,b	b	a	9
Brooks et al. (2005b)	a	b	a	a	a,b	b	a	9
Brooks et al. (2006b).	a	b	c	a	b	b	a	9
Brooks and Kemp (2011)	a	b	c	a	b	b	a	7
Brown et al. (2014)	b	b	c	b	a,b	d	B	4
Brown et al. (2016)	b	b	c	b	a,b	d	b	4
Deighan et al. (2012)	b	b	c	b	b	d	a	4
Dobbs et al. (2017)	c	b	c	b	b	D	b	2
Farnan et al. (2013)	b	b	a	b	b	c	a	5
Kenneally-Dabrowski, Serpell, et al. (2019b)	a	b	c	a	b	b	a	7
Kenneally-Dabrowski, Brown, et al. (2019)	b	b	c	a	a,b	b	b	7
Mendiguchia et al. (2016)	c	b	c	a	a,b	d	b	4
Mondin et al. (2018)	c	b	c	a	b	d	a	4
Reid et al. (2013)	C	b	c	a	a,b	b	b	6

Roberts et al. (2013)	a	b	c	a	b	b	a	7
Severo-Silveira et al. (2018)	b	b	a	a	b	a	a	8
Turl and George (1998)	b	b	c	a	a,b	a	b	7
Upton et al. (1996)	b	b	c	b	a,b	c	b	5
Yamada and Mastumoto (2009)	b	b	c	b	b	b	b	5

Methodology quality assessment score based on Newcastle-Ottawa Quality Assessment Scale adapted for cross-sectional studies, weak (0-3 stars), moderate (4-6 stars), and strong (7-10 stars).

Appendix F. Appendices for Chapter 7:

Appendix F1. Isometric neck strength values for male semi-professional players (n = 158) by position. Values are mean and standard deviation (SD).

	Flexion (kg)	**Extension (kg)**	**Left lateral flexion (kg)**	**Right lateral flexion (kg)**
Props (n = 27)	25 ± 7.0	25 ± 7.0	24 ± 6.5	24 ± 6.3
Hookers (n = 12)	27 ± 7.0	35 ± 7.7	26 ± 6.0	25 ± 8.0
Locks (n = 18)	25 ± 8.0	31 ± 6.0	22 ± 6.5	22 ± 7.7
Loose forwards (n = 17)	27 ± 8.0	33 ± 7.2	25 ± 9.0	24 ± 7.0
Inside backs (n = 26)	20 ± 4.5	28 ± 5.6	21 ± 5.5	21 ± 5.6
Midfield (n = 23)	22 ± 7.0	31 ± 7.7	22 ± 8.8	23 ± 7.6
Outside backs (n = 35)	23 ± 6.2	29 ± 5.5	21 ± 6.0	21 ± 7.0

Appendix F2. Isometric neck strength values for male professional players (n = 102) by position. Values are mean and standard deviation (SD).

	Flexion (kg)	Extension (kg)	Left lateral flexion (kg)	Right lateral flexion (kg)
Props (n = 20)	34 ± 9.0	39 ± 6.4	31 ± 8.0	31 ± 8.6
Hookers (n = 9)	25 ± 13.0	33 ± 4.8	24 ± 5.0	24 ± 5.0
Locks (n = 14)	29 ± 8.0	36 ± 5.0	26 ± 7.7	26 ± 6.8
Loose Forwards (n =17)	29 ± 7.8	29 ± 7.7	26 ± 6.7	24 ± 6.5
Inside (n =11)	28 ± 4.5	30 ± 5.6	26 ± 5.0	23 ± 6.0
Midfield (n =13)	28 ± 6.0	29 ± 7.5	25 ± 6.5	22 ± 7.0
Outsides (n =18)	28 ± 6.0	29 ± 7.5	24 ± 7.2	23 ± 7.6

Appendix F3. Isometric neck strength values for female semi-professional players (n = 44) by position. Values are mean and standard deviation (SD).

	Flexion	Extension	Left lateral flexion	Right lateral flexion
Props (n = 7)	16 ± 4.5	23 ± 3.0	16 ± 5.0	16 ± 4.0
Hookers (n = 2)	22 ± 7.0	23 ± 7.0	17 ± 4.0	19 ± 6.6
Locks (n = 5)	18 ± 3.0	23 ± 4.0	16 ± 6.0	17 ± 7.5
Loose forwards (n =8)	14 ± 3.0	20 ± 4.3	15 ± 5.0	15 ± 4.0
Inside backs (n =5)	16 ± 5.4	20 ± 3.1	21 ± 5.5	16 ± 3.1
Midfield (n =5)	22 ± 9.0	20 ± 7.0	14 ± 6.5	20 ± 7.0
Outsides backs (n =12)	15 ± 4.3	19 ± 5.0	16 ± 5.0	15 ± 4.5

Appendix F4. Hamstring eccentric strength values in semi-professional players (n = 166) by position Values are mean and standard deviation (SD).

	Left absolute (N)	Left relative ($N{\cdot}kg^{-1}$)	Right absolute (N)	Right relative ($N{\cdot}kg^{-1}$)	Strength balance (%)[a]
Props (n = 33)	440 ± 99	3.8 ± 0.8	424 ± 100	3.6 ± 0.9	10 ± 6.5
Hookers (n= 12)	390 ± 117	3.6 ± 1.2	390 ± 110	3.6 ± 1.1	11 ± 5.0
Locks (n = 17)	392 ± 87	3.5 ± 0.7	365 ± 112	3.6 ± 3.2	12 ± 7.0
Loose Forwards (n= 23)	429 ± 114	4.1 ± 1.1	418 ± 106	4.0 ± 1.0	12 ± 7.0
Inside (n=26)	365 ± 96	4.0 ± 1.1	366 ± 83	4.0 ± 0.9	10 ± 6.0
Midfield (n=19)	416 ± 116	4.1 ± 1.1	238 ± 100	4.1 ± 1.0	9 ± 9.0
Outsides (n=36)	383 ± 99	4.0 ± 1.0	377 ± 90	3.9 ± 0.9	11 ± 7.0

[a] Difference between left and right legs over the left leg strength value expressed as a percentage (%): abs[(left leg – right leg)/left leg]*100].

Appendix F5. Hamstring eccentric strength values in professional players (n = 131) by position Values are mean and standard deviation (SD).

	Left absolute (N)	Left relative ($N \cdot kg^{-1}$)	Right absolute (N)	Right relative ($N \cdot kg^{-1}$)	Strength balance (%)[a]
Props (n = 23)	470 ± 100	3.8 ± 1.0	477 ± 113	3.8 ± 0.7	8 ± 5
Hookers (n = 8)	431 ± 63	3.9 ± 0.6	405 ± 57	3.9 ± 0.2	12 ± 7
Locks (n = 22)	391 ± 121	3.7 ± 1.0	416 ± 122	3.6 ± 1.0	11 ± 9
Loose Forwards (n=25)	444 ± 103	4.0 ± 0.9	443 ± 118	3.9 ± 1.0	12 ± 8
Inside (n=17)	376 ± 98	4.2 ± 1.0	363 ± 83	4.2 ± 0.9	7 ± 7
Midfield (n=14)	431 ± 121	4.2 ± 1.2	421 ± 115	4.1 ± 0.1	7 ± 10
Outsides (n=22)	381 ± 80	4.0 ± 0.8	397 ± 77	4.0 ± 0.7	12 ± 10

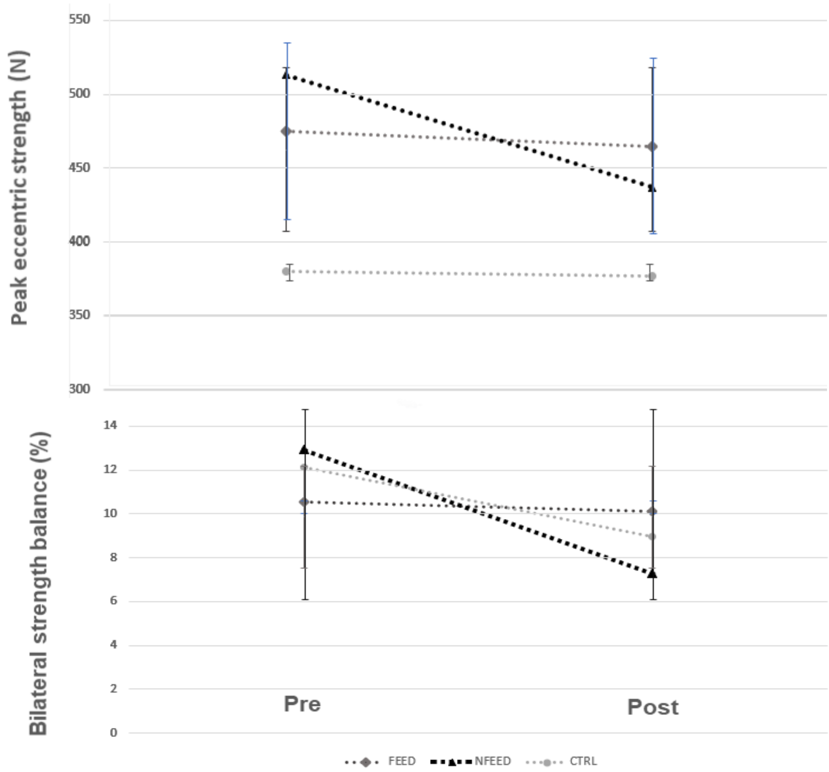
[a] Difference between left and right legs over the left leg strength value expressed as a percentage (%): abs[(left leg – right leg)/left leg]*100].

Appendix F6. Hamstring eccentric strength values in female semi-professional players (n = 42) by position Values are mean and standard deviation (SD).

	Left absolute (N)	Left relative ($N \cdot kg^{-1}$)	Right absolute (N)	Right relative ($N \cdot kg^{-1}$)	Strength balance (%)[a]
Props (n = 7)	308 ± 77	3.0 ± 0.8	288 ± 69	2.8 ± 0.7	8.0 ± 3.8
Hookers (n = 2)	311 ± 0	3.5 ± 0.0	320 ± 0	3.5 ± 0.0	3.0 ± 0.1
Locks (n = 3)	255 ± 107	3.0 ± 1.5	260 ± 64	3.0 ± 0.9	15.0 ± 10
Loose Forwards (n= 8)	277 ± 69	3.4 ± 0.9	262 ± 72	3.1 ± 0.9	10.0 ± 6.0
Inside (n=5)	226 ± 41	2.8 ± 0.5	232 ± 33	2.9 ± 0.5	6.0 ± 6.0
Midfield (n=5)	295 ± 65	3.8 ± 0.6	274 ± 58	3.5 ± 0.6	10.0 ± 6.5
Outsides (n=12)	258 ± 53	3.4 ± 0.0	270 ± 58	3.6 ± 0.7	12.0 ± 5.4

[a] Difference between left and right legs over the left leg strength value expressed as a percentage (%): abs[(left leg – right leg)/left leg]*100].

Appendix G: Appendices for Chapter 8:



Appendix G1. Peak eccentric strength (N, above) and bilateral strength balance (%, below) from Nordic testing. Values are mean ± standard deviation at Pre and Post timepoints for the feedback (FEED), non-feedback (NFEED), and control (CTRL) groups.

Appendix G. Co-authorship forms for Chapter 2 to 7.

Appendix G1. Co-authorship form for Chapter 2.

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.
Chapter 2
Neck strength in Rugby Union players: a systematic review of the literature.
Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K.(2021). Neck strength in Rugby Union players: a systematic review of the literature.
Physician and Sportsmedicine. 49 (4), 392-409

Nature of contribution by PhD candidate	Development of research question and protocol, literature search, study selection, risk of bias assessment, data extraction, summarising evidence, interpretation of results, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision of all stages and critical revision of the manuscript.
Dr. Martyn Beaven	Supervision at all stages and critical revision of the manuscript
Dr. Nicholas Gill	Supervision at all stages and critical revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	
Dr. Martyn Beaven	[signature]	
Dr. Nicholas Gill	[signature]	

Appendix G2. Co-authorship form for Chapter 3**.**

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CHAPTER 3
To Make or to Break in Isometric Neck Strength Testing?
Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K.(2021) (under review).
To Make or to Break in Isometric Neck Strength Testing?

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of the results, mansucript preparation, and journal submission
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Dr Kim Hébert-Losier	Supervision at all stages and critical revision of the manuscript
Dr Martyn Beaven	Supervision at all stages and critical revision of the manuscript
Dr. Nicholas Gill	Supervision at all stages and critical revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:
- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier		
Dr. Martyn Beaven		
Dr. Nicholas Gill		

Appendix G3. Co-authorship form for Chapter 4.

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CHAPTER 4
Reliability of repeated isometric neck strength in Rugby Union players using a load cell device.

4. Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. (under review)
. Reliability of repeated isometric neck strength in Rugby Union players using a load cell device.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of the results, manuscript preparation, and journal submission .
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision at all stages and critical revision of the manuscript
Dr. Martyn Beaven	Supervision at all stages and critical revision of the manuscript
Dr. Nicholas Gill	Supervision at all stages and critical revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Dr. Kim Hébert-Losier	[signature]	
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Dr. Nicholas Gill	[signature]	

Appendix G4. Co-authorship form for Chapter 5

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CHAPTER 5
Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review

2. Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K.(2021). Hamstrings injury incidence, risk factors, and prevention in Rugby Union players: A systematic review. Physician and Sportsmedicine. Advance online publication. doi:10.1080/00913847.2021.1886574

Nature of contribution by PhD candidate	Development of research question and protocol, literature search, study selection, risk of bias assessment, data extraction, summarising evidence, interpretation of results, manuscript preparation and journal submission.
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision at all stages and critical revision of the manuscript
Dr. Martyn Beaven	Supervision at all stages and critical revision of the manuscript
Dr. Nicholas Gill	Supervision at all stages and critical revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

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Dr. Nicholas Gill	[signature]	

Appendix G5. Co-authorship form for Chapter 6

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CHAPTER 6
Reliability of Repeated Nordic Hamstring Strength in Rugby Players Using A Load Cell Device.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of the results, and mansucript preparation.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision at all stages and critical revision of the manuscript
Dr. Martyn Beaven	Supervision at all stages and critical revision of the manuscript
Dr. Nicholas Gill	Supervision at all stages and critical revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

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Dr. Martyn Beaven		
Dr. Nicholas Gill		

Appendix G6. Co-authorship form for Chapter 7

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CHAPTER 7
Effect Of a 6-Week Feedback Vs Non-Feedback Training With Nordic Eccentric and Isometric Exercises on Hamstring Strength and Bilateral Strength Balance in Rugby Union Players- A Randomized Control Trial.

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of the results, and mansucript preparation.
Extent of contribution by PhD candidate (%)	85%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision at all stages and critical revision of the manuscript , data analysis, interpreatation of the results
Dr. Martyn Beaven	Supervision at all stages and critical revision of the manuscript
Dr. Nicholas Gill	Supervision at all stages and critical revision of the manuscript

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Dr. Nicholas Gill	[signature]	

Appendix G7. Co-authorship form for Chapter 8.

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Chapter 8
Anthropometric and Physical characteristics of isometric neck strength and Nordic eccentric hamstrings strength in female and male Rugby Union players

Nature of contribution by PhD candidate	Development of research question and protocol, data collection, data analysis, interpretation of the results, and mansucript preparation.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Dr. Kim Hébert-Losier	Supervision at all stages and critical revision of the manuscript
Dr. Martyn Beaven	Supervision at all stages and critical revision of the manuscript
Dr. Nicholas Gill	Supervision at all stages and critical revision of the manuscript

Certification by Co-Authors

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