DOCTOR OF PHILOSOPHY

Neck strength testing in professional rugby union
a novel approach

McBride, Lesley

Award date:
2024

Awarding institution:
Coventry University

Neck strength testing in professional rugby union – a novel approach

by

Lesley McBride

PhD

August 2023

Neck strength testing in professional rugby union – a novel approach

Lesley McBride

A thesis submitted in partial fulfilment of the University's requirements for the Degree of Doctor of Philosophy

August 2023

Ethics certificates

Certificate of Ethical Approval

Applicant:

Lesley McBride

Project Title:

To explore current practice in gym and field-based exercise provision for the strength, flexibility and proprioception of the cervical spine in rugby union players.

This is to certify that the above-named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Medium Risk

Date of approval:

15 August 2017

Project Reference Number:

P60723

Certificate of Ethical Approval

Applicant:

Lesley McBride

Project Title:

Reliability study of the ForceFrame dynamometer for measuring cervical spine isometric strength

This is to certify that the above-named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Medium Risk

Date of approval:

16 September 2019

Project Reference Number:

P93801

Certificate of Ethical Approval

Applicant:

Lesley McBride

Project Title:

Neck strength measurements of professional rugby players

This is to certify that the above-named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Medium Risk

Date of approval:

05 August 2019

Project Reference Number:

P93396

Abstract

Recent audits have indicated that some of the most common injuries affecting professional rugby union players occur to the head and neck and can have serious, long-term consequences. Over recent years, researchers have found promising evidence to suggest that the stronger a player's neck, the lower the incidence of head- and neck-related injury. To test this causal relationship, more robust data is required from a larger population of players. However, there remains no single, standardised method for neck strength measurement, meaning that there is little consensus among researchers and practitioners alike and, in turn, that it is impossible to establish broader trends across such a methodologically heterogeneous data set. The overall aim of this thesis was therefore to establish a novel, unified, practically oriented method for neck strength measurement that can serve to facilitate larger-scale, longer-term studies of the impact of neck strength on injury prevention in rugby union.

First, the thesis reviewed existing literature pertaining to injuries in rugby union and their possible relationship with neck strength and identified gaps in the research relating to current neck-screening practices in professional rugby contexts (Chapter 2). As there was little consensus regarding best practices in neck strength measurement across the academic and professional sporting communities, an initial exploratory survey was conducted highlighting the diversity and prevalence of neck strength measurement practices currently employed by professional rugby clubs (Chapter 3). The results showed that there was a range of techniques and technologies used but little or no consensus in methodology, despite a clearly voiced need among practitioners for a standardised, commercially viable system that would be easy to administer and interpret outside of the scientific research community.

To begin to develop the requisite standardised model, a review was conducted of the available commercial technologies applicable to neck strength measurement (Chapter 4). Despite it never having been used to measure neck strength prior to this study, the VALD ForceFrame fixed-frame dynamometer was identified as a viable piece of equipment given its suitability and existing credibility as a measuring apparatus adopted within professional clubs. Chapter 4 assessed the reliability of the ForceFrame for neck strength measurement through testing a novel empirical protocol on a group of university-age participants (n = 40). Attention was also paid to how best to account for the influence of wider bodily force distribution on residual neck strength (Chapter 5). This was achieved through trialling a variety of test positions to assess their overall impact on neck strength. The results demonstrated that optimal reliability was achieved through participants' adoption of the quadruped position, wherein the ForceFrame demonstrated excellent reliability in the measurement of neck flexion and extension strength and good reliability with regard to left and right side flexion. Moreover, the quadruped position was also found to increase the face validity and ecological validity of the test, thereby serving to meet the adoption requirements of practitioners.

These findings were further applied to real-world sporting situations by testing 131 professional rugby players within several club settings (Chapter 6). The results not only affirmed the wider validity of the laboratory findings but also began to establish a rigorous data corpus that accounts for inter-player position variability, adding a further dimension to the thesis's original contributions to existing knowledge.

Acknowledgements

Completing this research was a labour of love and the culmination of my clinical knowledge and ideas, which germinated all the way back in early 2004 when I was working with the England Men's U19 rugby squad. That was when I realised that knowledge of neck strength was an area that was little understood. Planning the studies and completing data collection were thoroughly enjoyable (despite the hiatus caused by a pandemic). Writing the thesis and the data analysis, however, required strong-minded determination, and support from numerous individuals. It is with profound gratitude that I extend my appreciation to those who have played pivotal roles in the realisation of this significant milestone in my academic journey.

I extend my deepest gratitude to my three supervisors, whose guidance and expertise have shaped the trajectory of my research. To Sam, who has adopted my work and taken it in new directions: your support and guidance have been insightful throughout this journey. Thank you for your investment in my work. Your dedication to my academic pursuit, even during times of challenge, has been much appreciated. To Rob: your unwavering enthusiasm for excellence and your thoughtful insights, not just in this thesis but over our many years of working together, have been an immense source of inspiration. Your ability to challenge my thinking and encourage creative solutions has broadened my intellectual horizons and enriched the depth of my research. I am genuinely fortunate to have had the privilege of working with you. To Siân: thank goodness we met! Your profound expertise, dedication and shrewd guidance have been instrumental in shaping my writing and refining my scholarly abilities. Your continuous encouragement, intellectual stimulation and patient discussions have consistently inspired me to push the boundaries of my ability. I am truly fortunate to have had the privilege of learning from you, and I am immensely grateful for your belief in my potential.

I would also like to express my gratitude to my colleagues and peers, especially Gabbi, Jayne, Pippa, Glykeria and Andrew, who have contributed to the intellectual atmosphere that permeates my entire life. The countless discussions, debates and writing days have fostered an environment where ideas flourish and knowledge is shared.

My heartfelt gratitude goes out to my long-suffering husband, Mark, whose untiring support and understanding have been the foundation of my journey. Your constant willingness to stand by me during the long hours of research and the inevitable challenges of academia have been nothing short of remarkable. Your constant presence provided the solace I needed to persevere, and I am truly fortunate to have such a devoted man by my side.

To Millie: because of your passion for playing rugby and for being such a strong woman, I look to you now for inspiration to enable me to take this research into the relatively little understood realm of women's sport.

To my incredibly supportive son, James, and his partner, Jacob: your assistance and willingness to pitch in whenever I needed you have lightened my load and brightened my days. From proofreading drafts to offering technical support, your contributions have been truly invaluable. Your belief in my capabilities and your willingness to invest your time and effort in my success have meant the world to me. You both know I couldn't have done this without you.

This dissertation stands as a testament not only to my efforts but to the collective support of many people. The joy of it is that the benefits are already reaching the people it was meant to help in the first place, namely the global community of people who play rugby.

Table of contents

Ethics certificates iii

Abstract vi

Acknowledgements vii

Table of contents ix

List of tables xii

List of figures xiv

Abbreviations xix

Chapter 1: Introduction 1

1.1 Summary of thesis aims 6

1.2 Chapter synopsis 7

Chapter 2: General Literature Review 10

2.1 Overview 10

2.2 Rugby and player anthropometrics 11

2.3 Anatomy and biomechanics of the cervical spine 26

2.4 Rugby-related head and neck injuries 34

2.5 Protective strategies pertaining to head and neck injuries in rugby 42

2.6 Neck strength measurement 47

2.7 Conclusion 58

2.8 Thesis aims and research questions 60

2.9 Thesis overview 61

Chapter 3: A survey of current neck strength screening practices in professional rugby 62

3.1 Introduction 62

3.2 Methods 74

3.3 Results 78

3.4 Discussion 99

3.5 Conclusion 115

Chapter 4: Intra- and inter-rater reliability of a novel isometric test of neck strength 117

4.1 Context 117

4.2 Methods 143

4.3 Results 155

4.4 Discussion 161
4.5 Conclusion 169

Chapter 5: Assessment of the test position in terms of force distribution through the extremities 170
5.1 Context 170
5.2 Methods 182
5.3 Results 192
5.4 Discussion 224
5.5 Conclusion 235

Chapter 6: Neck strength in professional rugby players 236
6.1 Context 236
6.2 Methods 246
6.3 Results 255
6.4 Discussion 275
6.5 Conclusion 287

Chapter 7: Discussion 289
7.1 Introduction 289
7.2 Overview of findings 289
7.3 Surveying the state of the field and establishing need for best practices (RQ1) 292
7.4 Establishment of reliability of a novel neck strength test (RQ2) 297
7.5 Field testing of neck strength to determine potential differences between player positions and levels (RQ3) 302
7.6 Methodological coherence 304

Chapter 8: Conclusion 307
8.1 Contributions to scholarly knowledge 307
8.2 Limitations of the thesis 308
8.3 Recommendations for future research and applications 311
8.4 Ongoing and future impacts on clinical practice 315
8.5 Implications for the future of rugby 316

References 318
Appendices 343
Appendix 1: Questionnaire 343

Appendix 2: Publication 344
Appendix 3: Infographic of protocol 345
Appendix 4: Participant information sheet and Informed consent (Chapters 4–5) 346
Appendix 5: Gate keeper letter (Chapter 6) 350
Appendix 6: Participant information sheet and consent form (Chapter 6) 351
Appendix 7: Declaration of co-authors 354

List of tables

Table 2.1 Description of rugby player positions: forwards (adapted from Stoop et al., 2018) 13

Table 2.2 Description of rugby player positions: backs (adapted from Stoop et al., 2018) 14

Table 2.3 Summary of previous studies measuring neck strength in professional rugby players (adapted from Chavarro-Nieto et al., 2021) 54

Table 4.1 Summary of perceived advantages and disadvantages of the ForceFrame 140

Table 4.2 Inclusion and exclusion criteria for participation in the reliability study 145

Table 4.3 Anthropometric data, height (cm), mass (kg), neck girth (cm) for all study participants (*n* = 40) (mean ± SD) 147

Table 4.4 Anthropometric data height (cm), mass (kg), neck girth (cm) for inter-rater reliability study participants (*n* = 21) (mean ± SD) 147

Table 4.5 Anthropometric data, height (cm), mass (kg), neck girth (cm) for intra-rater reliability study participants (*n* = 36) (mean ± SD) 147

Table 4.6 Mean ± SD values for female and male maximum isometric neck force all four directions – flexion, extension, left side flexion and right side flexion – in hands apart 156

Table 4.7 Mean ± SD values and CV % for male (*n* = 16) and female (*n* = 20) maximum isometric neck force and intra-rater reliability values for all four test directions 159

Table 4.8 Association between neck girth and maximum voluntary isometric contraction of the neck in all test directions 160

Table 5.1 Anthropometric data for force plate study participants (mean ± SD) 184

Table 5.2 Mean ± SD for change in participants' (*n* = 35) force plate values and reliability values for all four neck test directions 204

Table 5.3 Bias and 95% limits of agreement for all force plates (left knee, right knee, left hand and right hand) in all neck test directions 205

Table 6.1 Inclusion and exclusion criteria for participation in the rugby player study 248

Table 6.2 Testing location criteria for the rugby player study 249

Table 6.3 Anthropometric data for rugby player study participants (mean ± SD) 256

Table 6.4 Mean difference and SD, significance (*p* value) and 95% confidence interval of playing position by height 257

Table 6.5 Mean difference and SD, significance (*p* value), and 95% confidence interval of playing position by mass 258

Table 6.6 Mean difference and SD, significance (*p* value) and 95% confidence interval of playing position by neck girth 259

Table 6.7 Discriminant function analysis of percentage classification of playing position by anthropometric variables of mass, height and neck girth 261
Table 6.8 Mean ± SD of neck force (N) in four test directions (flexion, extension, left side flexion, right side flexion) for all rugby playing positions 262
Table 6.9 Mean ± SD of neck force (normalised to body weight) in four test directions (flexion, extension, left side flexion, right side flexion) for all rugby playing positions 263
Table 6.10 Mean difference and SD of playing position by neck force (N) for flexion and extension 264
Table 6.11 Mean difference and SD of playing position by neck force (N) for left side flexion and right side flexion 265
Table 6.12 Discriminant function analysis of percentage classification of playing position by total neck force in all test directions 271

List of figures

Figure 2.1 Standard rugby pitch, showing dimensions and pitch markings 12

Figure 2.2 Player positions on the pitch during a scrum 15

Figure 2.3 Diagram showing the sagittal, transverse and frontal (or vertical) planes and axes 27

Figure 2.4 Diagram showing the seven cervical vertebrae (C1–C7) 30

Figure 2.5 Diagram showing some cervical muscles 32

Figure 2.6 Tackle sequence taken from Hendricks et al., 2014 36

Figure 2.7 Scrum engagement phase evolution through time. (**a**) Configurational scheme of a scrum with player's numbers corresponding to their positions. (**b**) Snapshot of a scrum in 1973, Ireland vs New Zealand, Test match. Front rows are in standing positions and separated by 2–3 m. (**c**) Scrum in 2000, Ireland vs France, Six Nations 2000. The apparition of first rows crouching, space between front rows remains big. (**d**) A scrum in 2019, Japan vs South Africa, World Cup 2019 with pre bind Taken from Lallemand et al., 2020 40

Figure 2.8 Conceptual framework (deterministic model) of neck strength testing decision making 50

Figure 2.9 A: Make test for neck extension; B: Break test for neck flexion 53

Figure 3.1 Exercises for front-row forwards 67

Figure 3.2 Neck strength test 67

Figure 3.3 A schema illustrating the relationship between knowledge generation, application and impact in elite sport 69

Figure 3.4 Respondents by team level (Q1) 79

Figure 3.5 Respondents by profession (Q2) 80

Figure 3.6 Sources used to inform screening protocols (Q8) 81

Figure 3.7 When in the season screening is performed (Q10) 83

Figure 3.8 Tools used to measure range of movement (ROM) (Q13a) 85

Figure 3.9 Movement directions measured for range of movement (ROM) (Q13d) 85

Figure 3.10 Direction of neck strength measurements taken by respondents (Q14a) 86

Figure 3.11 How often exercise provision is revised (Q19) 89

Figure 3.12 Type of exercise performed by position or positional group (Q20) 90

Figure 3.13 Equipment used to deliver neck strength and endurance programmes (Q21–22) 91

Figure 3.14 Equipment used to deliver neck proprioception programmes (Q23) 91

Figure 3.15 Frequency of exercises performed in season: front-row forwards (*n* = 25) (Q24–25) 93

Figure 3.16 Frequency of exercise performed in season: back-five forwards (*n* = 25) (Q26–27) 93

Figure 3.17 Frequency of exercise performed in season: backs (*n* = 25) (Q28–31) 94

Figure 3.18 Importance rating for the provision of exercise (Q41) 97
Figure 4.1 GSA Analyser™ 123
Figure 4.2 Adapted version of Chatillon DG series SS-DG-0210 124
Figure 4.3 MicroFet™ 126
Figure 4.4 Use of a mounted handheld dynamometer and a handheld dynamometer to measure neck strength 128
Figure 4.5 Use of a fixed handheld dynamometer to measure neck strength 128
Figure 4.6 Multi-Cervical Unit (MCU) 129
Figure 4.7 Testing neck extension strength 131
Figure 4.8 Neck strength testing apparatus 132
Figure 4.9 Positioning for testing 132
Figure 4.10 Rugby-specific bespoke rig 134
Figure 4.11 Fixed tension-scale instrumentation, seated and standing 136
Figure 4.12 Fixed MicroFet™ handheld dynamometer seated test using unsupported test position 136
Figure 4.13 Power calculation with different effect sizes for comparison 144
Figure 4.14 Participant involvement in each of the four trials conducted 146
Figure 4.15 The ForceFrame (Groinbar™) 148
Figure 4.16 The testing position, quadruped, for all directions 149
Figure 4.17 Test position adopted for (A) flexion, (B) left side flexion and (C) extension for the assessment of isometric neck strength in the VALD ForceFrame 150
Figure 4.18 Example of the force–time curve for flexion (Flex), extension (Ext), left side flexion (LSF) and right side flexion (RSF) for a male participant 152
Figure 4.19 Example of box plots to demonstrate three repetitions for Trial HA1 (hands apart) extension for all participants (*n* = 40) 157
Figure 5.1 GSA Analyser™ systems isometric neck test system 175
Figure 5.2 Handheld dynamometer testing 176
Figure 5.3 Four Pasco force plates in position to measure ground reaction force (GRF) during the flexion (Flex) hands-apart (HA) test 186
Figure 5.4 Example of ForceFrame traces produced during hands-apart trial HA1 into extension (Ext) (Participant 34, right hand (RH)) 187
Figure 5.5 Example of force plate traces produced during hands-apart trial HA1 into extension (Ext) (Participant 34, all extremities) 188
Figure 5.6 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (*n* = 35) for flexion (Flex) 192

Figure 5.7 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (n = 35) for extension (Ext) 193

Figure 5.8 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (n = 35) for left side flexion (LSF) 193

Figure 5.9 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (n = 35) for right side flexion (RSF) 194

Figure 5.10 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) for flexion (Flex) 194

Figure 5.11 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) for extension (Ext) 195

Figure 5.12 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) for left side flexion (LSF) 195

Figure 5.13 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) for right side flexion (RSF) 196

Figure 5.14 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (n = 35) by direction of movement for the left knee (LK) 197

Figure 5.15 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (n = 35) by direction of movement for the right knee (RK) 198

Figure 5.16 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (n = 35) by direction of movement for the left hand (LH) 199

Figure 5.17 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (n = 35) by direction of movement for the right hand (RH) 199

Figure 5.18 Change in force distribution between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) by direction of movement for the left knee (LK) 200

Figure 5.19 Change in force distribution between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) by direction of movement for the right knee (RK) 201

Figure 5.20 Change in force distribution between hands-apart and hands-together trials (HA1 and HT) by direction of movement for the left hand + right hand (LH+RH) and single plate left hand and right hand together (LHRH) 202

Figure 5.21 Bland–Altman plot for left knee (LK) and right knee (RK) in flexion (Flex) hands apart (HA1) 206

Figure 5.22 Bland–Altman plot for left hand (LH) and right hand (RH) in flexion (Flex) hands apart (HA1) 207

Figure 5.23 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in flexion (Flex) hands apart (HA1) 208
Figure 5.24 Bland–Altman plot for both hands (LHRH) in flexion (Flex) hands together (HT) and left hand (LH) + right hand (RH) in flexion (Flex) hands apart (HA1) 209
Figure 5.25 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in flexion (Flex) hands apart (HA1) 210
Figure 5.26 Bland–Altman plot for left knee (LK) and right knee (RK) in extension (Ext) hands apart (HA1) 211
Figure 5.27 Bland–Altman plot for left hand (LH) and right hand (RH) in extension (Ext) hands apart (HA1) 212
Figure 5.28 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in extension (Ext) hands apart (HA1) 213
Figure 5.29 Bland–Altman plot for both hands (LHRH) in extension (Ext) hands together (HT) and left hand (LH) + right hand (RH) in extension (Ext) hands apart (HA1) 214
Figure 5.30 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in extension (Ext) hands apart (HA1) 215
Figure 5.31 Bland–Altman plot for left knee (LK) and right knee (RK) in left side flexion (LSF) hands apart (HA1) 216
Figure 5.32 Bland–Altman plot for left hand (LH) and right hand (RH) in left side flexion (LSF) hands apart (HA1) 217
Figure 5.33 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in left side flexion (LSF) hands apart (HA1) 218
Figure 5.34 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in left side flexion (LSF) hands apart (HA1) 219
Figure 5.35 Bland–Altman plot for both hands (LHRH) in left side flexion (LSF) hands together (HT) and left hand (LH) + right hand (RH) in left side flexion (LSF) hands apart (HA1) 219
Figure 5.36 Bland–Altman plot for left knee (LK) and right knee (RK) in right side flexion (RSF) hands apart (HA1) 220
Figure 5.37 Bland–Altman plot for left hand (LH) and right hand (RH) in right side flexion (RSF) hands apart (HA1) 221
Figure 5.38 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in right side flexion (RSF) hands apart (HA1) 222
Figure 5.39 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in right side flexion (RSF) hands apart (HA1) 223

Figure 5.40 Bland–Altman plot for both hands (LHRH) in right side flexion (RSF) hands together (HT) and left hand (LH) + right hand (RH) in right side flexion (RSF) hands apart (HA1) 224
Figure 6.1 Body mass (kg) against peak Flex force (N) plotted by playing position (each point represents one player) 266
Figure 6.2 Body mass (kg) against peak Ext force (N) plotted by playing position (each point represents one player) 267
Figure 6.3 Body mass against peak LSF force plotted by playing position (each point represents one player) 268
Figure 6.4 Body mass against peak RSF force plotted by playing position (each point represents one player) 269
Figure 6.5 Discriminant function analysis (DFA) of extension (Ext) force against body mass plotted by playing position (each point represents one player) 272
Figure 6.6 Discriminant function analysis (DFA) of extension (Ext) force against height plotted by playing position (each point represents one player) 273
Figure 6.7 Discriminant function analysis (DFA) of extension (Ext) force against DFA of body mass plotted by playing level and playing position (forwards/backs) (each point represents one player) 274
Figure 6.8 Discriminant fuction analysis (DFA) of extension (Ext) force against height plotted by playing level and playing position (forwards/backs) (each point represents one player) 275

Abbreviations

AROM = active range of movement

CI = confidence interval

CV = coefficient of variation

DFA = discriminant function analysis

DNF = deep neck flexors

Ext = extension

F = force

FFD = fixed-frame dynamometer

Flex = flexion

GPS = Global Positioning System

GRF = ground reaction force

HA = hands apart

HHD = handheld dynamometer

HIA = Head Injury Assessment

HT = hands together

ICC = intraclass correlation coefficient

IMTP = isometric mid-thigh pull

LH = left hand

LK = left knee

LoA = limit(s) of agreement

LSF = left side flexion

MCU = Multi-Cervical Unit

MDC = minimal detectable change

MHHD = mounted handheld dynamometer

MRI = magnetic resonance imaging

MVIC = maximal voluntary isometric contraction

NSNP = nonspecific neck pain

PRISP = Premiership Rugby Injury Surveillance Project

PROM = passive range of movement

Q = question

RFU = Rugby Football Union

RH = right hand

RK = right knee

RM = repetition maximum

RQ = research question

ROM = range of movement

RSF = right side flexion

RTP = return to play

RTT = return to training

S&C = strength and conditioning

SE_{m} = standard error of measurement

sEMG = surface electromyography

SF = side flexion

SOE = suboccipital extensors

SPSS = Statistical Package for the Social Sciences

TBI = traumatic brain injury

Chapter 1: Introduction

Over recent decades, there has been a marked increase in the physical demands of contemporary professional sports on athletes' bodies (Bevan et al., 2022; Hill et al., 2018; Stoop et al., 2018; Tucker et al., 2021). This increase has posed significant problems for high-impact contact sports such as rugby union (hereafter "rugby"), in which there is a relatively high potential for life-changing injuries as a direct result of match play (Badenhorst et al., 2017; Brown et al., 2013; MacQueen & Dexter, 2010; Sato, 2015). Major audits now regularly highlight how the incidence and severity of rugby injuries such as concussion are increasing year on year (PRISP, 2022). In response, national governing bodies, medical professionals, athletes, and the families of injured and deceased players alike continue to assert the pressing need for greater attention to the causes of concussion and related sporting injuries (World Rugby, 2017), and media reports at a national level frequently foreground these issues (Meagher, 2022; PA Media, 2023; Walsh, 2022). Moreover, there has been a proliferation of initiatives, such as England Rugby's ongoing HEADCASE resource (England Rugby, 2021) and Sport Scotland's "if in doubt, sit them out" guidelines (Sport Scotland, 2018), that aim to tackle these issues and promote cautious and informed practices. Player welfare is therefore high on the agenda across the sporting world, and vital campaigning to raise awareness is ongoing.

Despite widespread outcries across a range of public forums, the academic literature exploring rugby-related head and neck injury remains in relative infancy. There is consensus among academics about certain statistical trends in injury incidence (West et al., 2021), and there is arguably now a foundation in epidemiological literature linking specific actions in a game of rugby with specific injuries (Brooks et al., 2005; Castinel et al., 2010; Chéradame et al., 2021; Prien et al., 2018; Viviers et al., 2018; West et al., 2021). However, the extent to which these causal links can be made remains limited, as does the impact of implementing actions based on consequent insights. At the heart of this issue is that, since its professionalisation in 1995 and the formation of an overarching governing body (World Rugby, n.d.), changes to sporting practices and player anthropometrics have been continual, and this has posed significant problems for establishing a cohesive framework for injury prevention that accounts sufficiently for such ongoing shifts.

In the simplest terms, the rugby world is in dire need of a robust system of recommendations and policies that go as far as possible towards preventing serious injuries such as concussions. However, before such recommendations can be made, it is crucial to have a cogent understanding of the on-field reality of the game – that is, the changing nature of the physical demands on players during a match, and in turn the requirements of their anthropometrics to cope with these evolving pressures. In this way, the first step towards effective injury prevention measures is the creation of a reliable, practically oriented framework for measuring anthropometrics so that any recommendations are always rooted in the very latest and most creditable evidence (Finch, 2006).

By developing initiatives that encourage continual measurement of players' anthropometrics to gain a clear understanding of how the game of rugby is developing over time, the goal is to establish the empirical foundations for a system of injury prevention recommendations with the greatest possible efficacy. There is a need for practitioners to adopt a proactive approach to maintaining an accurate and relevant evidence base that can inform the production of policy. Since 1995, the attention paid to injury in rugby has been reactive in outlook, taking the form of a piecemeal approach driven by specific, and therefore limited, epidemiological evidence. To achieve the wider goal of best practice in injury prevention measures, it is instead important to promote an approach that foregrounds ongoing, holistic strategies for collecting anthropometric data about players, one that is systematically disseminated and implemented. In this burgeoning field of study, there is therefore a pressing need to gather more high-quality, longitudinal data, as well as a parallel need to convey research findings and facilitate – via influence and buy-in – their translation into practice.

There is general agreement that a more systematic, and ultimately sustainable, approach to anthropometric monitoring would enable greater understanding of the relationship between bodily strength and susceptibility to injury. Without the development of this homogenous dataset it will be difficult to audit these proposed links. To focus specifically on the issue of rugby-related concussion, there is evidence of a growing interest in its aetiology within the academic literature. Over recent years, researchers have found promising evidence to suggest that the stronger a player's neck, the lower the incidence of head- and neck-related injury (Collins et al., 2014; Farley, Barry, Sylvester, Medici, & Wilson, 2022). Empirical research has indicated that there may be a predictive value to exploring neck strength in relation to this type of injury (Baker et al., 2019; Benson et al., 2013; Chéradame et al., 2021; Collins et al., 2014; Cosgrave et al., 2018; Cross et al., 2019; Daly et al., 2021; Farley et al., 2022; Farley et al., 2022; Fraas et al., 2014; Gardner et al., 2014; Kirkwood et al., 2015; Schneider et al., 2014), despite the growing support there is a lack of empirical evidence underpinning this claim. This body of work, while nascent, substantially heterogenous in methodological approach, participant characteristics and comprising multiple different sports, is promising and indicates that academic research should work more to prioritise awareness of athletes' vulnerabilities and their potential impacts.

The foundational research into the relationship between neck strength and concussion suggests that investigative priority should be given to how certain demands of the game impact more directly on areas of the body in which structural anatomy is characterised by an intrinsic vulnerability. Therefore, access to accurate, valid and reliable methods of quantifying the strength of bodily regions that are particularly vulnerable to sport-specific injury, such as the neck, should be a priority of research in this area. The human cervical spine is an extremely mobile region of the body that performs multiple roles. These include conveying afferent and efferent proprioceptive messages between brain and body; controlling balance and coordination; supporting the mass of the head (approximately 5 kg) at all times when not lying down; and, given its freedom of movement in all three cardinal planes, enabling the exteroceptors of the eyes and ears to move easily in all directions (Armstrong et al., 2008). High-velocity collision sports such as rugby are renowned for causing the neck and head to sustain a range of injuries from minor discomfort and stiffness to facet joint and disc injuries, traumatic brain injury and concussion, catastrophic major trauma such as spinal cord injury, and even death (Fuller et al., 2007; Hogan et al., 2010).

In order to reach the stage where the causal relationship between neck strength and injury incidence may confidently be identified, there must first be consensus regarding how best to measure an athlete's neck. The current state of neck measurement practice is highly variable, and the field is characterised by a diversity of methods (Peek, 2022). First, a range of technologies have been adopted as part of measurement protocols, including handheld dynamometers (administered by the tester, hence introducing the variable of tester strength) (Ashall et al., 2021; Farley et al., 2022; Geary et al., 2013; Gillies et al., 2022; Krause et al., 2019; Tudini et al., 2019; Vannebo et al., 2018), fixed-frame dynamometers (not dependent on tester strength), and other bespoke equipment comprising load cells, head harnesses, cables, weight stacks, and more (Fuller et al., 2022; Hall et al., 2017; McDaniel et al., 2021; Salmon et al., 2018). Second, within these studies, there are assorted procedures followed during testing, including requiring participants to adopt a range of starting positions such as seated (feet on floor, on "wobble cushions", etc.) (Barrett et al., 2015; Geary et al., 2013; Hamilton & Gatherer, 2014; Krause et al., 2019; McDaniel et al., 2021), standing (supported and non-supported) (McDaniel et al., 2021), lying (prone, supine, and side-lying) (Hall et al., 2017; Tudini et al., 2019), and adapted forward-lean stance (Hall et al., 2017; Salmon et al., 2015; Tudini et al., 2019). Third, the type of test being administered has varied across studies, focusing on either a "make test" (meaning the participant pushes until reaching their maximal voluntary isometric contraction) or a "break test" (meaning the tester exerts a force through the participant's neck until the neck can no longer withstand the force, again introducing an additional variable in the form of the tester's own strength). That said, all testing to date has been isometric in type (Chavarro-Nieto et al., 2023b). Fourth, there is some variation in the length of time over which a muscle test is conducted, as well as in the rest period between trials. Finally, the groups of people on whom tests are conducted vary dramatically from untrained participants to professional athletes.

Moreover, an overarching issue characterising the corpus of neck measurement research pertains to uniformity across research and practice: that there are many novel approaches but little wider adoption of methods by other researchers, and – perhaps most importantly – a scarcity of crosstalk between the research community and practitioners working with active athletes.

1.1 Summary of thesis aims

Clearly, then, while more robust data is required to ascertain any causal link between neck strength and injury incidence, there remains no single, standardised method for neck strength measurement, meaning that there is little consensus among researchers and practitioners alike. As a result, it is impossible to establish broader trends across such a methodologically heterogeneous data set, as there is no empirical foundation to claims of validity across measurement practices. The primary undertaking of this thesis is therefore to establish a novel, unified, practically oriented method for neck strength measurement that can serve to facilitate larger-scale, longer-term studies of the impact of neck strength on injury prevention in rugby union. At stake in the institution of a single, easily replicable method of neck strength measurement is another core ambition of the research “beyond” the thesis: to engage active practitioners working outside of the laboratory with professional athletes in adopting such protocols in their everyday practices, in turn facilitating knowledge exchange between the research and practitioner communities and initiating a wider project of longitudinal data collection that produces a rigorous, normative database of up-to-date anthropometric information. At present, there is little effective bilateral communication between the academic research and professional rugby communities, possibly due to the secrecy that surrounds practice at the professional level, between clubs and Nations, in order to preserve what may be seen as marginal advantages between competing clubs. Open discussions do not yet occur around training ground habits between clubs, and this hampers the dissemination of best practices between experts within the clinical community. The novel approach proposed by this thesis is therefore intended to counteract this current shortfall.

1.2 Chapter synopsis

To start to address the problems endemic to the field at present, the thesis begins by reviewing existing literature pertaining to injuries in rugby union and their possible relationship with neck strength, identifying gaps in the research relating to current neck-screening practices in professional rugby contexts (Chapter 2). It is found that there is little consensus regarding best practices in neck strength measurement across the academic community, and there is almost no published information regarding professional sporting communities' approaches to neck screening. In light of the literature review, a series of research questions are posed that serve to guide the remainder of the thesis's empirical investigations (Section 2.8).

To fill the identified gaps in the available literature, an initial exploratory survey is conducted charting the diversity and prevalence of neck strength measurement practices currently employed by professional rugby clubs (Chapter 3). The survey is designed using qualitative data collection methods to offer participants the opportunity to describe current practices and concerns in as much detail as they wish. The data is then analysed according to salient themes emerging from the corpus. The aim of this survey is to gain an empirically grounded perspective on current practices across a range of professional clubs, with emphasis on the specific techniques and apparatuses that are used. The questionnaire also serves to ascertain the main issues relating to neck health that face practitioners working in contemporary professional rugby.

Given that many practitioners who participated in the survey voiced a need for a standardised, well-tested approach to neck screening, the thesis then moves on to a review of currently available commercial technologies applicable to neck strength measurement (Chapter 4). Despite it never having been used to measure neck strength prior to this study, the ForceFrame fixed-frame dynamometer is identified as a viable brand of equipment given its suitability and existing credibility as a measuring apparatus adopted within professional circles due to the fact that all home nations and many clubs have access to at least one rig. Chapter 4 assesses the reliability of the ForceFrame for neck strength measurement through trialling a novel experimental protocol on a group of university-age participants (n = 40) involving testing two different starting positions – namely, the quadruped position with hands together and hands apart. Attention is also paid to how best to account for the influence of wider bodily force distribution on residual neck strength (Chapter 5). This is achieved through trialling the same test positions using force plates to measure force distribution via the hands and knees of participants during neck strength screening. The focus of these chapters is the overall reliability and validity (both face and ecological) of the ForceFrame as a tool for neck strength testing.

To translate the evaluation of the protocol beyond the laboratory, the findings are further applied to real-world sporting situations by testing 131 professional rugby players within several club settings (Chapter 6). This component of the study not only seeks to affirm the wider validity of the findings but also to begin to establish a rigorous data corpus that accounts for inter-player position variability, adding a further dimension to the thesis's original contributions to existing knowledge.

Finally, a discussion of the thesis's findings is offered, which serves to foreground the crosstalk between the results of each phase of the study (Chapter 7). The major ambition of the discussion is to promote the clinical applicability of the research findings by addressing both their commonalities with existing research and the extent to which they provide original contributions to the literature beyond those currently available. This section is followed by a summary of the results as they pertain specifically to the central research questions guiding the thesis, as well as an account of the study's limitations, its identification of future directions for research, and its wider applicability in real-world contexts (Chapter 8). Attention is also paid in this concluding chapter to presently ongoing initiatives involving the novel method with major professional clubs across the world.

Taken as a whole, the thesis represents a rigorous, multi-phase empirical and experimental study that addresses major issues facing practitioners by first canvassing opinions and experiences regarding current practices (Chapter 3), then testing the reliability and validity of a viable measurement device and its related protocols as they pertain to neck strength (Chapters 4 and 5), before finally positing a novel, best-practice approach that incorporates a widely available, easy-to-use technology and tests its efficacy in the field (Chapter 6).

Chapter 2: General Literature Review

2.1 Overview

The following literature review moves from broad to specific research themes. It is divided into six sections, beginning with a technical overview of the sport of rugby football union (hereafter "rugby") and the standard anthropometrics of the various player positions in the professional men's sport, including an outline of the epidemiology of injuries common to rugby players, especially those affecting the head and neck, and the relevant links established in the available literature between incidence and severity (Section 2.2).

Having established that the head and neck are common sites of injury for professional rugby players, an account of cervical spine anatomy is provided (Section 2.3), followed by a review of the detailed anatomical and epidemiological concerns of the neck and injuries associated with playing the sport of rugby and the techniques that may be used to prevent them, such as cervical spine strengthening (Section 2.5.2). There is also some consideration of recent and forthcoming law amendments resulting from increased scientific knowledge of rugby-related injuries (Section 2.5). Attention then turns to how neck movement and strength can be measured during cervical spine screening in rugby players, highlighting significant gaps in the scant literature on strength assessment (Section 2.6). Together, these sections illustrate the contemporary nature of this globally played contact sport, particularly in terms of what is known (and not known) about the risks posed to its players.

The review concludes with a summary of major insights, juxtaposing understanding of the particular vulnerability of the neck with inconsistencies and/or lack of understanding about how to prevent injury, particularly in terms of strength measurement (Section 2.7). Attention is paid here to the strengths and weaknesses of the existing literature on neck strengthening in professional rugby, with emphasis on the pressing need to apply well-established principles of resilience training already common to rugby specifically to the cervical spine. Finally, the thesis's central aims and hypotheses are outlined (Section 2.8).

2.2 Rugby and player anthropometrics

2.2.1 The laws of rugby and characteristics of playing positions

Today, rugby is played worldwide. According to a recent annual report published by World Rugby, the sport's global governing body, there were approximately 7.6 million active rugby participants in 2021, 4.2 million of whom were players registered to active teams with regular league fixtures (World Rugby, 2021b, p. 45), making rugby union "the most widely played team collision sport globally" (Viviers et al., 2018, p. 223). It is an inclusive sport played by men and women of all ages, as well as boys and girls over the age of six (World Rugby, n.d.). Rugby is also played by a range of disabled athletes: for example, wheelchair rugby was established as a full medal sport at the 2000 Sydney Paralympic Games (World Rugby, 2021b), and the deaf rugby community continues to burgeon (World Rugby, 2021a). In addition, variations on the traditional 15-a-side game exist including sevens, tag and touch forms of the sport.

A traditional rugby match lasts for 80 minutes and is played between two teams on a grass or artificial turf pitch measuring 100 m by 70 m (Figure 2.1). H-shaped goals, consisting of two vertical goalposts and a horizontal crossbar, are located on goal lines (or try lines) towards each end of the pitch. Behind the goal lines are the touch-in-goal areas, which end at the dead-ball lines. Between the two goal lines are regular delineations of the pitch: at 5 m and 22 m from the goal line, and 10 m from the half-way line.

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 2.1 Standard rugby pitch, showing dimensions and pitch markings
(from Pitchbooking, n.d.)

A traditional rugby team consists of 15 on-field players and a maximum of eight substitutes. At the most basic level, players can be divided into eight “forwards” and seven "backs". The various playing positions require very different anthropometric and performance characteristics, including strength, power, speed, agility and endurance, and have well-defined roles on the pitch (Roberts et al., 2008). Outlining such distinctions between player positions affords greater understanding of the specific strength and conditioning (S&C) needs of individual players, which can in turn improve the efficacy of performance-enhancing and injury-mitigating measures (Table 2.1 and Table 2.2).

Table 2.1 Description of rugby player positions: forwards (adapted from Stoop et al., 2018)

Number	Position	Key responsibilities	Desirable anthropometric qualities
1	Loosehead prop	**Front row**. Supports the hooker in the scrum. Lifts jumpers during line-outs. Contests for the ball during breakdowns.	Typically the player with the highest body mass on the team (alongside the tighthead prop). Strong neck for scrummaging.
2	Hooker	**Front row**. Contests for the ball during scrums and breakdowns. Throws the ball in during line-outs.	High body mass. Mobile shoulders. Strong neck for scrummaging.
3	Tighthead prop	**Front row**. Supports the hooker in the scrum. Lifts jumpers during line-outs. Contests for the ball during breakdowns.	Typically the player with the highest body mass on the team (alongside the loosehead prop). Strong neck for scrummaging.
4 and 5	Second-row forwards (Lock forwards)	**Second row**. Lifted during line-outs to contest for the ball and to pass it to the scrum-half. Bind (or "lock") the scrum together.	Tall. Strong legs. Strong lumbar spine for scrummaging.
6	Blind-side flanker	**Back row**. Add force during scrums. Compete for the ball in open play and during breakdowns.	Mobile and forceful. Usually the fastest forwards. High capacity for endurance. Strong legs. Strong lumbar spine for scrummaging.
7	Open-side flanker		
8	Number eight	**Back row**. Links forwards and backs. Controls the ball at the base of the scrum. Makes the highest number of tackles.	Mobile and forceful. Able to run with the ball in hand. Strong legs. Strong lumbar spine for scrummaging.

Table 2.2 Description of rugby player positions: backs (adapted from Stoop et al., 2018)

Number	Position	Responsibility	Desirable anthropometric qualities
9	Scrum-half	**Half-back**. Links forwards and backs. Typically picks up the ball from the base of the scrum and passes to the fly-half.	Typically the player with the lowest body mass on the team. Short. Agile and capable of sprinting. High capacity for endurance. Capable of long, accurate passes.
10	Fly-half	**Half-back**. Lead decision maker. Typically the player who receives the ball from the scrum-half after breakdowns. Typically the goal kicker.	Capable of long, accurate passes and kicks.
12	Inside-centre	**Centres**. Direct team attacks. Break defences by tackling regularly.	Strong. Fast. Agile.
13	Outside-centre		
11 and 14	Wings (Wingers)	**Back three**. Run with the ball along the left and right wings of the pitch. Tackle the least frequently.	Agile. Typically the fastest players on the team.
15	Full-back	**Back three**. Equivalent of a goalkeeper. Final line of defence during opposition attacks. Catches opponents' long kicks and kicks return balls.	Excellent hand–eye coordination. Fast. Strong tackler.

Rugby is a highly physical sport. During a match, players attempt to gain and maintain possession of the ball, which is oval in shape. Matchplay involves periods of running, passing and kicking the ball, interspersed with bouts of high-intensity activity comprising collisions ("tackles") followed by breakdowns (where the ball is relatively stationary), which occur with the ball either on the ground ("rucks") or in a player's hands while standing ("mauls"). The collisions require robust technical ability, as they represent events that pose some of the highest risks in a rugby match (see Section 2.4.2.1). There are also points in a match at which gameplay pauses, resulting in one of two set-piece situations, or "restarts", namely "line-outs” and “scrums”. If the ball goes out of the field of play, the method of restart is a line-out, which requires players (predominantly the second-row forwards) to be lifted by others (predominantly the props) to catch the ball. In line-outs, the ball is nearly always thrown in by the hooker. In addition, play stops (the ball goes “dead”) when certain laws are broken – for example, if there is a forward pass, or if a free kick is awarded due to an infringement on the pitch. In some instances, when the ball goes dead, a scrum is formed in which eight players (the forwards) bind together to push themselves over the ball to gain possession (Figure 2.2; see also Section 2.4.2.2). In a professional match of rugby, an average of 22 (19–25) scrums, 116 (63–170) rucks and 156 (121–191) tackles occur over the course of a match (Paul et al., 2022), all of which have a significant physical impact on players’ bodies, requiring them to be resilient to fatigue for a full 80 minutes in order to maintain performance and satisfy injury risk mitigation at the end of a match (Gabbett, 2016)

Figure 2.2 Player positions on the pitch during a scrum
(from UNC Women's Rugby, n.d.)

2.2.2 Changes in the anthropometric characteristics of rugby players in the professional era

In light of the substantial physical demands of rugby as a high-intensity collision sport, careful attention to the specific needs of players' bodies is vital in the pursuit of both welfare-focused practices and sporting excellence (Stoop et al., 2018). In addition to providing useful background information about the laws of rugby, what the previous overview section demonstrates is that, as with many team sports, individual players often have very different roles depending on the positions they are assigned. What is particularly noteworthy in the case of rugby is that individual player positions are characterised by markedly different anthropometric profiles. For example, while props are expected to have greater body mass in order that they can effectively support ("prop up") the scrum, scrum-halfs should be lighter so that feeding the ball into the scrum and receiving it back can be achieved in a fast and agile manner (Stoop et al., 2018). It is important to note that these anthropometric differences go far beyond a simple division of the team into forwards and backs; there are considerable distinctions between individual player positions. While complex for team sports that require players with multiple body types, it is nonetheless crucial to foreground the specific physiological needs and profiles of individual players to fully understand both athletic performance enhancement and sport-related injury prevention.

Close, sustained attention is increasingly being paid to the specific physical needs of individual rugby player positions, marked by efforts to record and maintain detailed anthropometric data (Stoop et al., 2018). Ideally, this requires that regular, standardised measurements of large samples of players are taken to evince significant trends in the physical characteristics of professional players. It is important to note that the anthropometric qualities of rugby players have never been constant, instead varying over time in line with changes in the developmental trajectory of the sport (Stoop et al., 2018).

Existing data suggests that the advent of professionalism in 1995 represented a major turning point in the history of player anthropometrics (Bevan et al., 2022; Hill et al., 2018; Tucker et al., 2021). Professionalism has since afforded players access to full-time, elite-level training facilities and coaches, as well as nutritional, medical and strength-conditioning services – all of which serve to maximise performance (Quarrie et al., 2017, p. 422; Sharples et al., 2021). This, alongside greater integration of sport and exercise science research into practice, has led to athletes becoming leaner and faster than had previously been recorded, as well as producing players who can collide harder than ever before (Seminati et al., 2017).

A range of recent longitudinal studies provide evidence for the changes in rugby players' physical attributes since professionalisation. One important example (Hill et al., 2018) involved harnessing data corpora relating to pre- and post-professional eras of men's rugby, which highlighted three consecutive eras of body mass changes: first, that male rugby players' body mass had remained constant from 1955 until 1985; second, that there was a 5% increase between 1985 and 1995; and finally, that there was a dramatic rise of around 20% occurring between 1995 and 2015. Overall, the data reveals a shift in average body mass from 84.8 kg in 1955 to 105.4 kg in 2015, albeit one that is significantly skewed towards the period's latter stages (Hill et al., 2018). These increased impacts from collisions may mean that there are greater demands on the neck for protection and performance.

Similarly, through analysis of the anthropometrics of male players at Rugby World Cups between 1991 and 2019, Tucker et al. (2021) demonstrated that the greatest increase in body mass occurred from 1991 until 2011. After 2011, there was a notable plateau in overall body mass change, as well as a partial decrease by the time of the 2019 World Cup for the first time since professionalisation, which the writers suggested may be interpreted as a necessary adjustment resulting from post-1995 shifts in rugby's laws – namely, that the ball must now be in play 44–50% of the time during a match of international professional club rugby (compared with 35% in 1995), requiring greater endurance capacity (Tucker et al., 2021). These significant, observable patterns of change underline the need for ongoing investment in meeting physical need based on robust and contemporary data.

The body mass statistics reported by Hill et al. (2018) and Tucker et al. (2021) are supported by the findings of a study conducted by Bevan et al. (2022), who similarly demonstrated that the anthropometric qualities of rugby players have changed measurably as a result of professionalisation. They conducted an analysis of observation data for a population of 291 elite-level European rugby players across some 910 seasons, which showed that body mass, fat-free mass and maximum speed all increased significantly over a monitoring period spanning 1999 and 2019. More specifically, they showed that the "front five" (front- and second-row players) exhibited a >25% increase in momentum (with the momentum of a body understood as the product of its mass and its velocity [$p = mv$]) over the test period, which the writers deemed to be a product of both increased speed and increased body mass, not simply due to increased body mass alone (Bevan et al., 2022). A limitation of the study by Bevan et al., (2022) was that over the ten year lifespan of the study different methods were used to quantify speed. This could affect the outcome reported of momentum, meaning that results should be interpreted with caution The priority task of meeting physical need via evidence-based means should therefore account for variables specific to player position in addition to ever-changing physical characteristics, and technological advances in the measurements of these properties.

2.2.3 Introduction to rugby-related injuries since professionalisation

It is apparent from the studies surveyed above that rugby's turn to professionalism in 1995 marked a watershed moment in the anthropometrics of players, which has implications for the injury potential of participation, not least with regard to the head and neck. Most notably, professionalisation has resulted in a major increase in body mass among professional rugby players, as well as an increase in speed and, therefore, an increase in momentum. The impact force generated during collisions can be calculated from the impulse–momentum relationship $\Sigma\bar{F}\ \Delta t = m(v_f - v_i)$, where $\Sigma\bar{F}$ is the "average net force acting on an object" (that is, on the player), Δt is the "interval of time during which this force acts" (that is, the period of time of contact between two players), m is the "mass of the object being accelerated" (that is, the body mass of the player), v_f is the "final velocity of the object at the end of the time interval" and v_i is the "initial velocity of the object at the beginning of the time interval" (McGinnis, 2005, pp. 92–93). The most important consequence of these findings is that such changes in body mass, together with the improved physical conditioning that results in greater player velocity, have caused the impact forces generated – and therefore the energy absorbed – during collisions to become greater than ever before (Bevan et al., 2022). In this way, since professionalisation, the likelihood of rugby players sustaining injuries as a direct result of matchplay has substantially increased, to almost double from 1993/4 to 1997/8 (Garraway et al., 2000). There is therefore a clear need to prioritise players' safety and welfare at the highest levels of the sport's governance, which in part involves giving due attention to how players' changing anthropometrics affect trends in the incidence of rugby-related injury.

Since the advent of rugby's professionalism, several initiatives have been established with the aim of monitoring the incidence and severity of rugby-related injuries sustained by professional athletes. Prior to professionalism, auditing of such data seems to have been based on a club by club basis with little to no "bigger picture" of injuries sustained from the game being reported. As a result, injury audits have substantially improved over recent years, including the ways in which injuries are measured and catalogued in recording systems. For example, the Professional Rugby Injury Surveillance Project (PRISP) – which is described as representing the longest-running and most authoritative injury surveillance project in professional rugby (PRISP, 2019, p. iii) – has published reports on injury incidence in the professional sport in England since 2002, monitoring English Premiership clubs and the England senior national team and providing targeted analyses of specific areas of injury risk (PRISP, 2022). An injury is classified by PRISP as an event that precludes the player from engaging in training or matches for more than 24 hours (PRISP, 2022, p. xxi). According to PRISP, rugby union has one of the highest occurrences of reported match and training injuries among contact sports. For example, in Premiership matches during the 2020–21 season, there were 79 injuries per 1,000 hours of matchplay on average (PRISP, 2022, p. i). Moreover, according to PRISP, this rate of injury has been broadly consistent since their records began in 2002, with the injury rate between 2002 and 2020 averaging around 87 injuries per 1,000 hours (PRISP, 2022, p. ii). Such trends make the case for prioritising injury prevention in rugby irrefutable. However, while the publicly accessible PRISP reports are derived from data supplied by the sports science staff at each Premiership club and using standardised coding for every injury, this data itself remains inaccessible for scrutiny. Thus the report's credibility depends upon the rigour applied during its compilation.

For consistency, this thesis will adopt the definitions for injury reporting used by the England Premiership and national squads (PRISP, 2022, p. xxi). First, the *severity* of an injury is defined as the number of days lost to play as a direct result of said injury. Second, the *incidence* of an injury describes how commonly it occurs per 1,000 playing (or training) hours.

Finally, the *burden* of an injury refers to the number of days absence per 1,000 hours it causes. According to the Orchard coding system (Orchard et al., 2010), which is used by England Premiership clubs' medical staff to classify injuries and illnesses sustained by the players in their care, there are 11 core musculoskeletal classification subsections for the cervical spine, and nine for the head and face. These classifications are used to inform the PRISP injury audit, which is completed annually (see, e.g., PRISP, 2022).

Research suggests that rugby carries an overall injury risk that is higher than that of many other team sports. For example, a range of studies conducted over the past 30 years suggest that the risk of injury in rugby is around three times greater than for semi-contact sports, such as soccer, hockey and certain martial arts, as well as for other team contact sports (Palmer-Green et al., 2015). Considering the reports by PRISP and other sources together, the data shows that injuries are common occurrences in the context of rugby and that, in general, the incidence of reported injuries has been consistent over time.

Importantly, rugby-related injuries are not necessarily specific to any one region of the body. For example, reporting on the most common and highest burden injuries (per 1,000 hours of matchplay) since the 2016–17 England Premiership season, PRISP lists the following: concussions; hamstring muscle injuries; medial collateral ligament (knee) sprains; acromioclavicular joint (shoulder) sprains; quadriceps muscle (thigh) injuries, including thigh haematoma; ankle syndesmosis joint sprains; calf muscle injuries; and radial (forearm) fractures (PRISP, 2022, p. xvii). Similarly, in their epidemiological study of scrum-related injuries, Trewartha et al. (2015) list calf muscle injuries, concussions, lumbar spine injuries, shoulder injuries, and neck injuries among the most common. Clearly, then, the high frequency of intense collisions during matchplay means that injuries may commonly occur to any regions of players' bodies, including the head and neck.

2.2.4 Epidemiology of head and neck injuries in rugby

While rugby-related injuries are not endemic to one region of the body, existing data shows that there is a notably high incidence of head and neck injuries sustained by professional rugby players. For example, data collected between 2002 and 2019 suggests that there was a reported incidence of 11.3 head and neck injuries per 1,000 hours of match play (West et al., 2021). Such injuries are relatively common because the sport involves considerable loading and impact to the head and neck from both the scrum and tackling (Cazzola et al., 2016; Seminati et al., 2017). In addition, there is data to suggest that elite-level male rugby players suffer damaging changes to the cervical spine earlier in life than the average person (Castinel et al., 2010). For example, in a study involving MRI scans of the cervical spines of front-row rugby players aged between 21 and 37 years, 66% were shown to have osteosclerosis of the vertebral bodies which were absent in age-matched controls (Berge et al., 1999). This is indicative of vertebral degeneration and can be attributed to repeated trauma, which in rugby would likely occur during rucking, mauling, tackling and scrummaging. Taken together, all of this data is of particular note given how susceptible the neck and head can be to serious, life-changing injuries.

There have been multiple epidemiological studies conducted regarding rugby-related head and neck injuries (Bleakley et al., 2011; Brooks et al., 2005; Castinel et al., 2010; Fraas et al., 2014; Haseler et al., 2010; Mellalieu et al., 2008; Prien et al., 2018; Roberts et al., 2013; Viviers et al., 2018). Despite this, there is an overall lack of detail in the available evidence, meaning that little progress has been made regarding the production of targeted injury prevention strategies. To give an example, according to PRISP, of the ten rugby players who retired during the 2017–18 season, four cited head and neck injury as the major reason

(PRISP, 2019, p. 25). However, no further information is given in the PRISP audit; the specific nature of the injuries that led to such career-ending decisions is omitted and, in turn, it is difficult to determine the injury prevention strategies that might best avoid such occurrences.

One reason for the lack of specificity regarding the nature of head and neck injuries in reports such as PRISP may be that since professionalisation, academic research has predominantly focused on catastrophic head and neck injuries, which are defined as life-changing or "permanently disabling" injuries (Bohu et al., 2009, p. 320). Catastrophic injuries were more common in rugby's professional infancy before the widespread introduction of injury prevention strategies (Bohu et al., 2009; Olivier & Du Toit, 2008). However, as a result of this research focus, relatively little attention has been paid to less severe head and neck injuries.

That said, in the PRISP injury report for 2020–21 (PRISP, 2022), concussion was a major focus. There were 131 match concussions reported, which accounted for 28% of all match injuries. This was an increase of 7% on the 2017–20 reporting period (though the impact of the COVID disruption should be considered here, not least in terms of the reduction in training activities during this period and the potential effect on injury incidence). There were 17 training concussions sustained in 2020–21, which represents 11% of all concussions and is lower than the 2017–20 period's mean of 16%. This finding shows that not only is there a high number of concussions reported in professional rugby, but also that interest in the area of less severe head and neck injury in rugby is burgeoning.

Common examples of head and neck injuries associated with rugby include: concussion; traumatic brain injury (TBI); spinal cord injuries; non-specific neck pain (NSNP); and a range of arthrogenic (joint), myogenic (muscle) and neurogenic (nerve) injuries, including "stingers" (or "burners"), which are traction or compression injuries to the brachial plexus at the junction between the neck and shoulder. In their review of match injury incidence, PRISP (2022, p. xvii) noted that concussions were consistently the most common reported injuries: the 2020–21 season marked the tenth consecutive year in which concussion came top of the list, with the incidence of concussion per 1,000 match hours averaging at 20.2 between 2016 and 2021. Moreover, Trewartha et al. (2015, p. 42m6) have also stated that head and neck injuries comprised 15% of all reported scrum-related injuries. It can therefore be argued that head and neck injuries represent significant challenges to the safety and welfare of rugby players, meaning it is vital that sufficient attention is paid to their epidemiology and prevention.

There is further evidence to suggest that associations can be drawn between certain head and neck injuries and particular player positions. For example, Brooks and Kemp (2011) used data from the 2010 PRISP report to analyse the match injury profile of 899 professional players in the English Premiership over the previous four seasons. This revealed differences in the injury profiles of players in different playing positions. The rigorous prospective cohort design study employed led to the conclusion that absence due to match injuries was not significantly higher in any of the specific playing positions, but that the pattern of injuries sustained was significantly variable depending on the different playing positions. According to Brooks and Kemp's report, the hooker, loosehead prop, open-side flanker and centre positions suffered the most neck injuries (defined as causing >150 days absence per 1,000 player hours). Neck injuries only made up 15% of the scrum injury burden, but an overwhelming 91% of the scrum injuries were sustained by the front-row forwards. However, these findings have yet to be linked to the anthropometric properties of these player positions, and when the injuries were sustained from a collapsed scrum the uncontrolled nature of that mechanism of injury has yet to be linked with neck strength. The PRISP injury audit can only report injuries which have been reported to the medical staff and included in the club's injury data output, meaning that if concussion is under reported by the players (Fraas et al., 2014) then the data may not represent the true extent of the problem. In the first study of it's kind to explore concussion rates in professional rugby players related to playing position, Fraas et al., (2014), found that in self-reported concussions from four clubs in Ireland over a single season there was no statistically significant difference in concussion rates between backs and forwards. Despite there being four clubs (n = 172 players), numbers of individual playing positions were small, and 70 players self-reported a concussion over the season being investigated, although only 47 of those were reported to medical staff, demonstrating how concussion is almost certainly underrepresented in official audits of the game. Scrum halves suffered the most concussions (n = 10; 12%) followed by flankers (n = 11; 11%), with full backs reporting the fewest concussions (n = 3; 3%), which concurs with the findings from a systematic review (Gardner et al., (2014) which concluded that backs suffered more concussions (4.85/1000 player match hours) than forwards (4.02 concussions per 1000 player match hours).

Further exploration of these links (such as those between neck injury and neck strength, injury prevention and performance) is clearly required to advance the important work of enabling player profiles to become more objective and measurable, thereby enhancing their applicability in practice.

To ascertain the specific epidemiology of rugby-related injuries to the head and neck, Section 2.3 reviews current understanding of the anatomy and biomechanics of this region of the body, paying specific attention to the cervical spine.

2.3 Anatomy and biomechanics of the cervical spine

2.3.1 Form and function of the cervical spine

While existing understanding of cervical spine anatomy is substantial, it is important to note that, as with any scientific discipline, anatomical knowledge is constantly evolving. Relevant anatomical literature pertaining to the cervical spine, both established and emerging, is therefore reviewed in order to establish sound scientific foundations for the thesis as a whole.

The human cervical spine, known more commonly as the neck, has multiple functional capabilities, including load-bearing, motion and neural protection (Oxland, 2015). It is an extremely mobile region of the body that enables a person to move their head along the three cardinal planes: sagittal, transverse and coronal (Figure 2.3). First, the *sagittal* (or longitudinal) plane divides the body into left and right sections. The cervical spine moves along this plane in two directions: forwards, in flexion (Flex) of the cervical joints, and backwards, in extension (Ext). Second, the *transverse* (or horizontal) plane divides the upper and lower portions of the body. The neck moves along this plane through the rotation of the joints. Third, and finally, the *frontal* (or coronal) plane divides the front (anterior) and back (posterior) parts of the body. Neck movement along this plane is referred to as side flexion (SF) of the cervical joints, both left (LSF) and right (RSF).

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 2.3 Diagram showing the sagittal, transverse and frontal (or vertical) planes and axes (from Paredes et al., 2017)

The cervical spine also serves to protect the nerves and blood vessels travelling towards and away from the brain. Moreover, it plays a large role in the balance system of the body via afferent (towards the brain) and efferent (away from the brain) proprioceptive messages, understood as the feedback and feedforward signals that travel between the brain and the rest of the body (Armstrong et al., 2008; Tortora & Derrickson, 2017). To protect itself while enabling dynamic movement to occur, the cervical spine requires both stability and mobility to support the substantial mass of the head while also affording it the three degrees of freedom it requires to respond to stimuli efficiently. The spine-stabilising system hypothesis (Panjabi, 1992) suggests that the body attempts to stabilise the spine to maintain balance through the cooperation of passive, active and neural bodily systems – in this case, the osteoligamentous (bone and ligament), muscular and neural components of the neck.

Anatomical accounts therefore show that the cervical spine is vital to the optimal functioning of a range of key bodily processes, including balance, proprioception and overall stability. To understand these functions in greater depth, and following Panjabi (1992), the remainder of this section provides a more in-depth exploration of the neck's passive and active systems: the osteoligamentous and muscular components of the cervical spine.

2.3.2 Osteoligamentous anatomy of the cervical spine

The strength of the cervical spine, conferred through complex anatomical mechanisms, underpins its protective capacity, which is a central concern in a contact sport like rugby. In order to effectively measure this strength, the cervical spine's underlying active and passive systems must be fully understood.

The cervical spine is comprised of seven articulating (moving) vertebrae (Figure 2.4). The cervical spine has two atypical vertebrae, C1 (atlas) and C2 (axis), which serve to provide support for the skull and to afford movement in the sagittal (C0/C1) and horizontal (C1/C2) planes. The mid and lower parts of the cervical spine (C3–C7) comprise five typical vertebrae, which afford movement in all three cardinal planes. Over the past 25 years, research interest in the internal morphology and morphometry of the vertebrae has increased, especially regarding issues of anatomical variability among diverse population groups (Oxland, 2015). This interest includes the clear dimorphism identified between male and female vertebrae, whereby female vertebral body height C2-C7 matures earlier in females than males, which means that care must be taken when researching the neck in male and female populations, and in adolescents who have yet to reach full osseous maturity (Miller et al., 2021), including caution regarding attempts to homogenise resultant data.

The typical range of motion for the human cervical spine consists of up to 90° of rotation (transverse, looking left and right), around 80° to 90° of Flex (sagittal, forwards), 70° of Ext (sagittal, backwards) and up to 45° of LSF and RSF (frontal, left and right) (Swartz et al., 2005, p. 156; Windle, 1980). However, there is no universally standardised method through which to measure the range of motion in the cervical spine, which means that measurements can suffer from poor reliability due to the instrumentation used for quantification. As a result, there is little consensus within the literature regarding exact, typical ranges of motion (Oxland, 2015; Sukari et al., 2021).

The cervical vertebrae are linked to one another via a system of ligaments. Spinal ligaments are uniaxial structures that serve to connect adjacent vertebrae. While traditionally perceived as entirely passive structures, more recent research has discovered the presence of mechanoreceptors in the cervical ligaments, suggesting the provision of sensory information which can alter muscular activity (Mattucci et al., 2012; Yahia & Newman, 1993). Ligaments have also been shown to have viscoelastic properties, which have important implications for the loading rate of the ligaments: the faster the ligaments are loaded, the stiffer they become. This finding may also have relevance to epidemiology and injury biomechanics, namely that if a ligament is not stretched to failure (beyond its limits to the point of tearing), it can also perform roles in energy absorption, energy transfer and passive stabilisation – all properties which are key when considering tissue characteristics in relation to collisions in sport (Mattucci et al., 2012).

Figure 2.4 Diagram showing the seven cervical vertebrae (C1–C7)
(from CrossFit, 2019b)

In addition to ligaments, further components of the passive stabilisation system in the cervical spine include the intervertebral discs. The role of the discs is to act as joints between vertebrae, affording movement between the bones, the absorption of “shock” (energy) and the distribution of load throughout the vertebral column (Lundon & Bolton, 2001). Moreover, the discs contain nociceptors, which means that they can be transmitters of pain signals if stressed or injured. However, substantive physiological and functional understanding of the discs is not yet robust, and further research is needed, especially in relation to injury susceptibility of previously stressed discs (Oxland, 2015).

Considering the vertebrae, ligaments and intervertebral discs together, it is apparent that the cervical spine's passive stability – understood as its ability to support the head osteoligamentously without the activation of muscles – is relatively low due to the amount of movement available to the region. However, stability is enhanced through collaboration with the active muscular system, and the role that these tissues play in energy absorption during body collisions cannot be ignored.

2.3.3 Muscular anatomy of the cervical spine

The muscles of the cervical spine play a multitude of roles, including working in conjunction with the passive system to afford overall stability, as well as acting as accessory muscles for breathing (Hrysomallis, 2016). There are two distinct groups of muscles in the cervical spine: the deep layers of stabilising muscles (e.g. scaleni, multifidus, longus capitis, longus colli, rectus capitis anterior, rectus capitis lateralis, sternohyoid, omohyoid) and more superficial muscles (e.g. sternocleidomastoid, upper trapezius, levator scapulae, splenius capitis and semispinalis capitis) (Figure 2.5). Within all of these muscles, there are three types of muscle fibre: *Type I* (slow-twitch, slow oxidative) fibres, which support postural control and are always, at least partially, active (tonic), but which are also relatively fatigue-resistant; and *Type IIa* (fast oxidative fibres) and *IIb* (fast glycolytic) fibres, both of which initiate higher (phasic) forces more rapidly to produce faster movements at the joints, but which fatigue more quickly than Type I fibres (Adams, 2016, p. 109). Generally, the deeper, more stabilising muscles contain a greater proportion of Type I fibres than Type II, and the more superficial muscles are composed predominantly of Type II fibres (Boyd-Clark et al., 2001). Together, these muscles elicit cervical movements. In addition, they work in tandem with the vestibular system to control posture and maintain bodily balance (Artz et al., 2015; Gosselin & Fagan, 2014).

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 2.5 Diagram showing some cervical muscles
(from CrossFit, 2019a)

An important anatomical component of the musculature of the cervical spine that performs a central role in the region's functionality is the muscle spindle. Spindles contribute to joint position sense by sending proprioceptive signals from the spine to the brain to trigger a response to stimuli affecting balance and positionality. Highly structured, high-concentration, dense arrangements of muscle spindles have been identified in intervertebral muscles (Armstrong et al., 2008). These are found in the deeper muscles of the mid-cervical region (C3–C6), as well as at the transitional junction of the cervico-thoracic spine (C7–T1). More specifically, higher densities of these muscle spindles appear in the medial column of upper cervical spine's deeper layer when compared with that of the lower cervical spine (Amonoo-Kuofi, 1983). Moreover, Armstrong et al. (2008) have proposed that these muscles may confer an additional role of protection to key neural structures such as the spinal cord as a result of their ability to react quickly to threatening stimuli.

In addition, a further protective feature of the cervical muscles is their size. The cross-sectional area of a muscle's tissue is directly proportional to the amount of force said muscle can produce. In terms of assessing the strength of a person's neck, it may therefore be pertinent to measure its girth as a means of estimating how much force it can exert or withstand (Li et al., 2014). By measuring muscle volume using three-dimensional reconstruction via magnetic resonance imagining (MRI) scans, Li et al. (2014) demonstrated that the trapezius muscle occupied 34% of the total cervical muscle volume, followed by transverso spinalis (12%) and sternocleidomastoid (11%). Volume is important as an estimate of muscle power: power output is the product of force and velocity ($P = Fv$), and force is proportional to a muscle's cross-sectional area, with velocity proportional to muscle length. It is therefore likely that these muscles contribute importantly to both the strength and overall protective capacity of the neck as a result of their size and major contribution to the circumference of the neck. Understanding the properties of the cervical muscles, their attachments, and actions upon the movements of flexion, extension and side flexion can guide decisions on strengthening exercises.

In summary, the cervical spine is composed of osteoligamentous and muscular components, which together perform a range of functions: enabling movement across the cardinal planes, providing the strength required to support the head, affording intrinsic passive stability and protecting its local neural systems. Given the multiple, complex roles performed by the various components of the cervical spine, it is important that their optimal health is maintained.

2.4 Rugby-related head and neck injuries

Following the review of relevant anatomical information pertaining to the cervical spine, the aim of this section is to account for the epidemiology of rugby-related cervical spine injuries. First, the difficulty of defining the specific terms used to describe these injuries is addressed, with particular attention paid to the degree to which consensus of use has – or has not – been reached (Section 2.2.3). The aetiology of rugby-related cervical spine injuries is then addressed with direct reference to specific actions in a rugby match during which head and neck injuries commonly occur – namely, the tackle and the scrum (Section 2.4.2). Focus is directed to the normative anthropometrics of individual player positions and their typical incidences of injury during training and matches.

2.4.1 Lack of epidemiological consensus regarding rugby-related cervical spine injury

Earlier in this chapter (Section 2.2.3), terms used to characterise injury (severity, incidence, burden) were defined based on consensus. It is important that epidemiological terms are also clearly and universally defined to enable meaningful comparison of injury statistics (West et al., 2019). However, such consensus has yet to be globally achieved, not least in relation to head and neck injury. In their systematic literature review, Swain et al. (2011, p. 384) classify rugby-related neck injuries in terms of the symptoms that they cause, including “neck pain, reduced neck mobility, neck deformity, neurological symptoms (sensory and motor loss), altered mental state or secondary injury (e.g. faciomaxillary, eye or limb trauma)". The review, which retrieved 33 appropriate articles, concluded that due to the lack of consistency in terminology across studies when defining sports injury, there was extensive variability in findings. More recently, this conclusion was echoed by West et al. (2019), who demonstrated that a lack of methodological homogeneity in athlete health and well-being monitoring within professional rugby in England has proven detrimental to the knowledge base. These disparities in the literature analysing the epidemiology of cervical spine injury in rugby highlight the complexity of calculating the exact prevalence of such injuries within the sport.

2.4.2 Rugby and the cervical spine: specific demands of the sport

To attempt to circumvent the issues identified that relate to a lack of consensus in terminological use, the remainder of this section pays direct attention to the aetiology of injury as opposed to solely considering injury types and symptoms in isolation. In this way, focus is drawn away from a generalised perspective on sport-wide issues (for example, those pertaining to changes in the rugby's laws) and directed instead to the causes of injuries, with focus on the anthropometrics of specific players and player positions. The aim of this approach is to begin to interrogate understanding of practical strategies for players that are rooted in evidence relating to specific actions and events that commonly cause cervical spinal injury.

2.4.2.1 The tackle

The tackle is the single most common action during a rugby match in which contact between players occurs. It involves 2 players, and a typical tackle sequence can be described as a contact event between the ball carrier and the tackler (figure 2.6). The high prevalence of tackles has been reported in several studies. For example, Fuller et al. (2007) examined two seasons of rugby across 13 English Premiership clubs and reported an average of 221 tackles per match. Alongside such high occurrence rates, the tackle is the single greatest cause of contact injuries in the sport. For example, 48% of all injuries sustained during match play were attributed to tackles in the 2020–21 English Premiership season (PRISP, 2022, p. x; Seminati et al., 2017). Video analysis of footage showing the occurrence of head injuries in rugby also demonstrates that the tackle causes the most neck injuries, followed by the scrum (Trewartha et al., 2015; Tucker et al., 2017).

Figure 2.6 Tackle sequence taken from Hendricks et al., 2014

Studies show that certain players are more adversely affected by tackles. For example, according to a 2022 PRISP report analysing statistics from the previous season, there was a notable difference in injury statistics between players who were tackled (ball carriers), who suffered an average injury incidence of 16.9 per 1,000 hours, and those executing tackles (tacklers), who suffered a notably higher average injury incidence of 21.0 per 1,000 hours

(PRISP, 2022). According to the same report, the most common injury to occur to both the ball carrier and tackler during tackles was concussion, which accounted for 48% of all injuries to tacklers and 32% to ball carriers. This data shows that tacklers are more likely to sustain head and neck injuries than ball carriers.

Similarly, Tucker et al. (2017) conducted a video analysis of matchplay injuries requiring head injury assessments (HIAs) in professional rugby over a three-year period. HIAs were introduced to elite male adult rugby in 2015 and elite female adult rugby in 2019 (Cooke et al., 2022), evolving over time to ensure that any player who sustains an impact force to the head or neck is removed from the match and substituted while an assessment is undertaken to identify whether a concussion has been sustained. Such players are only allowed back onto the field of play if cleared of injury. Tucker et al. (2017) found that 76% of HIA-provoking events occurred during the tackle. Again, the researchers found that tacklers suffered the majority of injuries when compared to ball carriers (1.4 HIAs versus 0.54 HIAs per 1,000 tackles, respectively). When considering variations among player positions more broadly, Tucker et al. (2017) also found that backs rather than forwards were subject to significantly greater numbers of HIAs, with an incidence ratio rate of 1.54. This suggests that while forwards make more tackles (Paul et al., 2022) and may therefore be more at risk of concussive events, backs are more likely to receive a head injury diagnosis.

Venturing into more specific detail by player position and turning attention to players' technique on the field, Sobue et al. (2018) found that outside backs took more pre-contact steps than any other position and were less regularly injured, as they had more time to get into the correct position. Even for those backs who were in the wrong position but took more steps, fewer tackles resulted in injury. This study also found that the front five forwards spent a significantly shorter amount of time with the ball when entering tackles and suffered more injuries overall, possibly as a result of having less time to adopt the correct position and, in turn, suffering direct impact to their heads and/or necks. According to Sobue et al. (2018), the most common injuries sustained in this situation were concussion, neck injuries, stingers and nasal fractures. This data suggests that good technique – in this case, being more likely to take pre-contact steps – can result in fewer injuries.

Moreover, existing data shows that greater attention to head position technique in tackles can also result in lower incidence of injury. By assessing the consequences of a tackler's head position in their analysis of injury statistics, Sobue et al. (2018) determined that incorrect head positioning by the tackler, where the head is in front of the ball carrier, accounted for 69.4 head and neck injuries per 1,000 tackles versus 2.7 per 1,000 when in the correct tackling position. These statistics clearly show that correct head positioning can have a positive effect on injury prevention in tackles.

That said, correct head positioning is one of many facets of good technique required to ensure optimal protection from injury during tackles. By examining the biomechanical loads experienced by tacklers using a tackle simulator, Seminati et al. (2017) also discovered that tackles in the frontal (as opposed to diagonal) direction made with the dominant shoulder recorded the highest impact forces of 5.3 ± 1.0 kN. Moreover, they found that head accelerations were lowest in diagonal tackles made with the dominant side of the body. This work suggests that if coaches can promote good tackle technique (whereby tackles occur with the head on the correct side) and encourage more symmetry in tackle impact forces from dominant and non-dominant shoulders, injury rates could be reduced.

Finally, in the multibody modelling simulation study conducted by Tierney and Tucker (2022), it was shown that the greatest head kinematics and neck dynamics were sustained by a lighter player tackling a heavier player (for example, a back tackling a forward) when both players were travelling at high speed, as dictated by the impulse–momentum relationship (see Section 2.2.3 above).

Taken together, these findings add depth to existing understanding of the tackle-related causes of head injuries in rugby and their statistical susceptibility among certain playing positions. In turn, they also help to show that robust accounts of the aetiology of tackle-related head and neck injuries must involve attention to a range of factors, including, but not limited to, player position (both on-field roles and typical anthropometrics) and technical skill.

2.4.2.2 The scrum

Another injury-intensive action during a match of rugby is the scrum. When opposing sides come together in a scrum, the eight forwards on each team bind together, and the two opposing front-row forwards engage (figure 2.7). The average mass of an elite pack (the forwards) is 900 kg (Hill et al., 2018), which places significant load demands through the bodies – and especially the necks – of involved players. According to one epidemiological study that focused on data from the early years of rugby's professionalism (Brooks et al., 2005), prior to 2000, the most severe head and neck injuries recorded were caused by the scrum. Moreover, data suggests that by 2002, approximately 40% of all catastrophic injuries in rugby – usually, though not exclusively, spinal cord injuries – resulted from involvement in a scrum (Quarrie et al., 2002). In addition, Fuller et al. (2007, p. 14) also reported that data from 13 English Premiership rugby union clubs playing between 2002 and 2004 showed that forwards involved in scrummaging suffered 3.88 spinal injuries per 1,000 match hours. These early findings strongly indicate that the scrum is a potentially injury-intensive action in a rugby match, especially with regard to spinal injury. Sustained reporting of high injury occurrence indicates an entrenched relationship between injury risk to the head and neck and the actions associated with a game of rugby.

Foul or unintendedly poor technique, such as a rotated body position, head on head collisions during the engagement or lack of strong binding between the front rows and locks, appears to be potential causes of injury in scrums (Cazzola et al., 2016). Over more recent years, awareness of the potential for scrum-related injury has led to greater emphasis on the analysis of professionals' technical skill to ensure that best practices are established and adopted, including some changes to rugby's laws (figure 2.7).

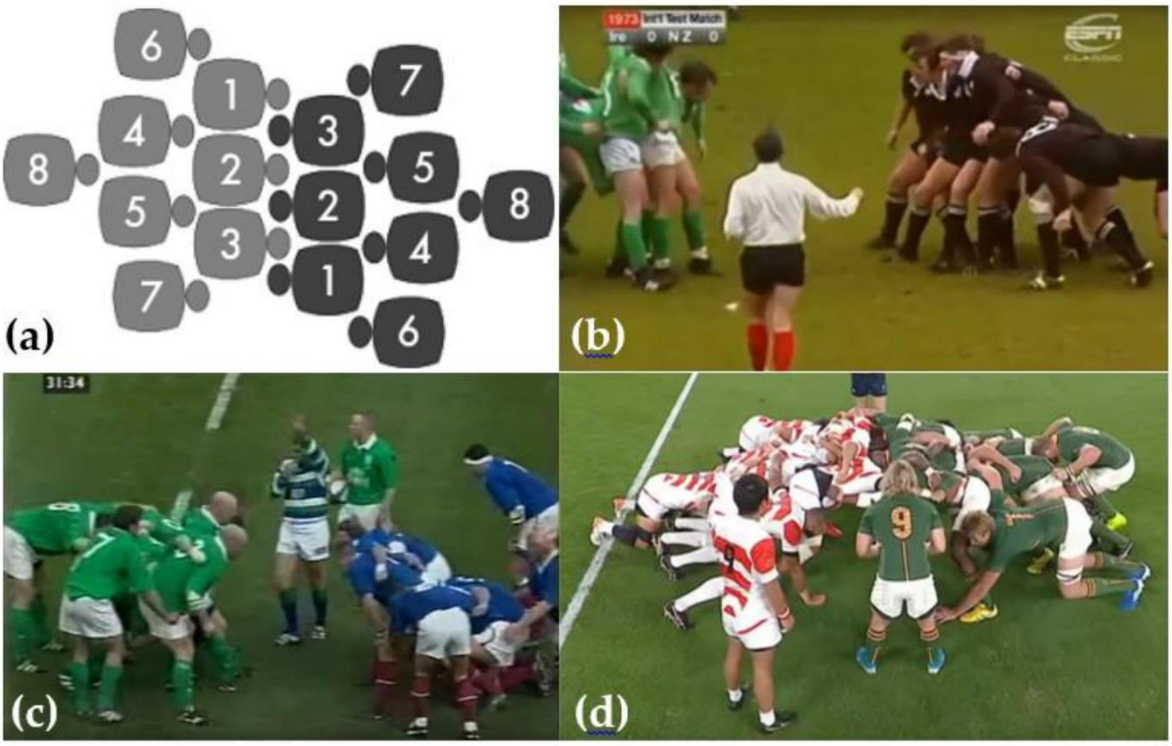


Figure 2.7 Scrum engagement phase evolution through time. (**a**) Configurational scheme of a scrum with player's numbers corresponding to their positions. (**b**) Snapshot of a scrum in 1973, Ireland vs New Zealand, Test match. Front rows are in standing positions and separated by 2–3 m. (**c**) Scrum in 2000, Ireland vs France, Six Nations 2000. The apparition of first rows crouching, space between front rows remains big. (**d**) A scrum in 2019, Japan vs South Africa, World Cup 2019 with pre bind Taken from Lallemand et al., 2020

Unlike tackles, scrums are highly controlled actions, which makes them ideal set-piece (or pre-organised move) situations for technical monitoring and injury prevention. Available evidence suggests that injury risk is much higher for those involved in a collapsed scrum than for those in successful scrums (8.6 vs 4.1 injuries per 1,000 scrums, respectively) (Taylor et al., 2014). In light of this potential for injury, sanctions are often applied when dangerous play is deemed to have occurred, such as in cases involving the intentional collapse of a scrum or the forcing of an opponent out of a scrum. At the time of writing, World Rugby is trialling a new law necessitating that the hooker must put one foot, known as the brake-foot, on the ground in front of his shoulders as a means of protecting the neck (World Rugby, 2022). This works to stabilise the scrum and avoid axial loading (pressure applied through the head directly onto the neck) caused by the top of the head touching the neck or shoulder of an opponent during a scrum. Failure to comply with this law results in a free kick for the opposing team. Such sanctions are designed to prevent the kinds of activities that can cause the most injuries to the spine (Taylor et al., 2014). Their existence attests to a longstanding concern for safety specific to a single set-piece and particular player positions.

In addition, research into the inner workings of scrums has led to the establishment of certain engagement laws that are intended to regulate and control these potentially dangerous actions. One such law, known as "crouch–bind–set", involves the careful moderation of the body positioning of the scrum's front row, ensuring that there is an incremental addition of force – and, in turn, overall engagement load – into the scrum. This law requires the two front rows to stand not more than an arm's length apart, further limiting the force of the engagement (Cazzola et al., 2015). As a result, since the introduction of rugby law changes that control scrum actions to a greater degree, spinal injuries have been significantly reduced (Cazzola et al., 2015; Hendricks et al., 2014; Reboursiere et al., 2018; Trewartha et al., 2015). Despite such a reduction in the potential for catastrophic spinal injury, heightened risk to certain player positions remains intrinsic to the sport.

As part of efforts to combat serious spinal injuries affecting rugby players, researchers have devised novel methods to measure how actions specific to a rugby match impact the body. In order to understand the demands of the scrum, which exerts a very high biomechanical stress on the forwards, several studies have recreated the action's forces and measured them, both in live scrums and simulated events involving the front-row forwards engaging against a scrum machine (Cazzola et al., 2015; Cazzola et al., 2016; Holsgrove et al., 2015). These amendments have proven effective: the tackle has now overtaken the scrum as the most injurious event on the pitch (West et al., 2021). Such action reflects an enduring commitment within the sport to player safety by continuing to advance knowledge of preventative measures.

2.5 Protective strategies pertaining to head and neck injuries in rugby

It is clear from the available evidence that rugby is a highly physically demanding sport that has the capacity to do serious damage to players, despite ongoing development of precautionary measures such as the changes to rugby's laws instituted over recent years in attempts to mitigate injuries during match play (Finch, 2006; O'Brien & Finch, 2014; van Mechelen et al., 1992; Vriend et al., 2017). Importantly, these laws can only go so far towards the prevention of injury. While laws can encourage best practices in technique and help to reduce the incidence of the most injurious situations, they have no express relationship to the potential benefits of directed training and specific anatomical strengthening. At stake here is what might be termed anatomical and biomechanical (as opposed to situational) prevention measures. Possible benefits of strengthening measures include positive impacts on injury prevention of training focused on specific regions of the body that require particular protection. A combination of anatomical and situational measures could potentially significantly reduce the risk of rugby-related head and neck injuries, but the evidence base needed to support such a hypothesis does not currently exist.

2.5.1 Rationale for protective measures

Over recent years, attention to the incidence and severity of head and neck injuries in rugby has progressively burgeoned (Brooks & Kemp, 2011; Murray et al., 2014; Swain et al., 2011; Viviers et al., 2018; West et al., 2021), which has in turn increased emphasis on the need to understand all aspects of the physicality of injury. For example, the growing prevalence of concussion and sub-concussive events (impacts that do not cause symptoms), as reported in the most recent PRISP report (PRISP, 2022), highlights a pressing need to explore preventative strategies for head- and neck-related injuries. Alongside making changes to the laws of the sport, such preventative work can be achieved through focus on players' physiques (Brooks & Kemp, 2011), thereby reducing injury incidence not solely through law changes but also through evidence-based physical conditioning. Increasing individuals' involvement in the proposed changes through active interventions, such as tackle skill training and strength-enhancing exercises, is seen as more desirable for effecting change than passive interventions such as tackle law changes (Verhagen et al., 2010).

2.5.2 The significance of neck strength in rugby

One such method of active intervention pertains to neck strength conditioning. Evidence has long existed to suggest that the large range of movement that can be achieved by the neck may mitigate the incidence of spinal cord-related catastrophic injuries when the body is subjected to an external force (Nightingale et al., 1996). However, this range of motion also engenders a distinct lack of rigidity in the neck, which means that axial loading can cause the spine to buckle, thereby potentially leading to injury (Swartz et al., 2005). In a rugby context, such loading frequently occurs during actions such as tackles and scrums (see Section 2.4.2), especially where regard for technical accuracy is lacking (Taylor et al., 2014). During a rugby match, then, neck structures are more likely to be exposed to greater loads than they are able to withstand, either in a single event or as cumulative loading over a particular timespan.

Injury-minimising measures, such as ensuring good body-positioning technique, require a rugby player to be strong and have good balance (Naish et al., 2013). Focusing on these efforts can, in turn, lead to performance enhancement. There is evidence to suggest that a stronger neck can result in reduced injury incidence as a result of the protections afforded by greater neck muscle mass. Substantial evidence shows that the higher the muscle mass, the greater the output force of said muscle (Krzysztofik et al., 2019; Schoenfeld, 2010). This means that by strengthening a particular muscle or muscle group, protection is conferred to the region of the body around which the muscle is located. When applying this logic to the neck, research has focused on the impact of neck strength on the incidence of TBI. Increased neck strength can reduce both the severity and incidence of potential TBI (Collins et al., 2014). This protective mechanism has become a major driving force behind recent research into concussion incidence in rugby (Cross et al., 2019; Eckner et al., 2014; Farley et al., 2022; Schmidt et al., 2014). For example, Farley et al. (2022) demonstrated that greater neck extension strength is correlated with lower incidence of concussion: the rate of concussion was reduced by 13% when a player's neck extension strength was increased by 10%. However, a normative measure of neck strength was not defined in relation to position played, meaning that there is no point of comparison for novel measurements. Despite these efforts, then, understanding of the prevalence and aetiology of rugby-related head and neck injuries and their relationship to neck strength remains in its infancy.

One method used to explore the impact of the neck muscles on neck movement and inertial head kinematics during tackles and scrums involves whole-body musculoskeletal modelling (Cazzola et al., 2016; Cazzola et al., 2017; Tierney & Tucker, 2022). Some such studies have demonstrated that front-row forwards exhibit increased stiffness in their cervical muscles and an overall reduced range of movement in their cervical joints when compared to anthropometrically matched non-rugby players, which suggests that stronger neck muscles may be associated with this subgroup of rugby players (Cazzola et al., 2016). However, while the specific demands of different player positions are important to consider in relation to head and neck injury prevention, such distinction by position has not been a consistent design feature of injury-related monitoring, physical conditioning or research.

Using the measurement of neck girth as an indicator of muscle size – and, therefore, the ability to exert force (strength) – has been suggested as a means of producing quantifiable data that may be linked to concussions and TBI (Cooney et al., 2022). Several studies have attempted to link overall strength (Collins et al., 2014; Farley et al., 2022), proprioception (Farley et al., 2022), rate of force development, speed at which peak muscle force output can be reached (Eckner et al., 2014) and cervical muscle endurance capacity (Baker et al., 2019) to predict concussive risk in sport and an athlete's likelihood of recovering from a concussion. However, due to this research being in its infancy, more work is required to substantiate such hypothesised causal relationships.

Fatigue resistance is also a strong consideration when working to improve the strength of any athlete. A study using tackle technique as the performance indicator among rugby league athletes who had relatively high lower-body strength demonstrated that improved strength was correlated with best tackle technique and a resistance to fatigue, which may lead to reduced performance (Gabbett, 2016). However, the strength measurements for the upper body – which consisted of a four-repetition maximum (4RM), bench press and chin tuck – did not correlate with fatigue resistance in the same way as lower-body strength (4RM squat) (Gabbett, 2016). This finding may therefore indicate that the upper-body strength tests that are currently used in performance analysis are not as effective as those used when measuring lower-body strength, pointing towards a need for alternatives.

While neck physiology data exists for rugby players, it is not yet easy to interpret with regard to injury prevention. Although foundational research has been conducted into the correlation between neck strength and injury prevention, more research is required to fully understand the phenomenon. Arguably, a more pressing problem that remains unsolved is the absence of a standardised measuring system that may be used to generate trustworthy neck strength measurements.

There have been numerous and diverse approaches to, and tools for, measuring neck strength reported in the literature, which has resulted in a lack of homogeneity in both the methods of measurement and the results reported. This lack of consensus regarding test equipment and test positions, as well as in the reporting of the results in published research, means that practitioners face challenges when selecting evidence-based tests for the measurement of players' neck strength. That said, more importantly still, there is markedly scant available information concerning current clinical practices relating to neck health within the realm of professional rugby.

2.6 Neck strength measurement

This section examines the need to have a standardised measuring system that affords easy comparability between players, universal acceptance and access to simple, standardised measuring protocols and equipment. The issue of how to measure neck strength most effectively relies on accurate measurement systems, and research in this area is nascent.

2.6.1 The importance of measuring strength for sport

Across the professional fields of sports science, medicine and rehabilitation, the measurement of strength and power is fundamental to performance analysis, the evaluation of exercise interventions, comparison of strength and power against normative values, performance monitoring and injury prediction (McGuigan et al., 2013). Strength is defined here as a measure of the production of force by a muscle or group of muscles (McGuigan, 2019, p. 19). However, as various categories of strength can be measured, it is important in experimental research to determine exactly which aspect of strength will be assessed, as well as to ensure sound rationale when selecting an appropriate test. Dynamic strength, which can be measured under either *isotonic* (constant force) or *isovelocity* (constant velocity) conditions, can incorporate both *eccentric* strength (the ability to exert a force while a muscle is elongating) and *concentric* strength (the ability of the muscle to exert force while shortening) (McGuigan, 2019, pp. 28–29). During *isometric* (constant length) strength measurement, no movement occurs because the muscle or muscles produce force against an equal and opposite resistance, thereby making the method ideal for measuring peak force during stable conditions. Given that athletes who generate high-power outputs tend to perform better in other physical tests (Sarto et al., 2020), the ability to measure isometric neck strength has potential wider use value in the context of performance enhancement.

Measures of both isometric and isotonic strength of various body parts have been linked to performance in many sports, including rugby. For example, Cunningham et al. (Cunningham et al., 2018) identified a strong correlation relationship between the isometric mid-thigh pull (IMTP) measured on 29 international rugby players and four key performance indicators for the backs positional group ($n = 14$). These indicators included the number of possessions ($r = 0.793$), passes made ($r = 0.792$), effective attacking rucks ($r = 0.628$) and number of offloads made ($r = 0.603$). In addition to the IMTP, other dynamic tests were also analysed against performance, including countermovement jumps, drop jumps, speed test of acceleration over 10 m, a weighted 5 m sled drive and yo-yo intermittent recovery test. For the forwards in the study ($n = 15$), the highest correlation to performance indicators was shown from the countermovement jumps and drop jumps. That the IMTP (alongside drop jumps) demonstrated the highest level of correlation with key performance indicators for the backs suggests that, despite the small total number of participants in the study ($N = 29$), isometric tests could be chosen as appropriate strength tests for rugby players in the context of performance enhancement. This finding may be due to the reliability of peak force testing using an isometric peak force measurement, which enables the researcher to eliminate confounding variables that can be inherent to dynamic testing, such as the available range of neck motion and the speed at which the test is performed, in a relatively simple and consistent manner.

In sum, there are many factors that can influence the force produced by the person being tested. These include physiological features, mechanical influences, anthropometric qualities, muscle cross-sectional area and motor learning. All such factors should be considered when designing a strength test that is intended for use as a key performance indicator for sport, as this enables the determination of parameters such as the number of practice tests required to overcome a learning effect without inducing fatigue during practice (McGuigan, 2019). Evidence of the decision-making process for the protocol developed in this thesis can be seen in the conceptual framework (deterministic model) (figure 2.8). Questions of consistency notwithstanding, current research underlines the importance both of measuring neck strength in sport and giving due consideration to the type of test required to generate the most useful data for addressing both research questions and practical issues.

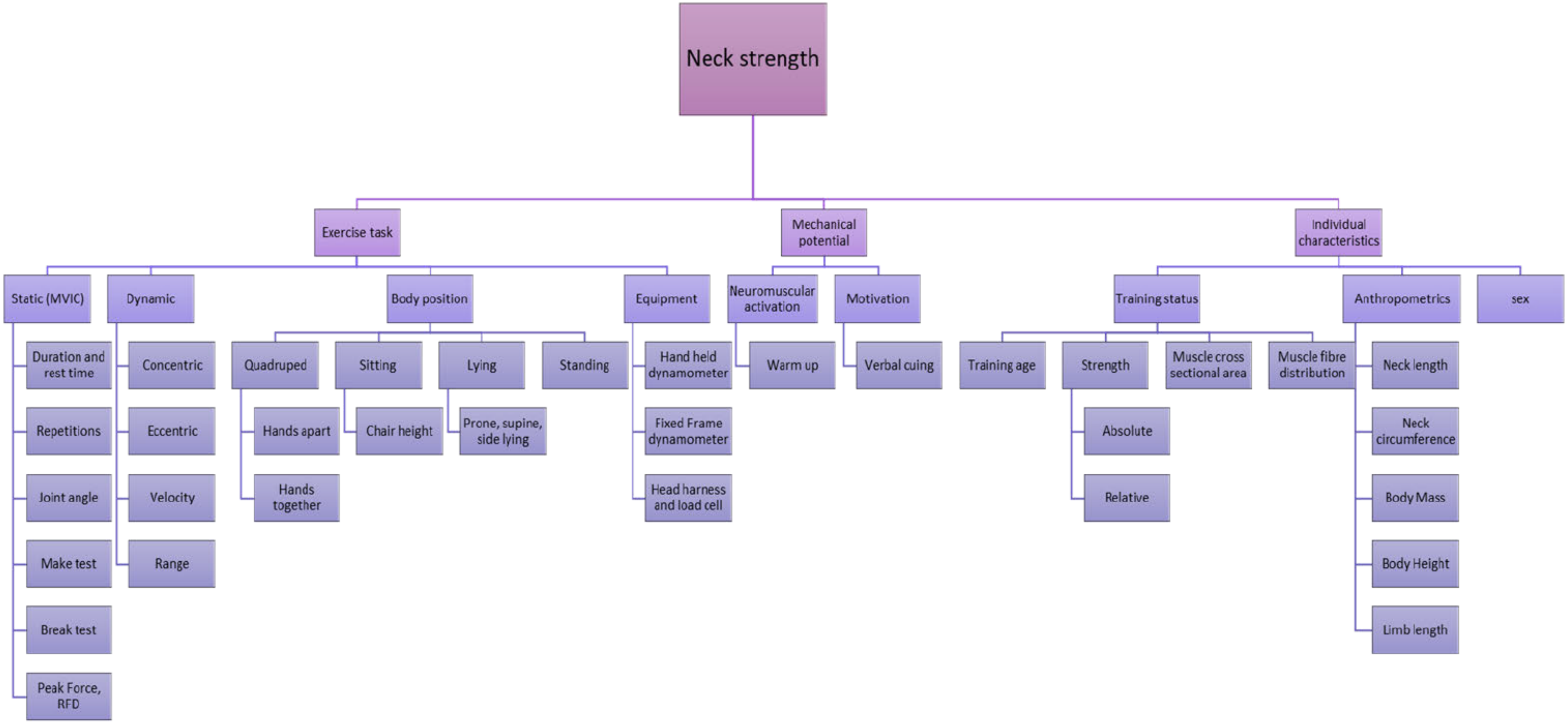


Figure 2.8 Conceptual framework (deterministic model) of neck strength testing decision making

2.6.2 Methods for measuring neck strength

Researchers have explored isometric neck strength measurement in the directions of Flex, Ext, LSF, RSF, and left and right rotation (Peek, 2022). Alongside this, endurance tests for Flex and Ext have also been conducted, as well as craniocervical flexion tests (Selistre et al., 2021). However, for a test that has been examined and reported through peer-reviewed research to be adopted in practical settings, it must demonstrate certain minimum qualities. Robust reliability is a key factor, and there is also a strong preference for good validity. These qualities are considered alongside other secondary concerns, including practical applicability, affordability and the ease with which the tests produce results (Buchholtz et al., 2022). To date, evidence relating to neck screening for strength-related parameters across professional sport has failed to demonstrate these qualities with any consistency.

Clearly, then, strength and power testing for athletes requires urgent standardisation to ensure that consistent measurements can be recorded. In addition, testing conditions often vary substantially between studies and techniques, which can in turn affect the reliability and validity of results. When investigating the reliability of a test, the following conditions should be quantified and stated in any research output relating to their application, as well as standardised where possible: time of day, instructions given, attentional focus, order of tests, control for fatigue, control for environmental conditions, knowledge of nutritional status and the warm-up protocol (McGuigan, 2019). As there is no accepted gold standard for the testing or reporting of the assessment of neck strength, meaning that many different protocols and types of equipment have been used, it is difficult to discern what best practice looks like with regard to maintaining the health of the cervical spine (Table 2.3).

The studies described in Table 2.3 are those published over the past ten years that have explored the neck strength of professional rugby players. It is notable that there is a wide range of peak force values described across the corpus of studies, suggesting that cross-test comparison and the validity of test equipment appear questionable. To give an important example, the measurement of Ext force in similar participant groups of professional rugby forwards ranges from 328 N (Konrath & Appleby, 2013) to 734 N (Geary et al., 2014) (see also Section 6.3.2). That said, there is some general consistency in findings relating to normative values for neck strength in professional rugby players quoted in the literature (Table 2.3). Ext, for example, was always the greatest force measured for all players regardless of type of test, and forwards always recorded greater forces than backs for all tests in which neck strength was reported by position (Davies et al., 2016; Farley et al., 2022; Geary et al., 2014; Hamilton & Gatherer, 2014; Konrath & Appleby, 2013; Naish et al., 2013). However, the range of these normative values remains wide due to variations in testing approach.

In addition, the different modes of data collection employed between measuring concentric isometric strength with a *make* test (where the participant pushes their head into the load cell) versus a *break* test (where the participant resists the lengthening of the muscle until the load is greater than the ability to counter the resistance, and the test is "broken") negatively impacts data comparison (Geary et al., 2013; Hamilton & Gatherer, 2014). The break tests consistently give rise to greater values in all test directions for the neck, a fact demonstrated in the most recent study to assess these differences within a single study (Chavarro-Nieto et al., 2023b). However, Chavarro-Nieto et al. (2023b) conclude that while both tests can be shown to be reliable when performed seated with a load cell and head harness, the make test is preferable due both to the participant confidence in the test and the intrinsic lack of tester influence (figure 2.9).

Figure 2.9 A: Make test for neck extension; B: Break test for neck flexion (from Chavarro-Nieto et al., 2023b)

Table 2.3 Summary of previous studies measuring neck strength in professional rugby players (adapted from Chavarro-Nieto et al., 2021)

Authors	Test position	Testing equipment	Testing protocol	Playing level of participants (*n* =)	Average peak force recorded	
Konrath and Appleby (2013)	Lying, supine and prone	Customised load cell with head harness	Make test Average peak force (3RM) 5-s hold/60-s rest	40 professional	**Ext**	**Forwards:** 328 N **Backs:** 229 N
					Flex	**Forwards:** 295 N **Backs:** 244 N
					LSF	Not measured
					RSF	Not measured
Naish et al. (2013)	Seated on weights bench, height unspecified; feet on air-inflated balance discs	Customised load cell attached to a frame	Make test Average peak force (3RM) 5-s hold/30-s rest	27 professional	**Ext**	372 ± 51 N
					Flex	288 ± 64 N
					LSF	372 ± 51 N
					RSF	384 ± 52 N
Geary et al. (2014)	Seated on chair; hips, knees and ankles at 90°	HHD and head harness	Break test Average peak force (3RM) 30-s rest	25 professional and semi-professional	**Ext**	734 ± 127 N
					Flex	396 ± 76 N
					LSF	657 ± 123 N
					RSF	668 ± 142 N

Authors	Test position	Testing equipment	Testing protocol	Playing level of participants (*n* =)	Average peak force recorded	
Hamilton & Gatherer (2014)	Seated on chair; hips, knees and ankles at 90°	HHD (Gatherer Systems Analyser)	Break test Average peak force (3RM) 30-s rest	27 professional	**Ext**	**Forwards:** 44.9 ± 7.1 kg **Backs:** 39.5 ± 5.2 kg
					Flex	**Forwards:** 32.0 ± 5.6 kg **Backs:** 28.5 ± 3.9 kg
					LSF	**Forwards:** 42.9 ± 7.7 kg **Backs:** 35.0 ± 4.5 kg
					RSF	**Forwards:** 43.1 ± 7.5 kg **Backs:** 35.0 ± 4.5 kg
Davies et al. (2016)	Seated on chair; seat height 90 cm	HHD (Gatherer Systems Analyser)	Break test Average peak force (3RM) 15-s rest	21 professional front-row forwards	**Ext**	71 ± 9 kg
					Flex	44 ± 12 kg
					LSF	59 ± 11 kg
					RSF	61 ± 11 kg
Farley et al. (2022)	Seated on treatment bed, feet firmly on floor	HHD (Lafayette, digital HHD)	Make test Average peak force 3RM 3-s hold/no set rest	225 professional	**Ext**	44.2 ± 1.3 kg
					Flex	34.2 ± 1.3 kg
					LSF	25.7 ± 1.3 kg
					RSF	25.6 ± 1.3 kg

Authors	Test position	Testing equipment	Testing protocol	Playing level of participants (*n* =)	Average peak force recorded	
Gillies et al. (2022)	Seated	HHD (Gatherer Systems Analyser)	Break test Average peak force (3RM) 30-s rest	39 professional (26 forwards, 13 backs)	**Ext**	**Forwards:** 60.8 kg **Backs:** 44.3 kg
					Flex	**Forwards:** 43.7 kg **Backs:** 32.8 kg
					LSF	**Forwards:** 50.2 kg **Backs:** 37.3 kg
					RSF	**Forwards:** 49.6 kg **Backs:** 37.2 kg

Ext = extension; Flex = flexion; LSF = left side flexion; RSF = right side flexion; 3RM = three-repetition maximum; HHD = handheld dynamometer

The variety of tests employed within this area of sport and exercise medicine potentially render decision-making for practitioners extremely difficult. Moreover, where research has been robust, it has often involved bespoke equipment designed for the research laboratory, rendering it inaccessible to practitioners (Geary et al., 2013; McDaniel et al., 2021; Salmon et al., 2015). Other research that has adopted comparatively cheaper tools (Farley et al., 2022; Versteegh et al., 2015) has been subject to the reliability issues consistently reported regarding handheld devices (Farley et al., 2022; Krause et al., 2019; Malliaras et al., 2009; Ryan et al., 2019; Versteegh et al., 2015). This limitation regarding the potential for multi-study comparison due to variations in test procedures contributes significantly to the piecemeal condition of current research understanding, with clear consequences for practical application.

The measurements recorded in these studies (Table 2.3) demonstrate that when the same equipment and technique is employed (Gillies et al., 2022; Hamilton & Gatherer, 2014), professional rugby players' normative peak neck strength measurements are characterised by a range of peak force measurements, greater than the minimal detectable change (MDC; used to indicate the minimum change in strength required to demonstrate a meaningful change in strength has occurred, thereby indicating the ability of the tool to measure this variable) limits calculated by Gilies et al. (2022). One issue with interpreting this diversity of measurements is that it is unclear whether differences between studies are the result of measurement error or actual differences between the strength of the participants in the studies. It is worth noting that no reference is made to the consistency of start positions in any of these studies, for example, chair heights for the seated postures and any bracing allowed from the limbs for any of the tests, which may impact on the strength measurements recorded.

However, in a live match situation, there is no method of recording how much force the neck sustains, which limits understanding of player neck strength in real scenarios (Roberts et al., 2013), as well as affecting the comprehensiveness of the evidence base of normative data. Across multiple levels of conceptualisation and practice, then, it appears that neck strength measurement in contemporary rugby is characterised by inconsistency of approach.

2.7 Conclusion

This literature review has served to foreground the strong and ever-developing interest in the physical demands of rugby and, more specifically, its impact on the heads and necks of players. The head and neck are of particular interest in this context due to the acknowledged seriousness of any injury to these vulnerable regions, as well as the longer-term consequences of degenerative changes and neurodegenerative diseases – all of which are increasingly being linked to trauma from collision sports.

In addition, it has highlighted the limited possibility for forging links between neck strength, injury prevention and performance enhancement on the basis of existing neck strength measurement practices. The review has identified inconsistencies in current engagement with and approaches to measuring neck strength in rugby, as well as exposing how little is known about current practices of neck strength testing in professional sporting contexts. Fundamental to the usefulness of laboratory-based research is its applicability in the field. It is therefore important to establish a knowledge base regarding the existing neck strength measurements practices used in professional rugby contexts, as well as to ascertain the kinds of exercises being prescribed to enhance player neck strength. That such a knowledge base is currently lacking is especially problematic given high risk of injury in professional rugby; the sport and its participants require constant monitoring for the best chances of injury mitigation and prevention (PRISP, 2022), and this involves the use of a reliable and valid neck strength test. As rugby players demonstrate widely varying physical characteristics, any proposed interventions need to have the potential to suit all players and, importantly, need to be fully informed by evidence.

As adduced above, there is evidence to suggest that enhanced body strength is positively correlated with both injury prevention and improved performance. It is therefore in the best interest of all stakeholders in rugby to maximise the strength of their players. In the case of neck strength in particular, the impact of specific training exercises remains unknown due to the lack of a standardised measurement method.

The foremost insight gained from the literature review is the pressing need for a reliable method of measuring neck strength that not only meets the requirements of research laboratory rigour but also has the potential to gain acceptance from sports practitioners. Given the extent of the knowledge gap and resultant inconsistency of solutions relating to neck strength measurement, it appears most pragmatic to take the professional side of the sport as a starting point for research because – while neck strength measurement is unquestionably relevant at all playing levels for both the men's and women's sport – good practice is most likely to be adopted in professional contexts due to the attention paid by clinical practitioners to new best practice research. The institution of a universally accepted method of neck strength measurement in this context would therefore afford widespread applicability over time, in turn leading to the longitudinal collection of a robust normative data corpus. Such a database would allow for injury audit to be consistently compared to neck strength data, ultimately directly benefitting players.

2.8 Thesis aims and research questions

2.8.1 Thesis aims

The overarching aims of this thesis are to enhance understanding of current neck-screening practices in professional rugby in the UK and, drawing from these insights, to establish, test and implement a reliable, practically applicable, evidence-based method of measuring neck strength for professional rugby players.

2.8.2 Research questions

The research questions (RQs) that underpin these aims are cumulative: RQ1 informs RQ2, which in turn informs RQ3.

RQ1 What, if any, neck management practices (screening and strengthening provision) are used in elite-level rugby union in England?

RQ1a What characterises existing neck-screening practices (in terms of neck strength, proprioception, range of motion and neurological sensitivity, as well as tester, type, protocol, equipment used, and timing)?

RQ1b What characterises existing neck-strengthening provisions (in terms of prescriber, type, protocol, equipment used, setting and frequency), and do they vary according to player position?

RQ1c What existing areas of screening and strengthening have greatest potential to enhance current neck management practices?

RQ2 Can neck strength be reliably tested using existing equipment?

RQ2a Can reliability be achieved in terms of intra- and inter-rater response, participant sex and planes of motion?

RQ2b Can test position reliability be achieved?

RQ3 Can neck strength be measured in elite rugby players using the VALD ForceFrame?

RQ3a What are the normative values of player neck strength?

RQ3b What is the relationship between neck strength and player position?

2.9 Thesis overview

To begin to ascertain the scope of existing practices of neck screening in professional rugby, a survey was first distributed to the sports science departments of English Premiership and Championship clubs to discover what neck-related strength and other health indices were commonly being measured, and which tools were employed to take measurements (Chapter 3). Questions will also explore current exercise provision for neck strength and which evidence is used to underpin choices relating to this provision. Building on insights from survey analysis, a commercially viable and accessible tool for measuring neck strength was then tested for reliability, and a standard usage protocol will be established (Chapters 4 and 5). The protocol was then taken out of the research laboratory and used to measure the neck strength of elite rugby players (Chapter 6).

Chapter 3: A survey of current neck strength screening practices in professional rugby

3.1 Introduction

The previous chapter revealed the lack of comprehensive scientific investigation into common neck strength measurement practices within rugby union (hereafter "rugby"). With this chapter, the aim is to begin to fill the gap in knowledge regarding clinical practices of neck healthcare in the context of professional rugby.

The main aims of sports medicine and science are injury prevention and performance enhancement, and it has been demonstrated conclusively that these two parameters are interdependent in rugby (Williams et al., 2016), as well as in other sports such as football (soccer) (Ekstrand, 2013; Hägglund et al., 2013). For example, there was a strong negative correlation between injury measures and performance in Premiership rugby over a seven-season period (2006–7 to 2012–13), demonstrated by the fact that a reduction in injury burden of 42 days per 1,000 player hours is associated with the smallest worthwhile change in league points (Williams et al., 2016). Alongside the improved performance of teams with lower injury rates, further benefits include a lower financial burden to the club and better overall long-term health of the players, making injury prevention an essential consideration for all clubs.

3.1.1 Screening and strengthening practices for the neck in rugby

As established in the previous chapter (Chapter 2), rugby involves contact situations that carry significant risks, including concussion and injury to the cervical spine (Fuller et al., 2007; Roberts et al., 2013; Tucker et al., 2017). A recommendation frequently made to reduce this injury burden is to strengthen neck muscles, which is underpinned by the theory that a stronger neck will potentially dissipate the energy from the force of the collisions, meaning less damage is sustained (Collins et al., 2014; Eckner et al., 2014; Geary et al., 2014; Hamilton & Gatherer, 2014; Lisman, 2009; Naish et al., 2013; Salmon et al., 2018). To enable the development of appropriate exercise programmes, a reliable and valid method of measuring neck strength is required to measure the effectiveness of a prescribed strengthening programme (Barrett et al., 2015). In athlete monitoring, it is also considered important to establish a set of baseline normative data regarding key performance indicators such as strength, range of motion and proprioception so that objective, measurable pathways may be established to support players in returning to training and play after injury (Schwab et al., 2020; Selistre et al., 2021; West et al., 2019). These could also be used for academy players, enabling comparison with senior players and thereby determining whether they are ready to progress to the next level of playing (West et al., 2019). When choosing a screening programme, it is important to ensure that all tests are based in evidence, that they provide players and clubs with meaningful data relating to performance and/or injury prevention and that they can be reliably remeasured at specific times during the season (Ross et al., 2018; Schwab et al., 2020)

Previous research indicates that neck strength can already be reliably measured (Chavarro-Nieto et al., 2021). However, the tests reported in the literature have used a range of different technologies and protocols to produce neck strength data, making the results heterogeneous and specific to each research situation. As revealed in the literature review, previous research has relied on either a custom-built fixed frame constructed by the authors (e.g. Salmon et al., 2015) or a handheld dynamometer (HHD), which has inherent reliability issues due to the added variable of tester strength (e.g. Farley et al., 2022; Versteegh et al.,

2015) or the way in which it is used (Krause et al., 2019). In addition, all research conducted to date investigating neck strength has involved the use of different test positions (see Table 2.3). The results are therefore specific to the research setting and not generalisable to the wider rugby population.

Moreover, all published work on measuring neck strength, both in sports and healthcare settings, is written by academic researchers who have either measured neck strength in a laboratory to determine its reliability or in the field as part of a research study (Chavarro-Nieto et al., 2021; Selistre et al., 2021). In other words, there is a lack of published work detailing common neck strength screening practices and neck exercise prescription at English rugby clubs as part of regular musculoskeletal screening, injury prevention efforts and performance enhancement practices.

Furthermore, a major limitation of the published research into neck screening and strengthening programmes for rugby players is that it has always taken place at a single club (Geary et al., 2014; Gillies et al., 2022; Maconi et al., 2016; Naish et al., 2013). The narrow populations in these studies make broader extrapolation from individual teams' data problematic. Collecting and disseminating data about the reality of day-to-day neck-screening and exercise-provision practices across a range of clubs would provide more useful evidence that could be harnessed to support practitioners in making evidence-informed decisions when conducting neck health screening and prescribing neck strength exercises.

Moreover, even within the limited corpus of published research into the efficacy of exercise programmes designed specifically to improve neck strength in rugby players, neither the neck-strengthening protocols nor the methods used to measure the effectiveness of the intervention have been consistent (Geary et al., 2014; Gillies et al., 2022; Maconi et al., 2016; Naish et al., 2013). For example, the study by Geary et al. (2014) – conducted with 15 professional players and involved the strength-and-conditioning (S&C) coach pushing against the players' heads for 3 x 10-s holds into flexion (Flex), extension (Ext), left side flexion (LSF) and right side flexion (RSF) twice a week for five weeks – demonstrated a significant increase in strength in all test directions over the study period when compared with a control group. However, as the control group was not matched, instead involving semi-professional players with no description of playing position, it is not possible to ascertain whether the improvement was due to the increase seen across a season as a result of the training effect of participation (Salmon et al., 2018) or to the exercise programme.

Unlike the study by Geary et al., Maconi et al. (2016) devised a strengthening programme comprising isometric holds and resistance work against bands, which was performed three times per week by all players regardless of playing position. Due to the use of resistance bands, actual load was not calculated. It was delivered to amateur rugby players at a single club for 12 weeks. The results showed a significant ($p < 0.05$) increase in the neck's maximal voluntary isometric contraction (MVIC) into Flex, Ext and both left and right rotation. However, there was no reported difference in side flexion (SF) strength, as measured using a bespoke seated strength test against a mounted load cell, one that had not been previously tested for reliability in measuring neck strength.

Differently again, Naish et al. (2013) implemented a neck-strengthening protocol over a period of 13 weeks, undertaken once or twice per week (depending on the exercise; see Figure 3.1), with 27 professional elite rugby players. Exercises selected specifically for the front row were different from those for all other players. However, strength was only retested in the fifth week, at which point there was no significant change in strength recorded in any test direction. Again, a bespoke method of measuring neck strength was devised, which incorporated a head harness attached to a load cell (Figure 3.2).

To give a further example, most recently, the exercise programme described in the research undertaken by Gillies et al. (2022) used a head harness and resistance cord to deliver both the exercises and measure the force output from the neck in Flex, Ext, LSF and RSF. Unlike the previously cited studies, an advantage of Gillies et al.'s protocol was that the exercise programmes were adapted for each player depending on their one-repetition maximum, as measured at the start of the programme. However, the exercises were not fully described in the published report, making any inferences from the results difficult to translate into practice. In addition, this programme was interrupted by the enforced COVID-19 break in the playing programme so is not wholly comparable with a normal season. The findings demonstrated that following the season-long intervention (practiced three times per week), all forwards significantly increased strength in Flex and LSF only, and backs in Flex only. The lack of a control group for this study is a limitation that requires consideration, not least in light of Salmon et al.'s (2018) findings: that in a normal season of rugby, without a bespoke neck-strengthening programme in place, rugby forwards demonstrated a significant increase in strength into all measured directions (Flex, Ext, LSF and RSF), with the backs displaying a significant increase in Flex and Ext as compared to a matched control group of non-rugby players.

The bespoke nature of the exercise programmes and methods of measuring neck strength surveyed here, as well as the studies' disparate findings, make the landscape of neck exercise provision and neck strength testing a confused field of study.

Figure 3.1 Exercises for front-row forwards
(from Naish et al., 2013)

Figure 3.2 Neck strength test
(from Naish et al., 2013)

3.1.2 The role of warm-ups in neck strength exercises

Only one study has examined neck exercises performed on the field as part of a general warm-up performed prior to both training and matches, and this was in community-based – rather than professional – rugby (Attwood et al., 2018). The neck exercises performed in this study were short isometric holds wherein each player pushed their head against their own hand. They were performed by all players, regardless of position, as part of a larger motor control-based warm-up protocol delivered prior to training (twice a week) and matches (once a week). The study yielded promising results, with a likely 60% reduction in concussion incidence in the clubs who complied with the exercise programme. That said, no attempts have yet been made to replicate the warm-up study with professional rugby players.

In professional rugby, field-based training consists of both exercises that are performed by the whole team and more specific activities tailored towards smaller units of players, usually for skills-based training (Campbell et al., 2018). In the latter case, players are often divided into forwards and backs, and sometimes more specifically still into units such as front-row forwards or half-backs (see Section 2.2.1). As a result, on-field warm-up is usually specific to either playing position (for matches) or to the training session that is about to occur (for training). However, there is no published information regarding the type of exercises normally provided for the neck that is specific to warm-up situations.

As there is no evidence in the literature for the existence of a standard protocol for the measurement of neck strength in professional rugby players, or methods for determining optimal neck exercise provision, an investigation aiming to establish current practices would be an important contribution to this field of study. This would also be a vital step in the determination of whether there is a need to develop such a standardised approach.

3.1.3 Rationale for the methodological approach

Due to the essential element of competition in sport, which is especially pronounced in professional domains, the exchange of information between the support services of sports medicine and science departments is limited, whether between individual clubs or more generally across the sport. As a result, the main methods of knowledge transfer for medical and sports science-related information are through published literature and conferences (Owoeye et al., 2020). However, one of the overarching problems identified with laboratory-based research is the difficulty of its translation into meaningful behaviour change in the field, where practices need not only to be seen as worthy of the time and effort taken to master and implement, but also to be both financially viable and possible to adopt within a reasonable timeframe (Ross et al., 2018). The impact value of research directed towards effecting in-field change can be represented as a combination of the extent of generation of new knowledge and of its implementation in practice (Figure 3.3).

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 3.3 A schema illustrating the relationship between knowledge generation, application and impact in elite sport
(from Ross et al., 2018)

Having identified the existence of several conflicting methods for measuring neck strength (Chavarro-Nieto et al., 2021), together with a relative dearth of reporting regarding neck-strengthening exercise programmes making use of a sound evidence base (Daly et al., 2021), it was considered important to investigate current professional practice in these key areas of neck care. In this way, the present chapter aligns with the study conducted by McCall et al. (2015) in relation to football (soccer), albeit focusing on rugby.

The purpose of this preliminary inquiry, undertaken in 2018, was threefold. First, it aimed to discover what neck-related screening data was being collected from professional rugby players by medical and S&C staff, as well as what protocols and equipment were being used. Second, it sought to document the kinds of cervical spine exercises currently being prescribed for professional rugby players. Third, in order to determine the best methods of subsequent knowledge transfer, it was also deemed important to canvass practitioners' preferences for sourcing information when researching which neck measurement and exercise practices to implement for players.

The most efficient method to survey many participants is to use a web-based questionnaire (Eysenbach, 2004). An important methodological concern for this study was to develop a valid tool with which to assess the provision of neck exercises of rugby players, as well as to encourage wide engagement with the questionnaire from an appropriate participant group.

3.1.4 Survey development

3.1.4.1 Sample

The potential population for the study comprised two discrete groups of stakeholders: rugby players and medical and sports science staff associated with rugby clubs. Through early discussions with several potential participants in both populations, it became apparent that asking players about the details of and rationales underpinning the neck exercises they were performing would yield poor results. Players frequently reported being prescribed a new exercise programme each week by their physiotherapist, S&C coach or sports rehabilitator, which they duly performed without necessarily knowing or asking why. The population deemed most appropriate to survey was therefore those who devised players' exercise programmes (McCall et al., 2015) on the basis of *judgemental sampling* (Sim & Wright, 2000, p. 49), which requires the researcher to reach a decision based on their evidence-based assessment of the potential efficacy of the sample.

Snowball sampling was also used (Blair et al., 2013, p. 127), whereby the initial participants were encouraged to recruit further participants by independently disseminating the questionnaire, ensuring that as many members of the eligible population were reached, which in turn increased the likelihood of receiving an appropriate range of responses. A limitation of this type of sampling is the lack of control that the researcher retains regarding who takes part in the study. This can make interpretation of the results more challenging than when having a discrete sample frame.

3.1.4.2 Design

To ensure that there was a clear purpose and scope to the questionnaire (Dillman & Smyth, 2007) and that the most appropriate set of questions were asked, the structure of the questionnaire was carefully considered. A mixture of open and closed questions was used to ensure the greatest insights could be achieved. Closed questions afford clear, simple answers that can be analysed quantitatively. When closed questions are followed by the chance for additional material to be added in the form of open questions, this data can be analysed qualitatively, affording greater richness of data (Blair et al., 2013, p. 121). To be most effective, a questionnaire should involve a series of questions within each theme, progressing from the more general (often a simple "yes/no" question) to the more specific (for example, more detailed questions seeking information on how, or the frequency with which, something is done) (Appendix 1).

The following four main themes were identified from this literature review that would lead to novel insights regarding current neck screening practices in rugby:

1) Evidence of the neck health screening practices currently in use, encompassing the basic components that comprise a healthy musculoskeletal system: strength, flexibility (range of motion), proprioception and peripheral neurological health (reflexes) (Schwab et al., 2020);

2) The sources of knowledge relied upon by practitioners to inform the devising of screening and exercise protocols at their clubs;

3) Differences in the provision of neck exercises according to player position and grouping, both in the gym and on the field;

4) Respondents' perceptions of the relative importance of the various purposes for which they might implement neck screening and exercise programmes, including injury prevention, performance enhancement and pain control.

3.1.5 Aims, research questions and objectives

3.1.5.1 Aims

The aim of this chapter is to explore the current knowledge, understanding and practice in professional rugby in England regarding neck strength measurement and neck exercise prescription. This fills an identified gap in the literature regarding the development of a cohesive understanding of contemporary neck testing and strengthening exercises in rugby.

3.1.5.2 Research questions

RQ1 What, if any, neck management practices (screening and strengthening provision) are used in elite-level rugby union in England?

RQ1a What characterises existing neck-screening practices (in terms of neck strength, proprioception, range of motion and neurological sensitivity, as well as tester, type, protocol, equipment used, and timing)?

RQ1b What characterises existing neck-strengthening provisions (in terms of prescriber, type, protocol, equipment used, setting and frequency), and do they vary according to player position?

RQ1c What existing areas of screening and strengthening have greatest potential to enhance current neck management practices?

3.1.5.3 Objectives

The first objective of the questionnaire study is to measure the opinions of sports science and medicine practitioners working in professional and semi-professional rugby union in England regarding the nature and extent of *neck-screening and management practices* (neck strength, proprioception, range of motion and neurological sensitivity), including tester, type, protocol, equipment used, and timing.

The second objective is to measure the opinions of sports science and medicine practitioners working in professional and semi-professional rugby union in England regarding *neck-strengthening provision* (including prescriber, type, protocol, equipment used, setting and frequency) and to determine the areas of neck screening and strengthening that are reported as the most impactful to enhancing current practices.

3.2 Methods

3.2.1 Ethical considerations

Ethical approval was provided by the Coventry University Human Research Ethics Committee (P60723). The covering page of the questionnaire provided all participant information and advised respondents that by completing the questionnaire, they were consenting to the use of their data for analysis (Appendix 1).

3.2.2 Survey procedure

3.2.2.1 Preparatory work

To ensure that the most appropriate questions were developed for the questionnaire, the researcher undertook telephone conversations and face-to-face meetings with two professional rugby players at two different Premiership rugby clubs, as well as with medical and S&C personnel at one Premiership, one Championship, one National League 1 clubs and three community-level club physiotherapists in England.

It was established that in order to survey medical teams and S&C coaches who play a role in the provision of neck care for their rugby players, the sample would need to consist predominantly of those working at professional and semi-professional clubs. During these initial scoping discussions, medical staff at the community-level clubs reported that there was little or no input from support staff for the provision of neck screening or exercise provision.

It was important that everyone working at the club or team who was involved in the provision of cervical spine care for players answered the parts of the questionnaire pertaining to their specific professional contribution, hence the decision to allow for snowball sampling. This would allow for comparison between the delivery of certain aspects of the care by physiotherapists, S&C coaches and doctors. It would also serve to identify similarities and differences between professional and semi-professional levels and between senior and academy levels, as well as those between data collected regarding exercises prescribed for different playing positions.

3.2.2.2 Questionnaire construction

The questionnaire was constructed via the Bristol Online Survey (BOS) software. The Checklist for Reporting Results of Internet E-Surveys (Eysenbach, 2004) was followed to ensure validity. The questionnaire consisted of 42 main, numbered questions, as well as 41 supplementary sub-questions seeking further information. Most of the main questions (n = 34) were closed, though there was often the opportunity to add further information via an “Other” field. There were eight open-ended questions affording respondents the opportunity to write free text. The questionnaire was divided into four main sections: the first section (Q1–6) comprised demographic and professional experience questions to ascertain who was completing the questionnaire; the second section (Q7–16) addressed cervical screening tests and the tools used to perform these activities; the third section (Q17–34) addressed gym-based cervical spine exercise provision, broken down by playing position; and the fourth section (Q35–40) addressed field-based cervical spine exercise provision, broken down by event (pre-training and pre-match). Finally, Q41 asked respondents to rank the perceived importance of cervical spine exercise provision, and Q42 was an open question giving the participants the opportunity to state any further relevant and useful information that had not been requested in the questionnaire.

3.2.2.3 Pilot studies

Two pilot studies (*n* = 4 participants in each, all physiotherapists who were not in the sample frame for the main study) were conducted to assess questionnaire usability, to check for bias in questioning and answer options, and to ensure all relevant subjects were covered in questions.

Following the initial pilot study, several changes were made to the questionnaire. The distribution had not initially included the option for respondents to indicate involvement in women's rugby because it was not a professional sport; however, as there were women's teams affiliated with Premiership clubs whose staff could conceivably receive the questionnaire, this category was added to the demographic information section to ensure that all respondents could fully and accurately answer this question (Q1).

Wording of the questions in the main body of the questionnaire was also changed to place greater emphasis on players' exercise performance (e.g. "Please indicate which neck programmes are provided for each player in your team"), rather than the emphasis being on the provider of the exercises (e.g. "What exercises do you prescribe?"). This change was to allow for information to be gathered from respondents who were not themselves directly involved in provision of these exercises, as feedback from the pilot study suggested that players sometimes perform their own exercises or those they have learnt from other environments (such as personal trainers or national team involvement) in addition to or in place of those prescribed at their club.

The second pilot study also allowed for the usability and technical functionality of the link in the email to be checked. As the questionnaire was open to anyone who had received an email with the webpage link, which would potentially permit a participant to submit multiple responses, demographic information was requested with the aim of ensuring that all answers to be analysed were from unique respondents.

3.2.2.4 Sample

The target population for the questionnaire was providers of neck care for professional and semi-professional rugby players. It was deemed by the researcher that this sample group would have the necessary expertise to be able to answer the questions from an informed standpoint with limited risk of bias, as each respondent would be reporting a factual account of what practices occurred at their club. Response bias may be seen if the questionnaire was written in language associated explicitly or exclusively with physiotherapy, so care was taken to use accessible, non-jargonistic language that would not exclude professionals working in other disciplines. The structure of professional rugby in England changes periodically, but at the time of this study it comprised 24 professional teams: 12 Aviva Premiership teams (Saracens, Wasps, Exeter Chiefs, Leicester Tigers, Newcastle Falcons, Gloucester, Worcester Warriors, London Irish, Northampton Saints, Harlequins, Bath, Sale Sharks); 12 Greene King IPA Championship teams (Richmond, Nottingham, Bristol, Yorkshire, Bedford, Doncaster, Ealing, Jersey, Rotherham, Hartpury, Cornish Pirates, London Scottish); and 16 semi-professional teams, all in National League 1 (Coventry, Darlington, Plymouth Albion, Ampthill, Blackheath, Birmingham, Old Elthamians, Bishops Stortford, Caldy, Rosslyn Park, Cambridge, Esher, Hull, Loughborough Students, Old Albanians, Fylde). Each club comprised a senior men’s squad and an academy comprised of a variable number of players between the ages of 16 and 19 years.

Questionnaires were distributed to the head of medical services personnel at the 40 professional and semi-professional clubs in England via an email featuring a live link to the online questionnaire. Recipients were also requested to share the survey link with appropriate members of their sport and exercise medicine and science team. In addition, it was sent to the physiotherapists (*n* = 4) for each of the national teams of England, Ireland, Wales and Scotland. Snowball sampling was allowed, whereby the initial contacts could distribute the questionnaire to an untracked number of further contacts. A follow-up link to the questionnaire was sent to all clubs six weeks after the initial request.

3.2.2.5 Analysis

Raw data was exported from BOS to Microsoft Excel 2008. The questionnaire was analysed descriptively. The closed questions were simple tick-boxes where the overall numbers of boxes checked were recorded. The answers are described individually and also in relation to each other, where appropriate, to give a more holistic picture of the current situation regarding neck screening and strength in the professional and semi-professional rugby landscape.

3.3 Results

The presentation of findings in Section 3.3.1 relates to all questionnaire responses (*N* = 42).

3.3.1 Q1–6: Demographic and background information

Questions 1–6 enquired about respondents' professional demographic details. The majority of respondents were from the English Premiership (*n* = 16, 38%) (Figure 3.4).

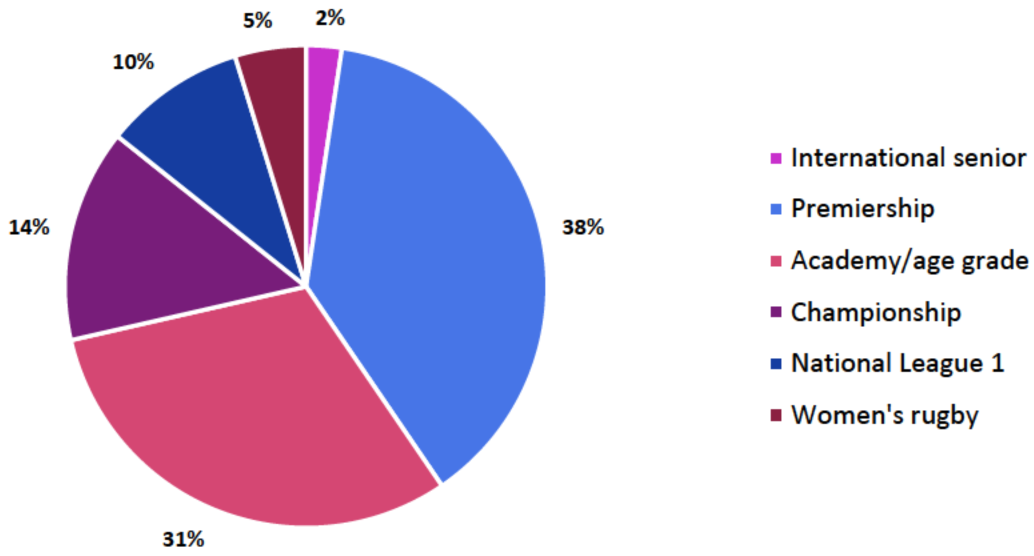


Figure 3.4 Respondents by team level (Q1)

Fewer responses were received from non-Premiership teams: 13 (31%) respondents from academy-level teams (of whom eight worked at academies belonging to Premiership or Championship clubs, three with national-level age-grade rugby teams and two with under-18 and under-16 age groups); six (14%) respondents from Championship level (n = 4 in the UK and n = 2 in New Zealand); four (10%) from National League 1 and two (5%) from women's teams.

Over two thirds of all respondents (n = 27) were physiotherapists. The remainder were those directly involved in S&C, rehabilitation, athletic performance, and professional medicine (Figure 3.5).

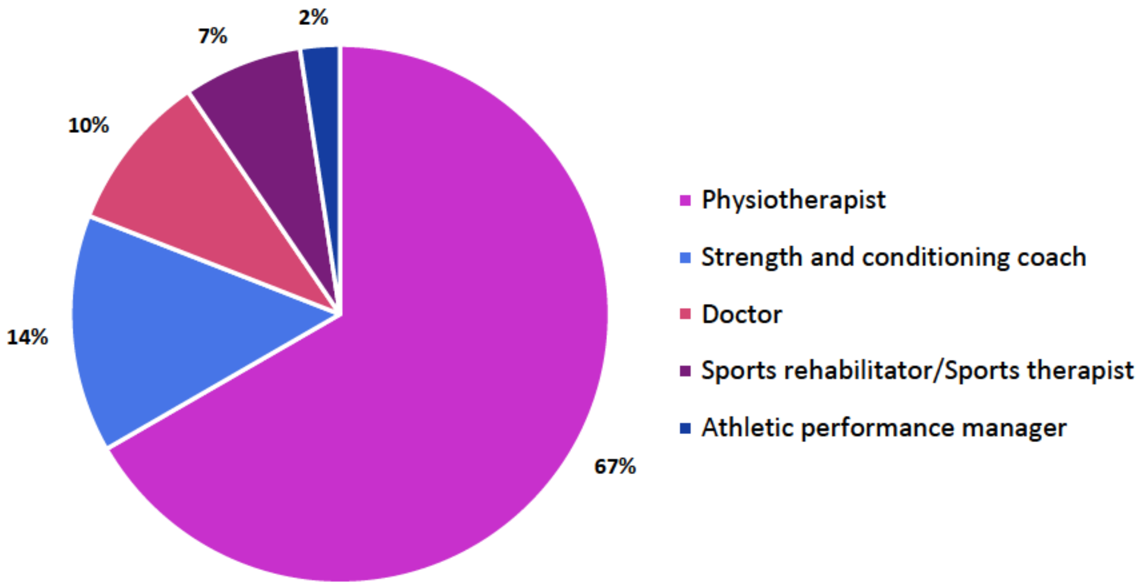


Figure 3.5 Respondents by profession (Q2)

Of the four doctors (10%) who responded to the questionnaire, two were from Premiership clubs, and one each from a Championship and a National League 1 club. Since none of the respondents had responsibility for neck screening or the provision of exercises, all have been excluded from the subsequent analysis in this section.

The presentation of findings from Section 3.3.2 onwards focuses on the information provided by respondents from the professional and semi-professional, UK-based clubs of male players for whom the questionnaire was originally designed, totalling 36 responses. Therefore, the results from the women's teams (*n* = 2), the university and age-grade teams below under-18 level (*n* = 2) and the New Zealand-based teams (*n* = 2) have been omitted from this presentation of results to ensure that this study is focused on its original aim.

3.3.2 Q7–16: Cervical spine screening

3.3.2.1 Information on screening practices and evidence to underpin decisions (Q7–12)

In response to Question 7, 64% (*n* = 23) indicated that that they were involved in players' cervical spine screening. These respondents included 18 physiotherapists, three S&C coaches, one sports therapist and one doctor. All nine Premiership physiotherapists reported that they screened their players' cervical spines, while four of the six academy physiotherapists reported screening, three of whom were attached to Premiership academies. One S&C respondent at academy level was also involved in screening, as was one Premiership doctor.

In Question 8, respondents were required to select the sources of information used to inform their screening protocols, with 87% (*n* = 20) reporting using journal articles, 57% (*n* = 13) from courses (*n* = 13), 43% (*n* = 10) from conferences and 39% (*n* = 9) from books (Figure 3.6).

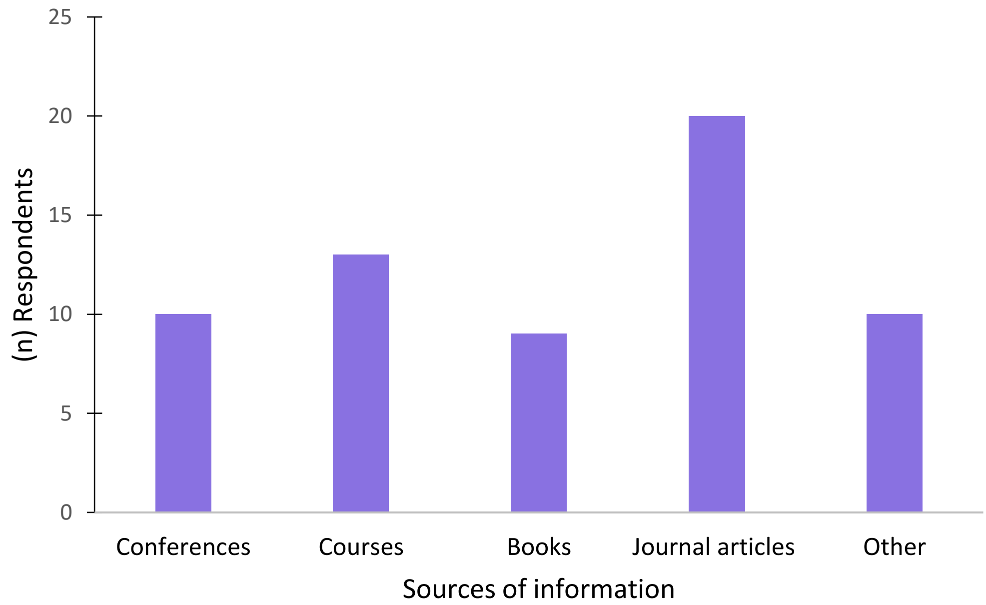


Figure 3.6 Sources used to inform screening protocols (Q8)

“Other” information sources mentioned (Q8a) included collaboration with peers and specialists (*n* = 6), online sources such as Twitter (*n* = 2), experience from clinical practice and other sports (*n* = 3), and MSc studies (*n* = 1). Question 8b was an open question where respondents were asked which sources of information they found particularly useful. Three participants commented that journals and conferences provided information on current best practices based on recent evidence. One respondent commented that journals gave them the option of sourcing perspectives from other sports such as judo, while conferences and courses were seen to incorporate evidence-based practice but also the thoughts and opinions of the presenters. In-service training was commented on by one respondent, and another cited the work of Geary et al. (2014) and Olivier et al. (2008).

In answer to Question 9, of the 23 respondents who screen their players, 39% (*n* = 9), of whom four were Premiership physiotherapists, reported that their screening protocols were only reviewed or changed annually. According to 52% (*n* = 12) of respondents, five of whom were Premiership physiotherapists, protocols were only reviewed when new information became available. One Premiership S&C coach reported that they review the weekly, monthly and annual trends for the whole group, though this only involved monitoring trends according to weightlifting ability rather than by any other method of measuring cervical spine strength.

In response to Question 10, which explored when players were screened, 82% (*n* = 18) reported screening at pre-season, with 50% (*n* = 11) screening after a head or neck injury, and 41% (*n* = 9) both pre-return to training (RTT) and pre-return to play (RTP). The national team’s physiotherapist reported that he “only had the opportunity to screen in camp” (i.e. when the team were in the preparation phase for a fixture). However, post-injury and pre-RTT neck strength were consistently tested at all the Premiership clubs, with just one failing to retest before RTP (Figure 3.7). Qualitative responses detailing reasons for screening included as a means of monitoring axial-loading capability and for assessing measurements against minimum levels expected at professional level. Of the respondents who screened players, 96% (*n* = 22) reported that the data was used to inform gym programmes, and 87% (*n* = 20) reported utilising the data as a baseline marker in case of injury (Q11).

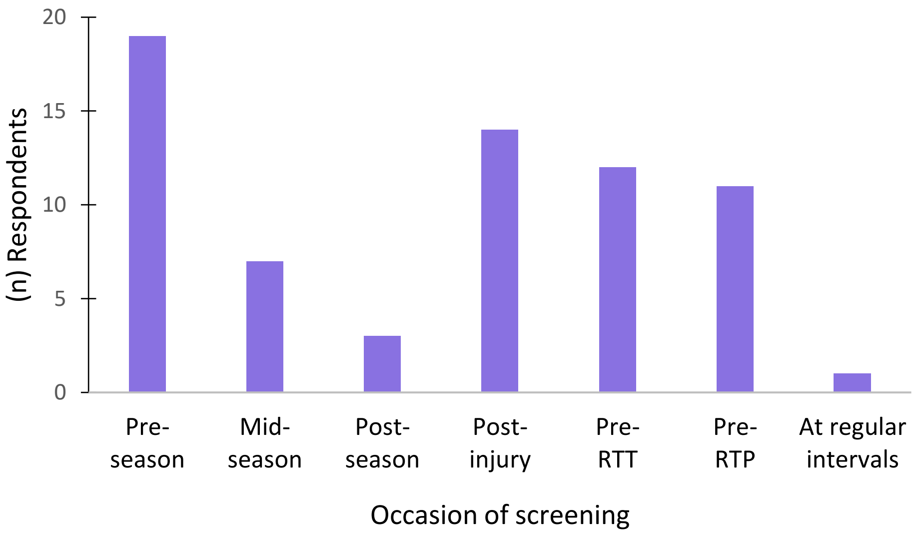


Figure 3.7 When in the season screening is performed (Q10)
(RTT = return to training; RTP = return to play)

In response to Question 12, 39% (*n* = 9) of respondents stated that they used published data sets as a comparison point for their own data. Of these nine, five were unable to state which data they were comparing against, one respondent quoted three published papers (Geary et al., 2014; Hamilton & Gatherer, 2014; Naish et al., 2013), and two commented on the “Don Gatherer ratios” but also stated “we have to adapt the data as our players far exceeded the values provided as reference values with the Gatherer system”. One Premiership team compared their senior team with their academy data. One respondent stated (as written): “I can’t remember off the top of my head, but our guys test significantly stronger than the research in semi-pro rugby players so they're compared LSF v RSF, ext v flex, inter position and front 5." In addition, six of the nine respondents to this question reported that they use their own data to compare against for expected normative values by position.

3.3.2.2 Cervical spine measurements (Q13–16)

3.3.2.2.1 Range-of-movement (ROM) measurements (Q13)

Question 13 sought to ascertain which respondents took measurements of range of movement, what planes of movement were assessed and what equipment was used to take the measurements.

Of the 36 respondents, 42% (*n* = 15) physiotherapists and sports therapists measured active range of motion (AROM). Passive range of motion (PROM) was only measured by 14% (*n* = 5) of respondents, all of whom were physiotherapists. One Premiership physiotherapist who performed regular screening did not measure ROM within their screening programme, and only one National League 1 physiotherapist measured AROM and PROM. Two of the six academy physiotherapists used ROM as part of their screening.

Question 13a required respondents to state which tool or tools they used to measure ROM. A Cervical Range of Motion Instrument (CROM™) or a standard goniometer was used by 47% (*n* = 7), while 40% (*n* = 6) used smartphone apps and 20% (*n* = 3) "eyeballed" (i.e. visually estimated) ROM (Figure 3.8). Of the 15 respondents who measured AROM, 60% (*n* = 9) measured all uniplanar movements of Flex, Ext, RSF, LSF and rotation, while 33% (*n* = 5) measured only SF and rotation. Moreover, one respondent measured only rotation, and one did not specify which ranges of movement were measured. One Premiership physiotherapist also reported measuring the quadrant of Ext with SF (Figure 3.9).

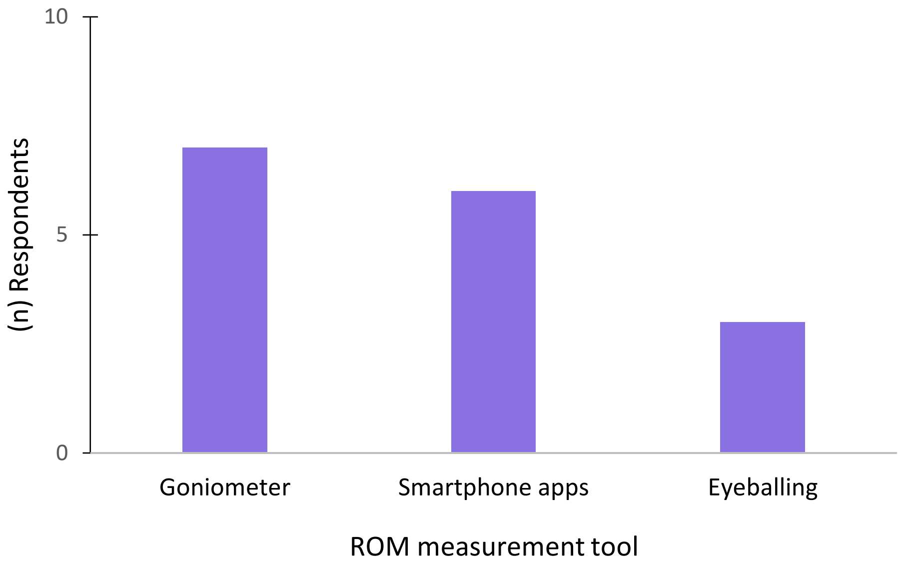


Figure 3.8 Tools used to measure range of movement (ROM) (Q13a)

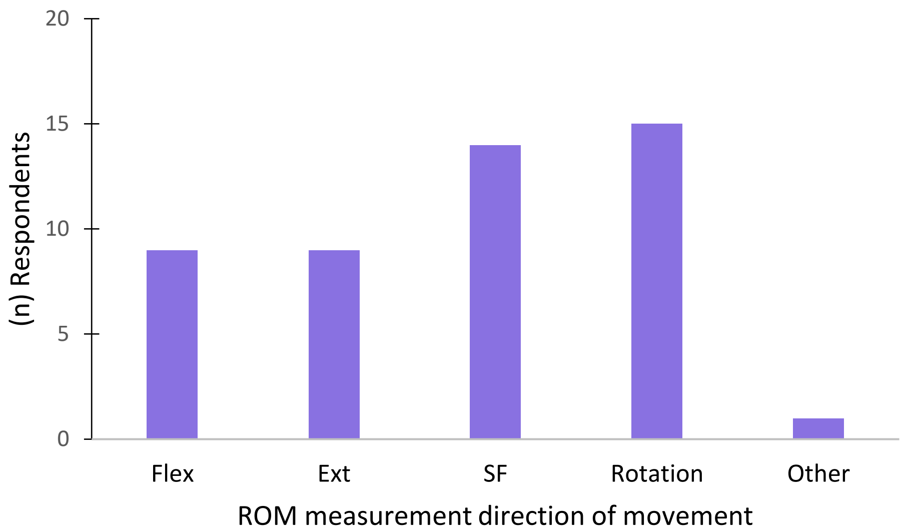


Figure 3.9 Movement directions measured for range of movement (ROM) (Q13d)
(Flex = flexion; Ext = extension; SF = side flexion)

3.3.2.2.2 Strength measurements (Q14)

Question 14 was related to cervical spine strength measurement, asking who recorded measurements of cervical strength, what strength measurements were recorded, what equipment was used and how the tests were performed.

Of the 36 respondents, 53% (n = 19) stated that strength was measured in their players. Measurement practices varied across the respondent groups: all the Premiership physiotherapists (n = 9), one Premiership S&C, two of the four respondents working for Championship clubs, two of the four National League 1 club respondents and four physiotherapists working at academy level reported measuring strength. All 19 respondents measured Flex and Ext, 18 also measured SF, ten measured rotation, five measured deep neck flexors (DNF) and four combined movements, with no one measuring suboccipital extensors (SOE) (Figure 3.10).

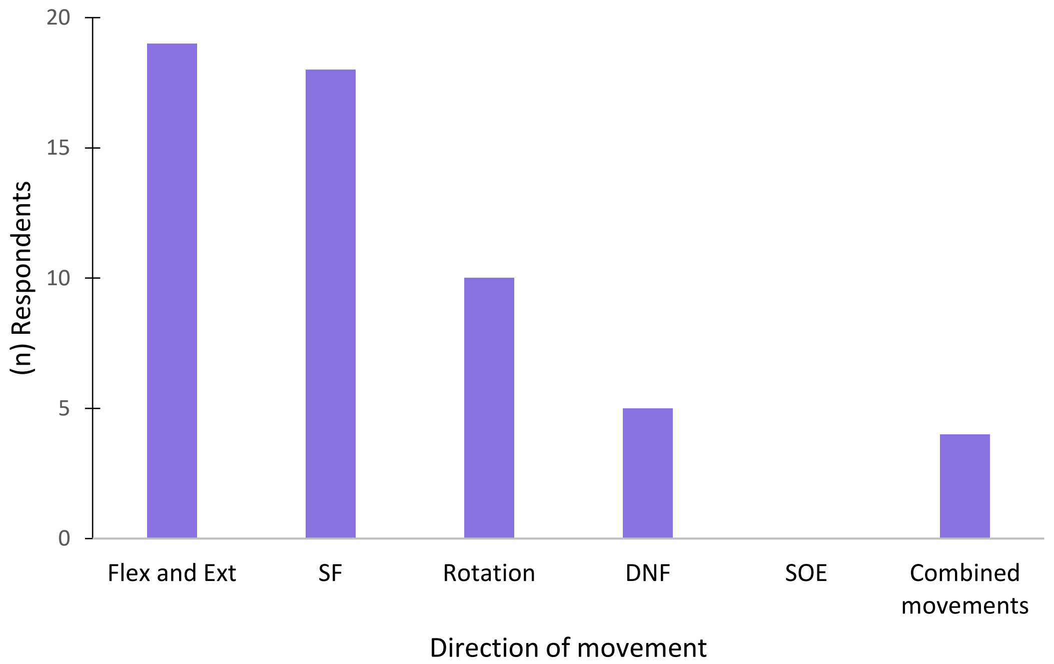


Figure 3.10 Direction of neck strength measurements taken by respondents (Q14a)
(Flex and Ext = flexion and extension; SF = side flexion; DNF = deep neck flexors; SOE = suboccipital extensors)

Of the 19 respondents, 84% (n = 16) used isometric dynamometry to measure strength, one a Keiser load cell, one a harness and weight measures utilising the maximal voluntary contraction achieved against a measured weight stack in the gym and one used the Oxford scale to quantify the strength. When exploring the type of dynamometry used, 63% (n = 10) respondents reported using the Gatherer system (Chatillon DG series SS-DG-0210) (break test), 38% (*n* = 6) used an HHD (make test) – and, of these, two used the Lafayette dynamometer, two used the Hogan microFET 2 and two did not specify the model used.

Of those 19 respondents who reported measuring strength, 58% (*n* = 11) also measured endurance capacity. However, none reported using pressure biofeedback units to explore DNF muscles with the cranio-cervical flexion test, though one described their protocol as being DNF holds and neck side-plank holds. Eight respondents stated that they used the Gatherer system, but with varying methodologies, reported as follows (as written):

"50% weight over 30s"

"flexion only, 50% MVC, props only"

"Flexion 30% peak"

"50% of MVC in flexion and extension maximum hold at 50%"

"2 min hold on pulls machine with head harness"

"50% of max strength iso hold"

"time to fatigue – half as endurance marker"

Two of the 19 respondents measured neck girth, one on all players and one on front-row players only.

3.3.2.2.3 Proprioception measurements (Q15)

Proprioception was reported to be measured by 14% (*n* = 5) of respondents (four Premiership physiotherapists and one Championship S&C coach). All used laser pens for this measurement. One measured the time taken to complete a set course, and the remaining respondents used a relocation test to measure head-repositioning error.

3.3.2.2.4 Neurological measurements (Q16)

Neurological sensitivity was measured by 8% (n = 3) of respondents. One respondent reported using surface electromyography (sEMG), another used dermatome and myotome testing along with an HHD for upper limb strength tests, and the third used two-point discrimination and light touch alongside neurodynamic testing.

3.3.3 Q17–40: Cervical spine exercise provision for professional rugby

3.3.3.1 Gym-based exercise provision (Q17–34)

This section asked respondents to report on neck exercise provision for players by position.

3.3.3.1.1 Information on gym-based exercise provision (Q17–19)

Question 17 referred to the provision of gym-based cervical spine exercise programmes and was reported by 78% (n = 28) of the respondents. No doctors answered this question. One sports rehabilitator answered the questions pertaining only to the forwards in their team, reporting that they had responsibility for these players in the gym.

Question 18 pertained to sources of information for planning neck exercise programmes, and the answers were the same as for Question 8a, which explored sources of information about neck-screening protocols (Section 3.3.2).

When asked how often the programmes were reviewed or revised (Q19), 46% (n = 13) of the respondents answered: "When pre-set objective markers had been reached". The remaining 54% (n = 15) of respondents reviewed programmes at pre-set intervals, with 57% (n = 8) reviewing between six to eight weeks, and the remaining seven respondents' answers ranged from four weeks to six months (Figure 3.11).

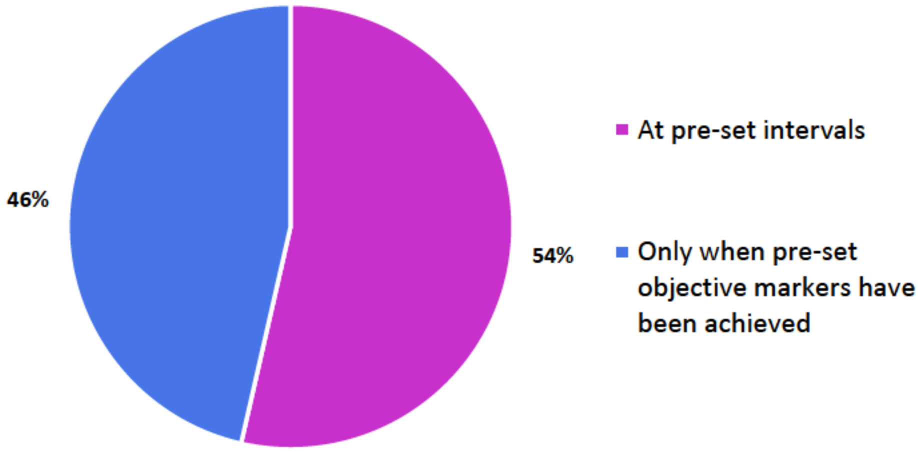


Figure 3.11 How often exercise provision is revised (Q19)

3.3.3.1.2 Gym-based exercises by player position (Q20–23)

Gym-based exercise provision by player position was explored through a series of closed questions with tick-boxes to explore which type of exercise (strength, endurance, proprioception) was undertaken (Q20) (Figure 3.12). Of the 28 respondents who declared that players performed specific neck exercises in the gym, 93% (*n* = 26) of props, 86% (*n* = 24) of hookers, 82% (*n* = 23) of second-row forwards, 79% (*n* = 22) of back-row forwards, and 75% (*n* = 21) backs engaged in complete strength training. The same trend was seen with endurance and proprioceptive exercises. However, the numbers completing these exercises were consistently lower in each of the playing positions (Figure 3.12).

One respondent stated that their "props and hookers only complete a set strengthening programme in pre-season or when injured", and another commented that the "neck exercise programme is part of the player's injury prevention strategy but it is quite repetitive and is followed/policed less aggressively".

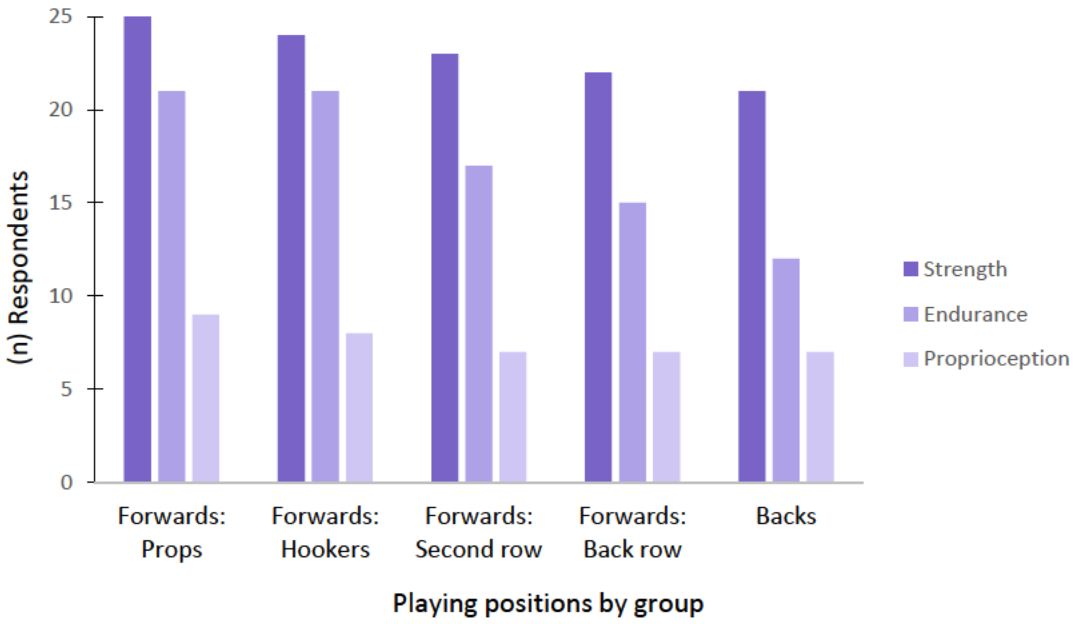


Figure 3.12 Type of exercise performed by position or positional group (Q20)

Questions 21–23 were open questions enquiring about the equipment used for neck strength exercises and proprioception exercises. A wide range of answers were given, with participants asked to list all equipment used (Figure 3.13 and Figure 3.14).

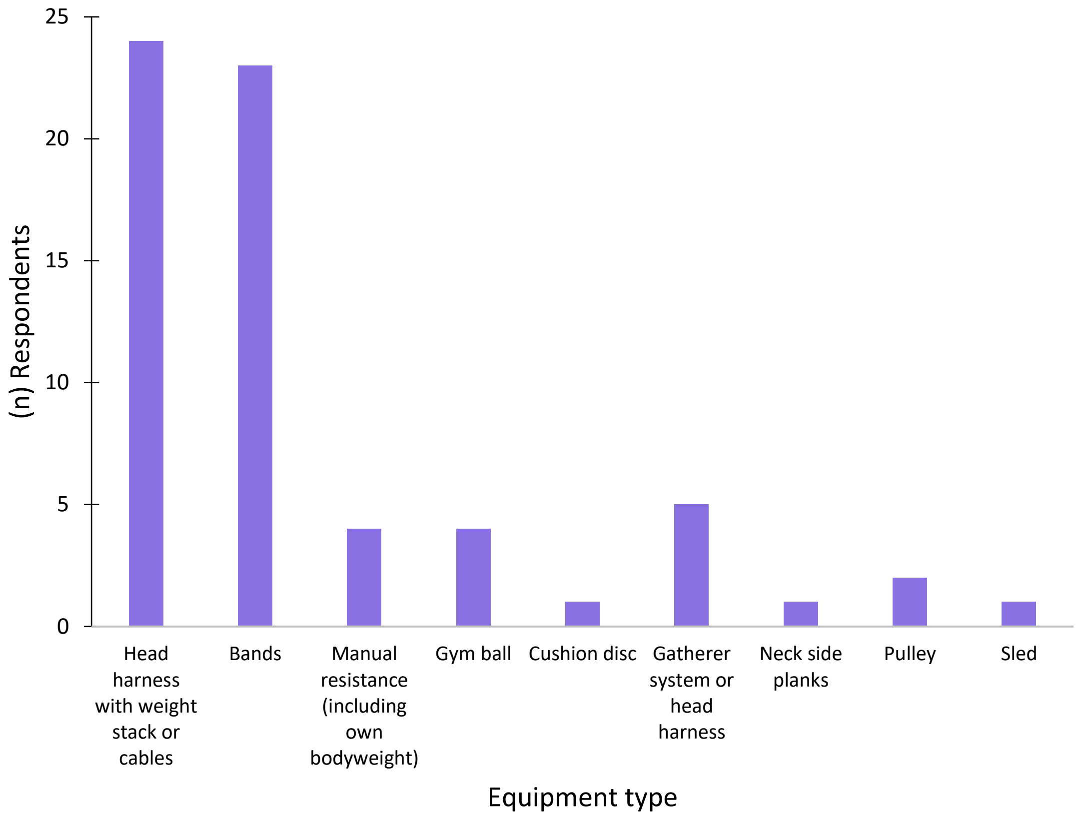


Figure 3.13 Equipment used to deliver neck strength and endurance programmes (Q21–22)

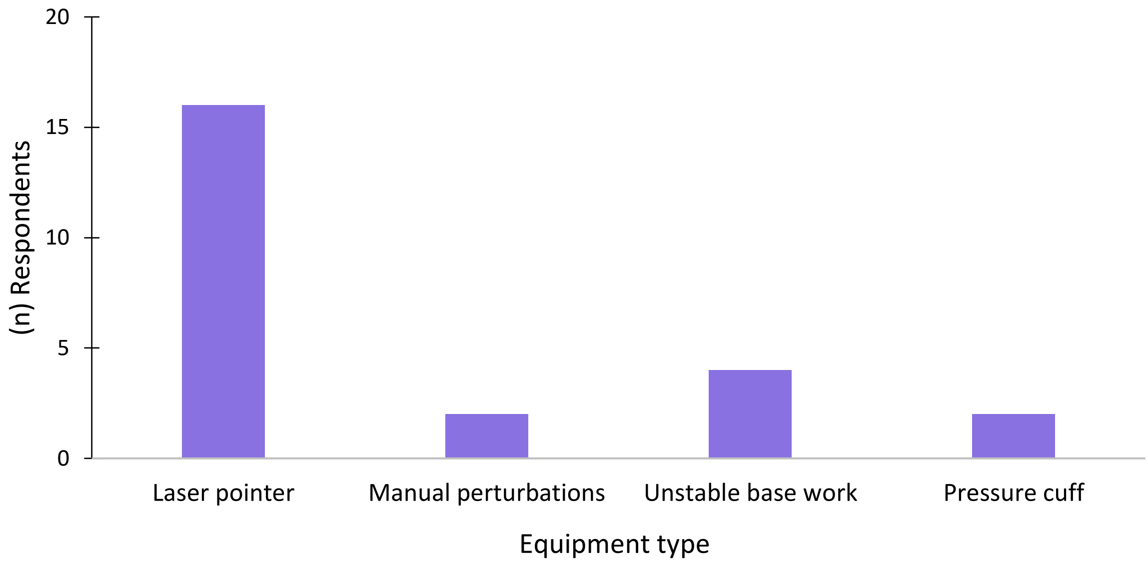


Figure 3.14 Equipment used to deliver neck proprioception programmes (Q23)

3.3.3.1.3 Frequency of exercise by player position (Q24–31)

The third section of questions were closed questions pertaining to each individual playing position, as well as to the type of strength exercise prescribed and its frequency per week during each season of gym-based cervical spine exercises undertaken by players. The responses were reported by grouping into front row (props and hookers), back-five forwards (second-row forwards and back-row forwards) and backs (scrum-half, fly-half, centres, wing and full-back), as all responses in these playing position groupings were recorded as completing the same exercises, each with the same frequency (Figure 3.15 to Figure 3.17). The most common frequency for front-row forwards (*n* = 16) was to complete isometric neck exercises regularly (once/twice per week) (Figure 3.15). Position-specific and banded exercises were also common exercises for this group of players to perform regularly (*n* = 13). Flexibility (*n* = 6) and proprioceptive (*n* = 3) exercises were the least reported exercise types performed regularly by front-row players. The back-five forwards demonstrated a similar pattern of exercise type, but with fewer numbers (*n* = 12) completing isometric, position-specific neck exercises regularly (Figure 3.16). The backs displayed a similar pattern to the back-five forwards, but again with fewer numbers reported as completing neck exercises regularly, with isometric exercises reported as the most popular exercise type regularly undertaken (*n* = 11). However, only four of these were reported as being position-specific exercises (Figure 3.17). Flexibility, dynamic stability, reactive strength and proprioceptive exercises were all more commonly practised occasionally (for the purpose of rehabilitation) rather than as regular exercise types for all playing groups.

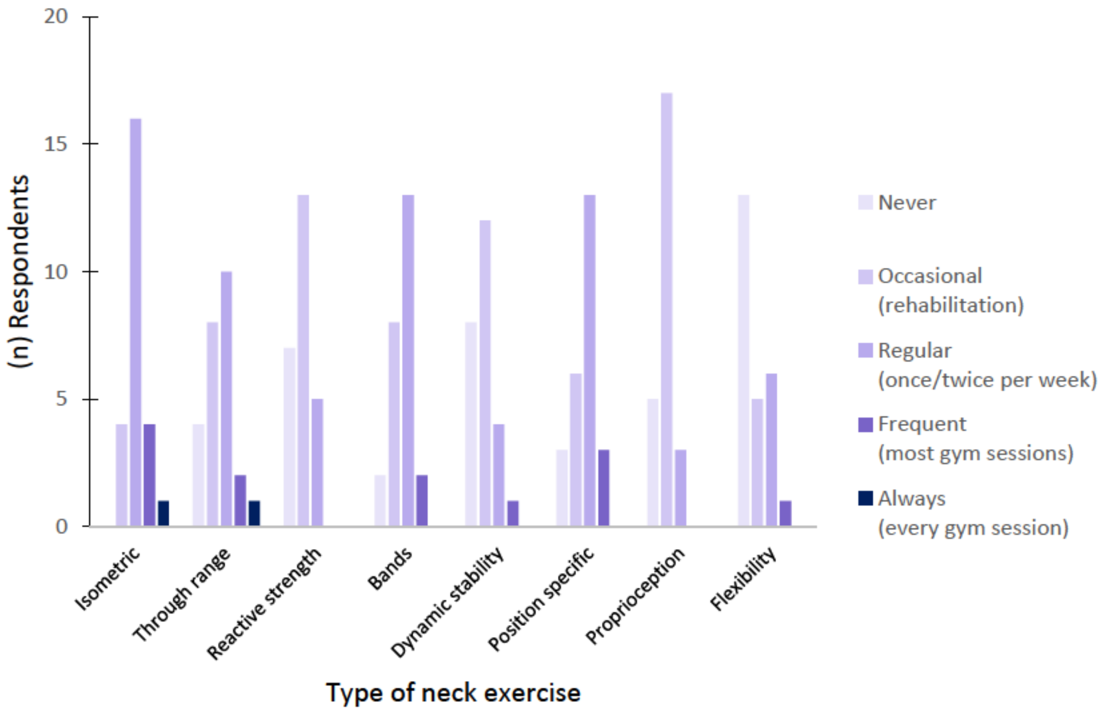


Figure 3.15 Frequency of exercises performed in season: front-row forwards (*n* = 25) (Q24–25)

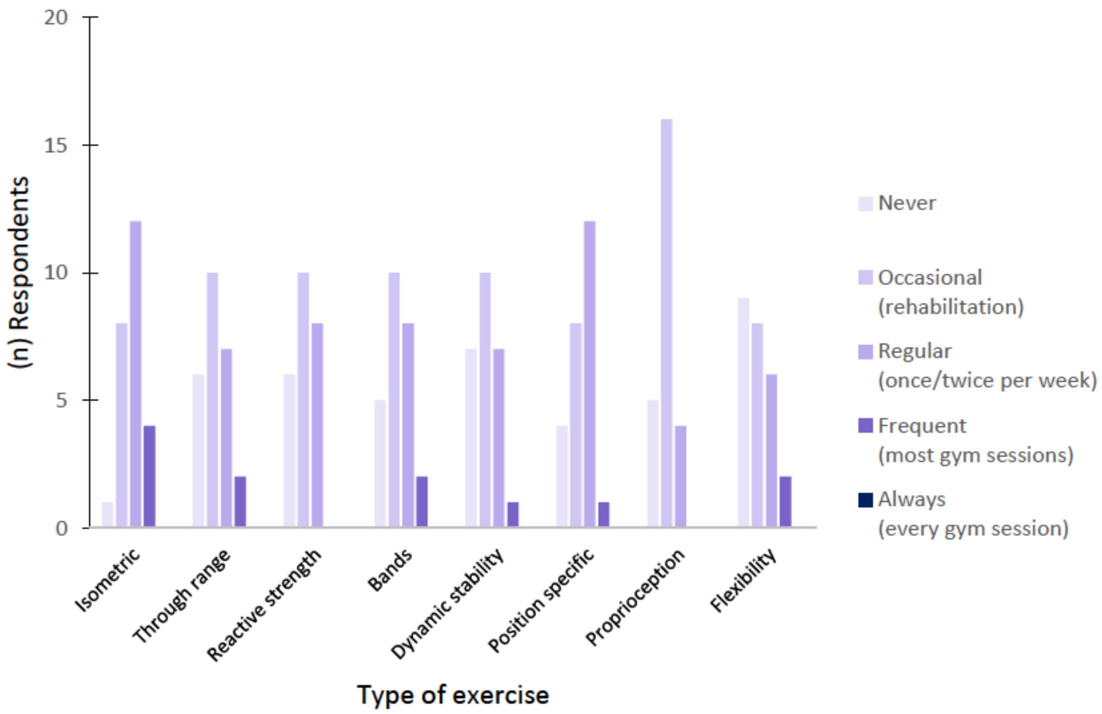


Figure 3.16 Frequency of exercise performed in season: back-five forwards (*n* = 25) (Q26–27)

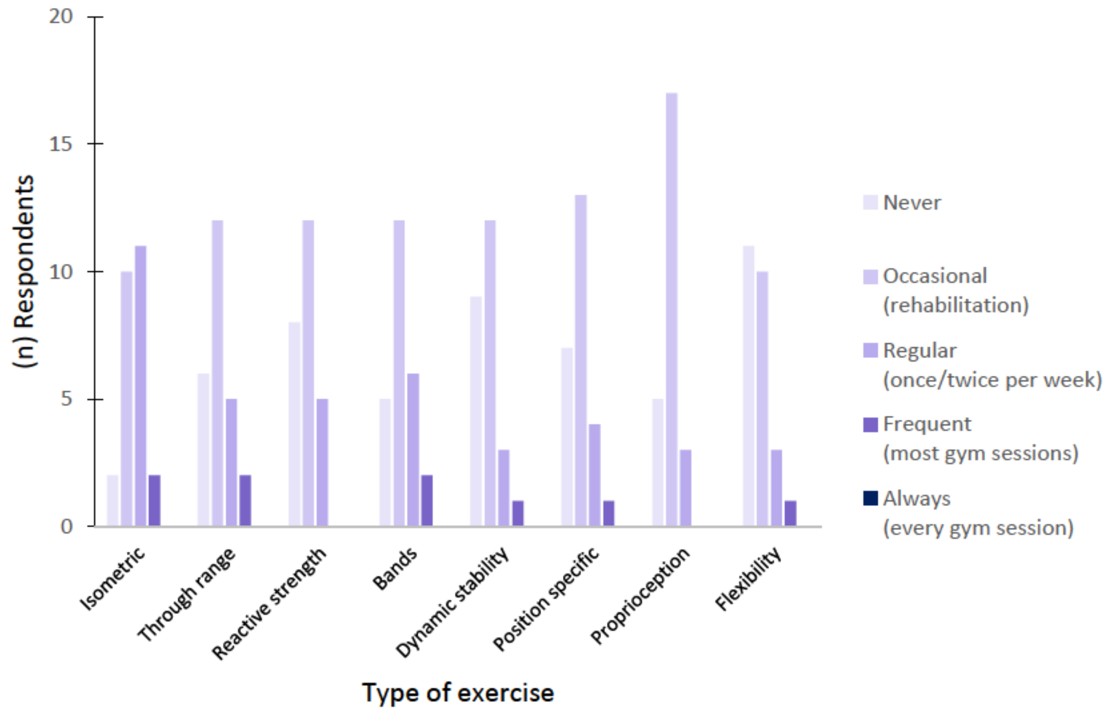


Figure 3.17 Frequency of exercise performed in season: backs (*n* = 25) (Q28–31)

3.3.3.1.4 Isometric strength, proprioceptive and other cervical spine exercises (Q32–34)

Questions 32–34 were closed, tick-box questions asking for details regarding the protocols for the isometric strength exercises, the global directional-through-range exercises and the proprioceptive exercises undertaken by playing position. Respondents could tick as many boxes as applied to their players' exercises. Responses to Question 32 showed that of the 25 respondents delivering isometric strength exercises, 48% (*n* = 12) prescribed maximal holds to breaking point; 44% (*n* = 11) reported that their players performed low-load isometric holds defined as endurance for a set length of hold; 40% (*n* = 10) prescribed global holds (direction driven); and 24% (*n* = 6) prescribed segmental DNF and SOE exercises. Nine respondents prescribed isometric holds in the sagittal and frontal planes (Flex, Ext and SF), five also worked into left and right rotation and three prescribed protraction and retraction exercises.

Question 33 requested details of protocols used for proprioceptive training. Of 22 respondents, 14% (*n* = 3) reported use of pre-set software on the GSA Analyser™ equipment, 73% (*n* = 16) reported use of a laser pen when returning the head to neutral, 50% (*n* = 11) reported use of the laser pen when returning the head to pre-set positions, 27% (*n* = 6) used rhythmic stabilisations, 41% (*n* = 9) used eyes-closed return to neutral and 27% (*n* = 6) used eyes-closed return to pre-set positions. One respondent claimed to use a “Position relevant to stress imposed in scrum position” (Q34).

3.3.3.2 Field-based provision of exercises (Q35–40)

Question 35 was a closed question about provision of field-based, pre-training or pre-match neck “prehabilitation” (pre-event warm-up) exercises. Eleven respondents (31% of the sample) reported using these exercises.

Question 36 revealed that sources of information to inform field-based exercises were mainly written sources: journal articles (*n* = 6) and books (*n* = 2). Other sources of information noted were other colleagues (*n* = 3), as well as clinical experience (*n* = 1). One respondent commented that as there were no specific protocols to be found targeting the cervical spine, they applied knowledge from research on general S&C principles.

Question 37 requested information on how often exercises were reviewed. Nine respondents answered this question, all stating that exercises were reviewed at pre-set intervals. Only two stated what those intervals were: one reported four weeks, the other six to eight weeks.

In response to Question 38, which explored the provision of specific field-based neck preparation exercises for various training activities that occur, eight respondents stated that front-row players undertook specific neck exercises prior to units sessions (scrummaging and line-out practice). Six of these were Premiership physiotherapists, one Championship and one National League 1, with four respondents answering that back-five forwards also completed these warm-up exercises. Prior to skills training sessions, only one Premiership respondent replied that all their forwards completed neck warm-up exercises. Prior to both a full contact rugby training session and a match, two respondents (one Premiership and one National League 1) stated that all the forwards completed a set of on-field neck exercises, and one (Premiership) stated that the front-row forwards were the only players who did. Prior to a skills session (practising set-pieces or tactical skills as a team, with little passage of play and not full-contact), one Premiership respondent stated that all their forwards would complete a neck exercise protocol. No respondents reported that any of the backs completed on-field neck exercise prior to matches, and one Premiership respondent reported that backs completed neck exercises prior to rugby training.

Question 39 was an open question for the respondents to describe the type of field-based prehabilitation exercises undertaken. All nine respondents reported players practising isometric holds (partner-resisted, band-resisted and static cable holds). Eight reported band-resisted exercises, and five mentioned scrum holds for the forwards. Swiss ball, neck bridge and DNF holds using a pressure biofeedback unit were mentioned by one each.

Two respondents reported that their players perform recovery-specific exercises for the cervical spine (Q40), which they described as cervical mobility exercises. Both were academy physiotherapist respondents.

3.3.4 Q41–42: Further comments

3.3.4.1 Perceived importance for exercise prescription (Q41)

The penultimate question (Q41) was designed to determine the perceived importance rating of various reasons for which neck exercises were prescribed. Injury prevention was rated as being of high importance by 86% (*n* = 31), with 11% (*n* = 4) stating it was of moderate importance and 3% (*n* = 1) perceiving it as being of low importance.

A similar pattern was found for strength optimisation, which was rated as of high importance by 64% (*n* = 23) of respondents, of moderate importance by 33% (*n* = 12) and of low importance by 3% (*n* = 1).

Performance enhancement was rated the next most highly desired outcome from neck exercises, followed in descending order by proprioception, pain control and, finally, flexibility optimisation (Figure 3.18).

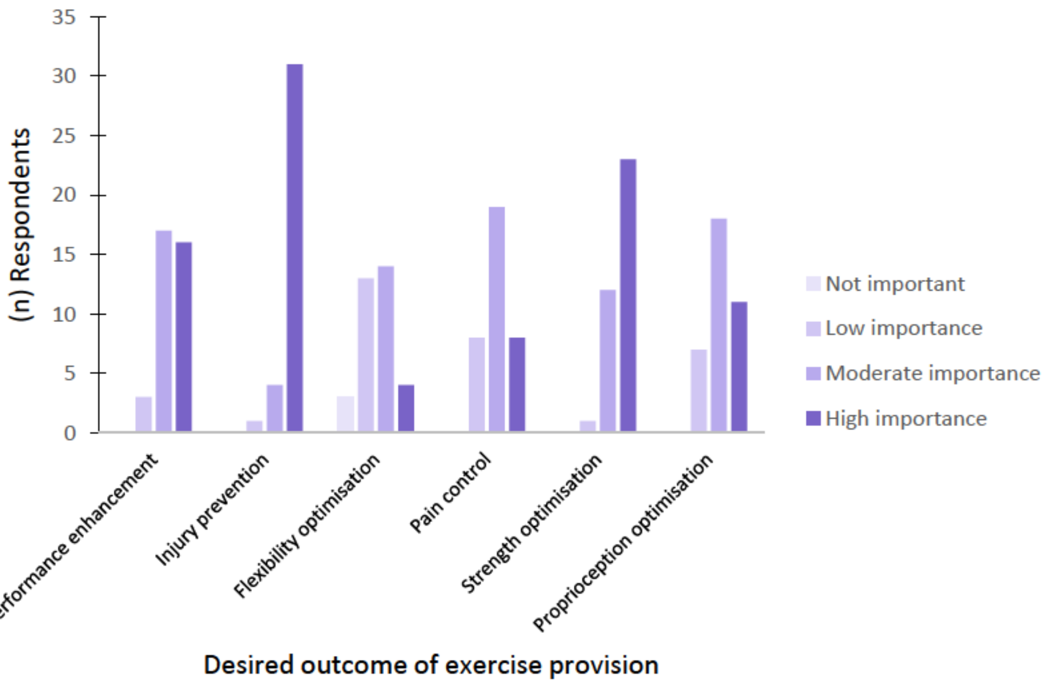


Figure 3.18 Importance rating for the provision of exercise (Q41)

3.3.4.2 Further information (Q42)

Question 42 was an open question that invited respondents to give any additional information that they had not yet had the opportunity to report on and which may help to inform the study. Responses were as follows (all as written):

National League One physiotherapist: “I am not directly involved in the prescription of specific exercises, but liaise with the S&C team regarding the types / aims of cervical spine exercise I would like included in the players' conditioning programmes.”

Premiership academy physiotherapist: “My role doesn't encompass a great of deal of screening or assessment of cervical mobility/strength/proprioception/neurological testing unfortunately, but will involve it as part of a rehabilitative process with the age group I work with.”

Premiership senior team physiotherapist: “Provision of cx management for large squads is hard. This needs to run alongside other injury prevention strategies, s and c and training. It can be hard to get ‘buy in’ from players as its monotonous relative to other parts of their day. The clubs strategy has been to build sessions of mobility and body protection into their week.

Premiership senior team physiotherapist: “Buy in from players mixed - many struggle to add additional load (i.e. specific strength training) to load demands of training (e.g. unit sessions). I feel our club do not have/use sufficient objective markers for proprioception. Re-screening in season rarely implemented - only if player has injury.”

Premiership senior team S&C coach: “As mentioned, our neck program is typically flexion holds and extension hold during upper body weights. At the end of upper body weights is some functional scrum specific work. On our whole-body weights day most forwards do static side holds. Some players do some pre-game also. Majority of forwards do this work, more so the front row. A few backs will also do it, mainly if they have had previous injury. I believe there is a performance aspect to it also especially from a scrum perspective."

3.3.4.3 Supplementary question

The higher response rate from physiotherapists led to a supplementary question being distributed post-analysis of the original questionnaire to the 12 Premiership clubs. This question asked respondents to indicate who at their club prescribed and administered neck strength programmes for the players. Seven responses were received, with two clubs stating that their S&C coach took this role, and the other five clubs all commenting that it was a joint approach shared between the physiotherapist and the S&C coach. One club added that their scrum coach also prescribed specific neck exercises for the front row.

3.4 Discussion

3.4.1 Overview

This study aimed to establish the practices employed in the assessment and management of the neck in the professional and semi-professional rugby community. It was further intended to explore the provision of neck strength exercises with regard to the individual playing positions. Practitioners involved in neck screening and exercise provision from a representative sample of sports science and medicine personnel at international, Premiership, Championship and National League 1 teams and academies were surveyed via an online questionnaire. Results from a subsample of 86% (36 of the 42) of returned questionnaires suggested that there is little consistency in approach to either the measurement practices (for neck strength, range of motion, proprioception and neurological testing) and subsequent exercise prescription. This reflects the lack of consistency in approach to these practices found in the review of the academic literature (see Section 3.1.1). The results therefore revealed a disjunct at two levels, resulting from a lack of knowledge surrounding neck strengthening: firstly, a complete absence of a set of objective markers for use as a baseline for exercise prescription; and secondly, a broad lack of consistency in the exercises performed by players across clubs and between different playing positions.

3.4.2 Issues of responsibility

Analysis of the professions of all 42 respondents to the questionnaire revealed that physiotherapists (67%) represented the largest group, followed by S&C coaches (14%), with doctors, sports rehabilitators/sports therapists and athletic trainers making up the remaining 19% of respondents. This representation from the various professions invited further analysis due to the accepted roles that physiotherapists and S&C coaches play at the elite level of sporting teams. Traditionally, physiotherapists work predominantly with injured players, and S&C coaches work daily with non-injured players, both in the gym and on-pitch, to further enhance their power, strength and speed (Buckner et al., 2016).

The higher response rate from physiotherapists led to a supplementary question being distributed post-analysis of the original questionnaire to the 12 Premiership clubs which asked respondents to indicate who at their club prescribed and administered neck strength programmes for the players, because from this group of respondents, only one was a S&C coach. It was originally hypothesised that the questionnaire had perhaps only been distributed to the physiotherapists as the author and person requesting the information was a physiotherapist. However, the secondary responses revealed that it was the physiotherapists who most commonly were involved with prescribing and administering neck exercises (see Section 3.3.4.3).

While the roles of S&C coach and physiotherapist overlap considerably in the world of elite sport, it is unusual that the physiotherapist would be involved in the day-to-day prescription of performance-enhancing exercise programmes in such a setting – yet these responses would seem to indicate that this is the case, at least with regard to the neck (Bolling et al., 2020; Downes & Collins, 2021). Literature pertaining to the provision of neck-strengthening exercises relates predominantly to those prescribed in the prevention of injuries and for the treatment of neck pain or mechanical disorders (Chavarro-Nieto et al., 2021; Cooney et al., 2022; Gillies et al., 2022; Hamilton & Gatherer, 2014; Naish et al., 2013; Peek, 2022), potentially explaining why this delivery falls under the remit of the physiotherapists rather than the S&C team. As an initial finding, this opens a debate around why S&C coaches at the elite level of rugby are not more involved in the provision of neck exercises.

3.4.3 Cervical spine screening: range-of-motion, strength, proprioception and neurological testing

All of the Premiership, Championship and National League 1 physiotherapists – 53% (n = 19) of the sample – who responded to the questionnaire screened their players' necks at the very least annually (pre-season). However, only seven of these followed this up with regular re-screening mid-season, and only three of those were Premiership physiotherapists; three re-screened at the end of the season, with only one of those being a Premiership physiotherapist. The conclusion that can be drawn from these findings was that the most useful value of screening was not the assessment of the health of the neck throughout the season, but rather in relation to injury. Results showed that 74% of respondents re-screen post-injury, 63% of those then re-screen pre-RTT, and 58% pre-RTP.

The penultimate question (Q41, Section 3.3.4.1) was asked to ascertain the perceived importance of managing neck health for rugby players through screening and the provision of exercises. Injury prevention was rated as of high importance by 86% of the respondents, which aligns with the findings from elsewhere in the questionnaire regarding the predominant use of screening data as a baseline measure which is followed up as a post-injury and pre-RTT and pre-RTP objective marker (see Figure 3.7). Taken in conjunction with the findings from Salmon et al. (2018), which concluded that neck strength measurements change over a season of rugby regardless of training programme, this suggests that taking only a single measurement pre-season might be misleading if used as the baseline figure in the second half of a season.

3.4.3.1 Range-of-motion screening

AROM of the neck was commonly assessed by 42% of respondents: 14 physiotherapists and one sports therapist, but not by any S&C coaches or doctors. Validated tools such as the CROM™ and universal goniometers were used by 47% of those respondents (n = 7), with the remaining respondents using smartphone applications or internal gyroscopes/tiltmeters (n = 6), and three respondents also sometimes simply using "eyeball" measurements.

In a study by Franko and Tirrell (2012), findings indicated that the use of smartphones for recording simple objective outcome measurements by the medical community was widespread, with 56% of those medical practitioners surveyed reported using application technology for clinical practice on their smartphones. However, only one study has been identified which explored physiotherapists' use of smartphone inclinometers to quantify cervical spine rotation ROM (Ullucci et al., 2019), and it was limited to the measurement of upper cervical spine motion. The results demonstrated excellent correlation between phones (ICC two-way mixed absolute agreement = 0.87) and testers (ICC two-way mixed absolute agreement = 0.81). That said, the experiment was conducted in a tightly controlled research facility, the two researchers were trained to doctoral level and had 40 years of experience between them. In this way, questions remain regarding the ecological validity of this method of measuring cervical spine ROM by sports practitioners in the field.

A study by Abu-Rajab et al. (2010) reported that most clinicians visually estimate ROM, but that the reliability has not been proven to be at an acceptable level for all joints, and no studies could be identified to state the reliability of this method at the cervical spine. It is somewhat surprising that only just over half of respondents did accord with clear protocols given that a loss of ROM is often a first indicator of a neck dysfunction, which should make it an outcome measure of choice for physiotherapists (Hrysomallis, 2016). Indeed, joint ROM was rated in the top three (of six) most common screening tests performed at the FIFA 2014 Football World Cup (soccer), with flexibility ranking at the top, and evaluation of muscle peak strength ranking sixth (McCall et al., 2015). Measurement of ROM does not require expensive equipment, is commonly measured in physiotherapy practice and yet in relation to rugby players there is once again a dearth of published information of expected range or the impact of the game on players' ROM (Lark & McCarthy, 2007). Therefore, it is noteworthy that only 15 of the 36 respondents involved in the present study who regularly perform neck screening chose to measure this parameter in professional rugby players in the UK.

3.4.3.2 Proprioception screening and exercise provision

With regard to neck proprioception, which correlates strongly with balance and coordination (Armstrong et al., 2008; Farley et al., 2022; Uremović et al., 2007), only five respondents (14%) reported measuring this aspect during screening, and all utilised a laser pen attached to a headband. This demonstrates methodological consistency, albeit across a very small sample of practitioners. This finding is again inconsistent with the finding that in football (soccer), proprioception testing was in the top four most common screening tests performed at the 2014 World Cup (McCall et al., 2015). Another noteworthy finding was that 16 respondents (44%) reported prescribing proprioceptive exercises occasionally (for rehabilitation), suggesting that respondents consider this aspect important in relation to injury. Due to loss of ROM (Pinsault et al., 2008) and chronic pain (Armstrong et al., 2008; Farley et al., 2022) negatively impacting proprioceptive acuity, practitioners who measure AROM should also be advised to consider measuring proprioception in order to add depth to their screening practice. As many rugby players suffer from neck pain throughout a playing season (Salmon et al., 2018), ignoring the measurement of proprioception may not only negatively affect performance but could potentially lead to more injuries (Farley et al., 2022). The reported lack of measurement therefore raises concerns about why such an important area is not being consistently attended to in rugby.

3.4.3.3 Peripheral neurological screening

Only three respondents (8%) routinely tested for neurological sensitivity, despite this test being used in rugby in conjunction with the commonly reported injury of “stingers” (see Section 2.2.4) (Sobue et al., 2018). Stingers affect the brachial plexus from either an over-stretch or compressive force to the upper quadrant (shoulder and neck) and are commonly sustained from the tackle, most specifically when the tackle is executed incorrectly (with a reported frequency of 12 per 1,000 tackles) (Sobue et al., 2018). The damage sustained to the nerve may result in long-term neurological deficit, which can have life-changing impacts including long-term neurological weakness or sensation deficits. The neurological screening findings therefore seem to conflict with reports that the respondents screen predominantly for injury prevention. This lack of engagement with procedures such as neurological and proprioceptive screening reflects a disjunct between reported and implemented practices, as well as between knowledge and its practical applications.

3.4.3.4 Neck strength screening

Several notable findings were recorded with regard to neck strength measurements (Q14b), the first being the extensive range of equipment reportedly used to quantify this measurement. While the majority (84%, *n* = 16) of the 19 participants who reported measuring neck strength used isometric dynamometry, the accepted “gold standard” of muscle strength measurements (Ryan et al., 2019), there were several different tools reported within this category. The most common tool employed (63%, *n* = 10) was the Gatherer system (Chatillon DG series SS-DG-0210). However, only one (Premiership) club had access to their own piece of this equipment, with the other respondents reportedly used the equipment belonging to the RFU, which was available to them annually during pre-season. This equipment utilises a break test method whereby the player must resist the pull until they cannot hold it any longer (Hamilton et al., 2010). This renders its use limited to players with no pain, which – alongside the lack of full-season access to this equipment – severely limited its use in RTT/RTP, post-injury situations and may explain why more measurements were taken pre-season (Figure 3.7) than at any other time throughout the season.

The remaining six respondents (37%) who used isometric dynamometry described a using variety of HHDs to conduct both make and break tests, which while relatively inexpensive and portable have yet to establish a universally accepted method for use within the sporting context for measuring neck strength (Peek, 2022; Stark et al., 2011). The remaining three respondents (19%) used their own methods: one took a subjective measurement against manual resistance; one utilised a Keiser load cell, which has no reliability test results published for neck strength measurements; and one used a voluntary hold against a known-weight stack. This latter technique was not described in detail; and while versions of this method have been reported in the literature, the cable has always been attached to a load cell in these contexts for accurate and safe measurement, rather than directly to a weight stack (Chavarro-Nieto et al., 2021; Krause et al., 2019). Overall, the range of equipment and approaches taken is starkly varied, even in this professional setting.

Muscle endurance strength was reported to be measured by 58% (*n* = 11) of the respondents. Despite there being a protocol published for measuring neck endurance by Lourenco et al. (2016), which involved measuring endurance of DNFs and which identified a minimal detectable change of 19.15 seconds, the survey responses indicate that every method described was different and unsubstantiated by evidence (see Section 3.3.2.2.2). This is an aspect of strength that requires exploration most specifically in relation to the scrum set piece play. The 2014 changes in the scrum laws from “crouch–touch–set” to “crouch–bind–set” (Cazzola et al., 2015) require players to hold a static neck Ext position against a load (in the case of the front row, against the variable load imposed by the opposition) (Chambers et al., 2019; Green et al., 2019). One anomaly in the research data that attempts to quantify the load from scrums is that the sensors designed by Chambers et al. (2019) would not be triggered to reflect a scrum until the horizontal position had been held for more than four seconds, which is in conflict with the information provided by Quarrie et al. (2017) suggesting that scrums take an average of 3 ± 1.4 s across 20–30 scrums per match. This confusion within the research is reflected by the variety of answers to the survey reported here (see Section 3.3.2.2.2). Therefore, if this measurement of strength is not reflected in the screening, there is a gap in knowledge about players' ability to withstand the load imposed by the game situation, as well as a lack of objective markers to measure the effectiveness and efficiency of neck strength programmes. Normal practice would be to plan exercise provision across the season (periodisation), moving between periods of relatively lower or higher intensity of gym-based training in order not to overload players during higher-intensity match periods (Tee et al., 2018). In light of periodisation, the singular annual pre-season neck strength measurement practice reported does not align with the standardised need for practices of continuous measurement across phases that inform the progression or regression of exercises (Tee et al., 2018). Given the high level of professionalism within this setting, one explanation for the reported lack of clarity is that there is a notable dearth of readily available knowledge, information or equipment to consistently measure neck strength. When screening of the neck does occur, the main source of information regarding the design of protocols was reported to be journal articles, and respondents suggested that this information is predominantly reviewed either annually or when new information became available (see Figure 3.6). However, only one respondent named published literature as the source of their information, and the three articles quoted (Geary et al., 2014; Hamilton & Gatherer, 2014; Naish et al., 2013) are all related to neck strength exercise provision. Moreover, while not having the same study populations as the adult elite team that said respondent works with, these studies did all use the same equipment (Chatillon DG Series SSS-DG-0210) as the respondent used for measuring neck strength.

Neck screening, including measurements of strength, ROM, proprioception and neurological status, therefore emerges as an area of particular ambiguity in rugby contexts, even among the most highly skilled professionals. If reliable normative data collected using a commercially available tool for assessment were available for practitioners to access, practitioners would have reference values that they could trust and against which they could compare their own data. Similarly, if practitioners use make tests and compare their data against published values for break tests, they will not be comparing like with like (Chavarro-Nieto et al., 2021; Chavarro-Nieto et al., 2023b), in turn confounding their understanding of their players' strength values in relation to published values. The plurality of methods, both of protocols and equipment cited in the questionnaire for measuring neck strength (see Section 3.3.2.2.2), clearly demonstrates a lack of consistency in measurement approach across practitioners and playing levels.

In addition, the dissemination and translation of research findings into clinical practice has been recognised as a difficult and a slow process (Owoeye et al., 2020). However, if there was more research which reflected real-world experience and which generated data that was simple to interpret, consistent practice with regard to neck screening in rugby could be facilitated.

3.4.4 Gym-based exercise provision by position

3.4.4.1 Rationale for neck-strengthening exercises

Analysis of the importance ratings given for providing neck exercises to rugby players (Figure 3.18) concluded that respondents considered injury prevention to be by far the strongest motivator, with 86% (*n* = 31) stating it had high importance. This was followed in importance by strength optimisation (64%, *n* = 23) and performance enhancement (44%, *n* = 16). This was expected, as the results of the present study confirm that it is predominantly physiotherapists who are responsible at professional English rugby clubs for the administration of neck care and, on the whole, while they aim for performance enhancement, their main remit is injury prevention and management (Bolling et al., 2018; Bolling et al., 2020). As this section of the survey questioned respondents about neck-strengthening practice for fit and healthy players rather than post-injury rehabilitation, the fact that it was predominantly physiotherapists who answered the questionnaire and responded to the questions around the provision of neck-strengthening exercises was surprising. The supplementary follow-up question, sent to ascertain if there was selection bias in the sample (see Section 3.4.2), confirmed that physiotherapists were the profession responsible for the provision of neck strength exercises at Premiership level. Therefore, as with the neck-screening practices, this finding augments the ongoing theme of confusion regarding remit and practice around neck healthcare in rugby.

3.4.4.2 Neck exercise provision

The results demonstrated a positional difference with regard to the types of exercises performed by players in different playing positions, which is consistent with knowledge that different playing positions perform different tasks on the field (Campbell et al., 2018). All front-row forwards performed isometric neck strength exercises, as reported by 26 respondents, but this was not the case for all backs or all back-five forwards (see Figure 3.12). These results conflict with the reported indication that the focus of neck strength exercises was injury prevention, as match analysis has demonstrated that tackling at speed results in the highest incidence of neck and head trauma, and that more tackles of this type – and subsequent head injury assessments – are completed by backs than front-row forwards

(Tucker et al., 2017). Although evidence is inconclusive about whether a stronger neck can reduce injury, there is a higher level of evidence suggesting that it does (Collins et al., 2014; Farley et al., 2022; Peek, 2022; Salmon et al., 2018) than there is that it does not (Liston et al., 2023).

Regarding endurance, front-row forwards require strong necks to scrummage effectively, efficiently and safely (Cazzola et al., 2015; Cazzola et al., 2016; Holsgrove et al., 2015), and this finding aligns with the survey data indicating that the majority of respondents required front-row forwards to perform neck strength endurance exercises (77%, n = 20 out of the 26 respondents whose players perform exercises in the gym). Conversely, fewer reported that their back-five forwards players (54%, n = 14) and backs (46%, n = 12) perform these exercises in the gym. Again, within the screening section of the survey, only 11 respondents reported screening for neck endurance, which raises the question of how these exercises are evaluated, assessed for effectiveness and – if appropriate – progressed. Evidence clearly shows that when neck muscles have undergone exercises to induce fatigue (isometric contraction held for 15 minutes to failure, as confirmed by surface electromyography readings) that the induced fatigue is highly correlated to loss of balance, as measured using posturography (Gosselin & Fagan, 2014). While Gosselin and Fagan's study involved rugby league players, it clearly demonstrated that postural sway velocity increased specifically when the extensor muscles of the neck had been worked to fatigue, suggesting that exercises to increase fatigue resistance would have the potential to enhance performance through maintaining good body balance, and thereby potentially reduce injury incidence (Farley et al., 2022). In this way, it is clear that endurance should be a key component of any neck strength exercise programme, and that screening should be undertaken to maximise the effectiveness of such programmes.

These survey results once again highlight the dissonance between the respondents and demonstrate that standard practices of neck exercise provision by playing position are often not linked to current evidence.

3.4.4.3 Equipment used for, and frequency of, neck strength exercise provision

There was a considerable variety of equipment reportedly used for the provision of gym-based neck strength exercises (see Figure 3.13). The largest number of respondents (n = 24) reported using a head harness and a cable stack to deliver the neck strength programme in the gym. This aligns with the findings of two of the four studies published describing the prescription of neck exercises for rugby players (Gillies et al., 2022; Naish et al., 2013). This approach gives the players the ability to strengthen muscles either isometrically or isotonically, concentrically or eccentrically, and using a quantifiable load. However, the two studies that have been performed using this technique both prescribed the exercises two or three times a week for between five and twelve weeks for research purposes, but this did not lead to an observed increase in neck strength in all trained directions by the end of the programmes (Gillies et al., 2022; Naish et al., 2013). There was a large variation in the answers within this study as to how many times a week neck strength exercises were performed in the gym (Figure 3.15 to Figure 3.17), and this differed by playing position. Isometric exercises were the most commonly performed type of exercise for all players, with the front-row forwards (n = 16), back-five forwards (n = 12) and backs (n = 11) performing the exercises regularly (once/twice per week). In the published researched, only the study by Naish et al. (2013) described prescribing different exercises by position, whereby exercises for the front-row forwards were performed in a modified scrum position (Figure 3.1). The reportedly high use of banded exercises (n = 23), which are difficult to quantify in relation to load and therefore difficult to progress or regress according to need, could be explained by how easy these exercises are to set up and perform. There is one published article investigating neck strength exercises for rugby players that used bands for concentric exercise provision through range (Maconi et al., 2016). However, if neck muscle hypertrophy is the aim, which is related to the time that the muscle is under tension, banded exercises are unable to afford the calculations of load required to achieve this outcome. A small number of responses mentioned seven other pieces of equipment (see Figure 3.13) used for delivering strength exercises, despite there being no current research to support these choices. Further research is therefore required to explore such novel neck-strengthening techniques. Data extracted from the subjective comments made by the physiotherapists about how difficult it is to maintain player compliance when undertaking neck exercises perceived as boring, especially those for which gains are not as obvious as they appear to be for other body areas, might go some way towards explaining this lack of compliance and general interest in neck measurements and exercises.

3.4.5 Field-based provision of exercises

Prior to rugby training sessions and matches, extensive and well-documented warm-up practices are reported by Attwood et al. (Attwood et al., 2018) as being adopted based on a wealth of evidence that stipulates that a dynamic and specific warm-up practice prepares the neuromuscular system for the specific activity and therefore has a key role in reducing injury. It is notable, then, that only nine of the 36 respondents (25%) in this survey declared that their players completed preparatory work specifically tailored towards the neck prior to contact training sessions and matches. This casual approach to a well-evidenced area of injury protection again demonstrates the lack of consistency of application of theory to practice regarding the role of preparing the neck for activity at the highest professional level of the game. Eight respondents (22%) stated that front-row forwards prepare for a unit session (i.e., scrummaging sessions) and rugby training sessions, and of these eight, four also included the back-five forwards in this grouping of players who prepared their neck for training, all by completing specific isometric hold exercises. From these eight respondents, only five reported that their hookers, four props and two back-five forwards perform this preparatory work for matches. These findings demonstrate a lack of reasoned approach to completing a warm-up, which is perhaps reflected in the lack of research specific to the incorporation of neck exercise in a standard pre-match warm-up. No backs were reported to perform neck warm-up exercises prior to training or matches, despite the fact that more neck injuries are caused by tackling than in set-pieces such as scrums (Kuster et al., 2012). This again highlights the disconnect between the physiotherapists, whose remit traditionally involves the provision of neck exercises but not that of warm-ups performed prior to training and matches, which instead tends to be under the auspices of S&C staff, who work with the rugby coaches to develop warm-up drills (Bolling et al., 2020; Campbell et al., 2018).

3.4.6 Limitations

As the analysis shows, this survey has provided a range of useful information regarding current clinical practices in English professional and semi-professional rugby clubs. Given the lack of pre-existing, validated questionnaire formats pertaining specifically to neck health, the survey was designed specifically to answer the research questions underpinning the project. In this way, the survey might best be viewed as a scoping review to determine the current state-of-play as opposed to a rigid measure intended to be replicated.

The survey's eligibility criteria can be regarded as a potentially limiting factor. To participate, respondents were required to be clinical leads at professional and semi-professional (men's) rugby clubs in England. Expanding these criteria (for example, inviting international participants) may have led to a greater overall number of responses. That said, given the scope of the overall research project, the eligibility criteria were deemed to be appropriate.

In an attempt to overcome issues relating to sample size for the survey, snowball sampling was selected as a means of enabling participants and gatekeepers to recruit further appropriate respondents who met the study's criteria. The survey was sent to 40 clubs, but 42 responses were received. It was therefore not possible to calculate the exact response rate (that is, the ratio between the number of individual clubs who were invited to participate and those who responded).

Moreover, anonymity was an important factor to consider in the survey's design, as it was ascertained that clubs would be far less inclined to share details of their current practices were they to be identifiable. While this was a positive factor in encouraging more (anonymised) responses from competing clubs, it was not possible to deduce whether there were multiple responses from a single club (for example, if two or more different practitioners associated with the same team responded separately). In a similar way, as the approved ethical gatekeepers were the heads of medical services at each club, it was impossible to determine whether the surveys were distributed to multiple members of their team. However, given that inferential statistics were not the ambition of the survey's analyses, these statistical factors did not have a significant impact on the findings of the survey, instead enabling contributions from as many relevant participants as possible. That said, the snowball sampling did lead to several responses being discounted, as the survey was shared with ineligible participants (e.g. university, international or underage teams).

Future studies in this vein could require each survey respondent to list the number of practitioners contributing to a single response and to remove the need for anonymity (see, e.g., McCall et al., 2015). However, such measures have strong potential to discourage participants who are sceptical of the non-anonymity of responses.

3.5 Conclusion

The aims of this survey were to document the methods employed in professional rugby in the UK to measure neck strength and explore which exercises were currently being undertaken by those rugby players. As a result of revealing the lack of a consistent approach in any of these measures, the survey established a need to determine whether neck strength can be reliably tested using a commercially available rig with a protocol that is viable during recovery from injury as well as in full fitness.

Current publications have measured neck strength, but mostly not using commercially available equipment. Therefore, as confirmed by the survey, there is no consistent best practice for practitioners to follow. Consequently, the practice is not consistent for players across rugby clubs but is rather predicated on the knowledge of individual practitioners, meaning that there is little consistency for players. The difficulty with this situation is threefold. First, the practitioners who measure and prescribe strength exercises are not able to use a standardised set of protocols to inform best practice, making the practice uncertain and not player-centred. Second, the players have no baseline measurements that can be used to determine when the academy players are strong enough to compete with the senior team;

and, following injury, there is no set protocol based on objective findings used to determine RTT and RTP safety. Third, the development of sound practices for strengthening and determining the most efficient and effective way to improve neck strength are not being developed due to an inability of the professionals involved in the exercise provision to access a reliable or valid method for measuring progress.

The investigation described in this chapter was initially intended to be the first step in an exploratory, cumulative research design which would have led to a Delphi study to gain consensus for neck-strengthening exercises to be trialled across professional rugby clubs in the UK. However, the findings demonstrated a pressing need to first establish an acceptable piece of equipment and protocol for measuring neck strength, without which objective records of neck strength would not be possible.

Chapter 4: Intra- and inter-rater reliability of a novel isometric test of neck strength

4.1 Context

4.1.1 Declaration

A version of this chapter has previously been published: McBride L., James R.S., Alsop S. and Oxford S.W. (2023). Intra and inter-rater reliability of a novel isometric test of neck strength. *Sports 11*(1), 2 (McBride et al., 2022; Appendix 2; see also Appendices 3 and 7).

4.1.2 Findings from survey of practitioners

The previous chapter (Chapter 3) surveyed practitioners working in professional rugby union to establish the state of current practice regarding the measurement of cervical spine strength in players for the purposes of screening and exercise provision, and to provide insight into practitioners' understanding of best practice in this area. It was discovered that while there is a desire to measure neck strength, measurement practices were inconsistent, and a gap in knowledge regarding the available evidence was revealed. A variety of tools and protocols for measuring neck strength were described by respondents, demonstrating that no consistent approach to recording baseline neck strength data is currently being implemented in practice. Objective markers are required in the determination of players' recovery from injury, including the production of normative values to inform decisions regarding injury prevention and evaluation of the effectiveness of the provision of exercises designed to improve neck strength.

4.1.3 Measurement of muscle strength

The measurement of muscle strength, defined as the ability to produce force against a resistance (Stone, 1993), has been recognised as an important marker of an athlete's ability to be resilient within their chosen sport, especially in relation to injuries sustained and post-injury recovery (Versteegh et al., 2015).

In order to monitor and evaluate training programmes, predict injury risk and enhance performance, the measurement of muscle strength has become commonplace in sport generally (Brady et al., 2020). An athlete's ability to generate maximal force can be evaluated using either dynamic tests, recording the force elicited throughout the range of the muscles, or isometric tests, which record the force elicited during a static contraction at a fixed length (Beckham et al., 2013; Haff et al., 2005). If undertaking a dynamic test, the force generated can be affected by both the length of the muscle (force–length relationship) and the speed at which the test is performed (force–velocity relationship), meaning that these two variables need to be carefully controlled for a repeatable test (Hall, 2015). The increased popularity of isometric tests means that it is important to ensure the reliability of the data obtained in order for it to be used in prescribing, monitoring and adapting training programmes (Brady et al., 2020). To date, the reliability of isometric muscle strength measurements has been demonstrated in multiple anatomical regions using observational, longitudinal and test–retest methods, especially in the lower extremities (Ryan et al., 2019). Establishing the reliability of both the equipment and the protocol for measuring muscle strength is a vital issue affecting the likelihood of acceptance and adoption by practitioners.

4.1.4 Defining reliability

Reliability refers to the consistency of a test or measure (Streiner et al., 2014). A measure is considered to have high test–retest reliability if it produces comparable results under consistent conditions over time (Roebroeck et al., 1993). Two attributes of reliability that can be measured are stability and equivalence (Heale & Twycross, 2015). Test–retest reliability is a measure of *stability*, which is the extent to which a test, method or instrument produces consistent results when tests are repeated with the same participants. Inter-rater reliability is a test of *equivalence*, which assesses the level of agreement between multiple testers.

Statistical tests for reliability can include measures of correlation, such as Pearson's correlation coefficient, and levels of agreement, which can be demonstrated in Bland–Altman plots. Both of these tests contribute to understanding how closely correlated results from two or more tests are. The level of agreement for this needs to be set *a priori* and based on clinical or biological goals (Giavarina, 2015). The intraclass correlation coefficient (ICC) is a commonly reported measure of reliability that incorporates both correlation and levels of agreement. It is reported as a value between 0 and 1, with the following definitions: values of <0.5 indicate poor reliability, 0.5–0.75 moderate, 0.75–0.90 good and >0.90 excellent (Koo & Li, 2016). In addition to the ICC, calculation of the coefficient of variation (CV) can contribute to the reporting of reliability, as it incorporates the standard deviation (SD) around the mean and shows the extent of variability within the sample data. When the CV is reported alongside the ICC, the levels of both the stability and the equivalence of the dataset can be determined (Atkinson & Nevill, 1998). Establishing and incorporating appropriate statistical analysis for reliability studies is key to the translation of research into clinical practice.

4.1.5 Measuring neck strength

Due to the perceived importance of having a strong neck to protect against injury and enhance performance, the necessity of measuring neck strength has received significant attention over the past decade (Daly et al., 2021). However, a review of the literature indicates a lack of consistent evidence supporting the techniques currently in use to assess neck strength (Hrysomallis, 2016; Selistre et al., 2021). Therefore, practitioners do not have access to a reliable method for measuring strength in this important anatomical region.

There is a clear need for the development of a uniform approach to measuring neck strength in both healthcare settings and sporting contexts (Peek, 2022). This approach requires a standardised, evidence-based protocol as well as equipment with proven reliability (Selistre et al., 2021). Current approaches to measuring neck strength can be classified by the type of equipment employed: those using mainstream, commercially available muscle strength testing equipment (in both healthcare and sports settings); and those using bespoke equipment specifically designed to measure the neck strength of sportspeople in a laboratory setting.

4.1.5.1 Mainstream neck strength dynamometry equipment

Current conventional options for measuring neck strength, as identified in the survey questionnaire of expert opinion (see Section 3.3.2.2.2) and in the existing literature (Chavarro-Nieto et al., 2021; Murray et al., 2014), include handheld dynamometers (HHDs) such as the MicroFet™ (Hoggan Health Industries), the Lafayette (Lafayette Instrument, Europe) and the Gatherer system (GSA Analyser™, Gatherer Systems, UK), as well as fixed-frame dynamometers (FFDs) such as the Multi-Cervical Unit (MCU) (BTE Technologies, Inc.™).

4.1.5.1.1 Handheld dynamometers (HHDs)

HHDs are a common choice for measuring neck strength in sporting and clinical contexts (Farley et al., 2022; Peek, 2022; Selistre et al., 2021; Versteegh et al., 2015). They provide the practitioner with a portable and affordable option for measuring maximal voluntary isometric contraction (MVIC), in four movement directions for the neck of flexion (Flex), extension (Ext), left side flexion (LSF) and right side flexion (RSF). However, the lack of consistency in methodology and testing protocols identified in the use of HHDs renders assessment repeatability difficult, and the cross-examination of normative reference values impossible (Chavarro-Nieto et al., 2021; de Koning et al., 2008). Therefore, usage and accessibility advantages are undermined by issues of reliability (Ashall et al., 2021). For example, the testing position employed in previous studies is varied, with most of the non-sporting neck strength research being performed in a seated position with the torso fixed by seat belts (Selistre et al., 2021). While this position may have specific sporting relevance (e.g. within motorsport), it does not for many sports in which neck strength is a perceived benefit. Moreover, this test position not only raises questions about the effective isolation of neck muscles due to the ability to brace against restraints during the test but also, importantly, is not transferrable to sports where many injuries occur when the body is unrestrained and either in the horizontal position or upright while running, such as in rugby.

In a systematic review of HHDs in correlation with the “gold standard” isokinetic dynamometry, Stark et al. (2011) concluded that HHDs could be considered a reliable and valid instrument for measuring muscle strength in the clinical setting. However, none of the 17 articles that met the inclusion criteria for the research involved testing on the cervical spine. Stark et al. (2011) also noted that the studies were mostly old (pre-2000) and that there was a lack of homogeneity in testing protocols between the studies, rendering a systematic review of the literature difficult to report.

The most commonly used commercially available equipment in the measurement of neck strength for professional rugby players in England (see Section 3.3.2.2.2) is the GSA Analyser™ (Gatherer Systems, UK) (Hamilton & Gatherer, 2014). Commonly referred to as the Gatherer system, this piece of equipment was developed by a physiotherapist in response to inconsistencies in measurement approaches. It utilises a test-to-failure technique (also known as a break test), whereby the subject is attached to the load cell via a head harness (Figure 4.1). The tester then applies a manual linear incremental load to the harness, which the participant resists until the force applied is greater than the participant's neck strength and the hold is in turn "broken" (Hamilton & Gatherer, 2014). In this type of test, muscles contract to overcome the resistance.

The Gatherer system is a custom-built device which has a 300 kg load cell and a bespoke software system. Reported methods of testing neck strength with this device vary, with evidence from photographs in published reports of a range of techniques used to stabilise the participant. For example, seat height is not usually specified, and participants' arm positions vary, which allows for different bracing mechanisms from participants (Davies et al., 2016; Geary et al., 2014; Hamilton et al., 2010). To date, there have been no published reliability studies with this equipment, though Hamilton et al. (2012) performed an intra-rater repeatability study with young rugby players, which gave excellent correlation coefficients (r = 0.9).

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.1 GSA Analyser™
(from Barrett et al., 2015)

However, these results were only presented at a conference and have not been published in a peer-reviewed journal (Hamilton et al., 2010). The lack of test–retest reported data from this method of measurement is a major omission, which means that it cannot necessarily be trusted for clinical use.

A study based on this equipment was designed by Geary et al. (2013), using the Chatillon DG series SS-DG-0210 design (an early version of the GSA Analyser System™) attached to a digital HHD (Chatillon MSC Series; Chatillon, Largo, Florida) (Figure 4.2). This work utilised the Gatherer system's test-to-failure method (Section 4.1.5.1.1), which means that it also imported the system's main limitations. Geary et al. examined the intra-rater reliability of this instrument. They recruited 25 academy-level rugby players and reported ICC values ranging from 0.80 to 0.92, representing good-to-excellent reliability, though CV was not reported (Geary et al., 2013).

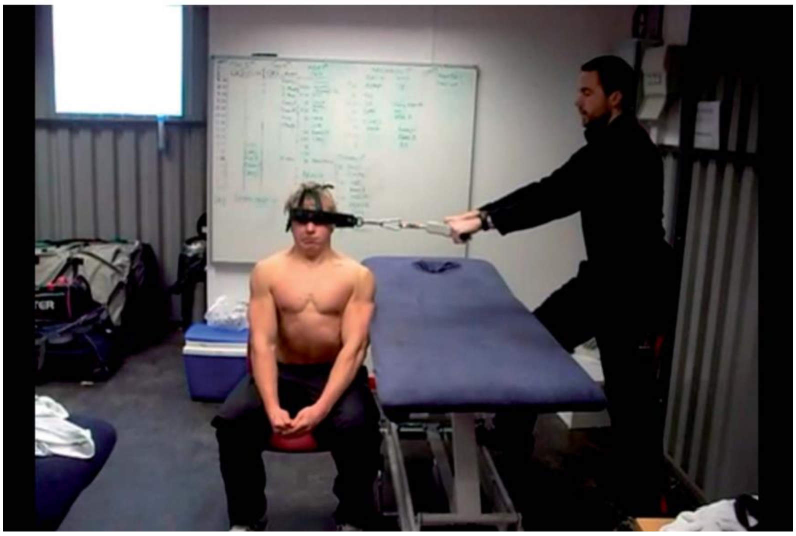


Figure 4.2 Adapted version of Chatillon DG series SS-DG-0210
(from Geary et al., 2013)

Another limitation on the effectiveness of this technique relates to participants' interaction with the equipment, as participants find the test-to-failure technique uncomfortable, which can lead to an unwillingness to produce the maximal resistance force, thereby rendering the results less reliable (de Koning et al., 2008). This aspect of the technique makes it inappropriate for use in measuring patients experiencing neck pain – a commonly reported symptom among the uninjured rugby population (Castinel et al., 2010) – or for post-rehabilitation, as the tester will be cautious of provoking further pain or injury. Due to these limitations on effective measurement – both in general and for use with specific groups who particularly require neck strength measurement, such as rugby players – the available evidence suggests that the Gatherer system should be used with caution.

In a study conducted by Versteegh et al. (2015) using the MicroFet™ (Hoggan Health Industries, Salt Lake City, UT, USA), the researchers attempted to overcome a commonly recognised problem with all HHDs: that usage is affected by factors such as the strength of the person conducting the test and device stabilisation. This was achieved by requiring the subject to hold the device in their own hand (or hands) and apply their own resistance (Figure 4.3). In contrast to the break test method (GSA Analyser System™), this is a *make* test, whereby the measuring tool is held in position while the participant applies the maximum force to it (Stark et al., 2011). In this type of muscle strength test, the muscles contract isometrically in order to exert their maximum force. However, the authors argued that if the subject's upper limb(s) could not generate sufficient force to overcome their own neck strength, the test was rendered invalid. It was therefore impossible to establish conclusively whether this approach can render reliable results. In addition to this known limitation of HHDs, the study also suffered from methodological limitations with regard to the number of participants. The power calculation determined that 27 subjects would be required for the reliability study, and this criterion was met by recruiting 14 male and 16 female participants. However, statistical analysis required the inclusion of all participants, combining both subsets, with the confounding issue that the overall strength data for the female subjects was significantly lower, being 50% – a notable difference from the 61% recorded for the male participants. As a consequence of this amalgamation of the two very different populations for the purpose of the reliability analysis, the results showing good-to-excellent test–retest reliability (ICC values of 0.87–0.95) were not shown to be applicable to either of the subsets included in the study. In addition, no CV was reported by Versteegh et al. (2015), further reducing the ability to interpret the findings. Therefore, relying on this study as a justification for the use of the same or a similar protocol on a population of solely male participants is not supported.

Nonetheless, this approach was also followed in Farley et al.'s (2022) study of neck strength in 225 male rugby players, using a pre-set order of testing (Flex, Ext, RSF, LSF, right rotation and left rotation). However, without randomising the order, there is the potential for an order effect, which can serve to confound the results. There was minimal reporting of the small reliability study undertaken, which stated overall agreement ranging from moderate to excellent (0.71–0.99) between two raters, with no intra-rater tester reliability study being undertaken.

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.3 MicroFet™
(from Versteegh et al., 2015)

In an attempt to overcome the recognised shortcomings of handheld dynamometry, Ashall et al. (2021) compared an HHD and a mounted HHD (MHHD) to determine concurrent validity for measuring neck strength. The study reported a significant ($p < 0.001$) reduction in peak neck force recorded by the HHD test when compared with the MHHD test, further bringing into question the validity of HHDs in the measurement of neck strength (Figure 4.4). In addition, a study by Tudini et al. (2019), in which an HHD was fixed to a stable surface, demonstrated excellent test–retest reliability, with ICC values of 0.91 to 0.97 (Figure 4.5). Neither study reported CV values or provided sufficient data for these to be calculated. Both studies indicated that HHDs' reliability is improved by fixing the dynamometer in place and removing the variable of tester strength. This methodological approach attempts to remove a major difference between HHDs and FFDs by mounting the former on a frame. However, this introduces a further major problem with the reproducibility of the testing set-up, which is less of a concern with FFDs, for which there is little to no variability in the testing set-up.

Moreover, an important omission from both Ashall et al.'s (2021) and Tudini et al.'s (2019) methods was the question of their between-test protocol regarding equipment set-up. Despite the very clear descriptions of the methods employed in these research laboratories for the mountings used to turn these HHDs into FFDs, the question of whether this can be replicated when the fixings are dismantled and subsequently reconstructed, either within or outside of the carefully controlled environment of a research setting, has yet to be tested or reported, thus violating the ecological validity of these testing methods.

A final consideration about neck strength data as recorded by HHDs reported in the academic literature surrounds the testing protocols described, which vary between studies. For example, Tudini et al. (2019) instructed participants to push for five seconds and rest for one minute, used verbal encouragement and completed two trials to gain the peak MVIC value. Both Versteegh et al. (2015) and Farley et al. (2022) used a three-second push, no rest between tests and no verbal encouragement. Finally, Ashall et al. (2021) used a three-second push with a two-minute rest period between tests and no mention of verbal encouragement.

Therefore, it is not feasible to compare the values obtained from various tools used in conjunction with differing protocols. The need for a clearly reproducible test position, equipment and protocol is clear from the variety of techniques described in the current academic literature.

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.4 Use of a mounted handheld dynamometer and a handheld dynamometer to measure neck strength
(from Ashall et al., 2021)

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.5 Use of a fixed handheld dynamometer to measure neck strength
(from Tudini et al., 2019)

4.1.5.1.2 Fixed-frame dynamometers (FFDs)

FFDs are considered to be the gold standard in the quantification of isometric neck muscle strength (Prushansky & Dvir, 2008; Strimpakos et al., 2004). In contrast to HHDs, FFDs can measure isometric strength without the tester providing resistance during the measurement, which is acknowledged as a limitation in reliability tests of handheld devices (Ryan et al., 2019).

There are several FFDs on the market that have been reported on within the research literature. A key example that has been specifically designed to measure neck strength is the MCU (BTE, Birmingham). The MCU is designed to be used with the participant seated (Figure 4.6). The head piece fits onto the skull, and the participant pushes their head against the sensors within the frame, enabling the recording of the MVIC of the neck by the machine. The MCU has excellent test–retest reliability, with ICC values of 0.92 to 0.99 (CV not reported), in the measurement of isometric cervical spine strength in combined movement patterns and in the cardinal planes (Chiu & Sing, 2002).

Figure 4.6 Multi-Cervical Unit (MCU)
(from Physiquipe, n.d.)

However, the MCU is not portable, which significantly limits its usability. Another limitation affecting this device's usage in sport is that the load cells are limited to 50 lbs (22.6 kg; 222 N), which has been shown to be insufficient for stronger athletes such as rugby players, who regularly record force readings >400 N (Farley et al., 2022; Salmon, Handcock, Sullivan, Rehrer, & Niven, 2018; Versteegh et al., 2015).

There are other large FFDs that have the capacity to measure isometric neck strength and have been subjected to reliability studies, such as the David Back Clinic, which was studied by Peolsson et al. (2001) and demonstrated excellent reliability (ICC values of 0.85–0.97; CV not reported). However, this equipment again tests only in the seated position and is not portable for use outside of a clinical environment.

While these tools are commercially available and have varying levels of reported reliability, their drawbacks are such that they have not been adopted in sporting settings due to their expense and lack of portability.

4.1.5.2 Bespoke neck strength-measuring dynamometry equipment

In response to, and in confirmation of, the limitation issues identified in the mainstream, commercially available dynamometry equipment explored above (Section 4.1.5.1), various bespoke, laboratory-based options have been created (Hall et al., 2017; McDaniel et al., 2021; Salmon et al., 2015).

One such bespoke option is the equipment designed by Hall et al. (2017). This instrument used a fixed frame with a single load cell attached (Chatillon, DFX II Series, Largo, Florida), which required the participant to lie on a plinth and push down against the load cell for Ext, Flex, LSF and RSF (Figure 4.7 to Figure 4.9). The protocol consisted of a four-second push and a five-minute rest between three tests conducted by three different researchers.

The order of direction testing was not randomised, and if the first three repetitions gave a CV of >10%, a fourth repetition was completed. This study demonstrated good-to-excellent inter- and intra-rater reliability of average peak neck strength (ICC values of 0.897–0.997) in a study on 13 participants, conducted over three trials with 442 of 468 data sets (94%) and demonstrating a CV of below 10%. While the authors justified their choice of contraction time, and the use of the same, non-randomised order of directional testing, this does not replicate any other testing protocols documented within the literature. In addition, the peak force results were higher than reported in any other literature for both males and females, despite being a make test which usually records lower force data than break tests.

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.7 Testing neck extension strength
(from Hall et al., 2017)

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.8 Neck strength testing apparatus
(from Hall et al., 2017)

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.9 Positioning for testing
(from Hall et al., 2017)

Moreover, despite identifying a significant difference between the forces recorded for the small numbers of participants (seven males and six females) in this study, the data for all participants was analysed together without regard to differences between sexes – a similar limitation to that identified in Versteegh et al.'s (2015) study (see Section 4.1.5.1.1).

A rigorous study undertaken by Salmon et al. (2018) involving 30 male, non-rugby playing participants investigated the reliability of a rig, designed specifically for rugby forwards, using a bench that replicated the rugby scrum position (Figure 4.10). The study reported excellent reliability (ICC values of 0.91–0.98) but did not report CV values, which would have better supported the reporting of the results. When CV was manually calculated from the data provided within the report, the calculation $(mean \div SD) \times 100$ returned values of 23.1 (Ext), 28.8 (Flex), 40.9 (LSF) and 44.0 (RSF), which demonstrates poor reliability, especially for the side flexion (SF) directions. The study further concluded that only one repetition of a 3-s push was required to test for neck strength as measured by MVIC. This novel testing position, specific to a very small cohort (namely rugby forwards), affords no comparison to any other research or equipment and was not tested on the proposed sporting population.

As in the case of Hall et al.'s (2017) equipment, Salmon et al.'s (2018) rig was designed for the research setting. In this way, it is not commercially available and therefore does not allow for multi-site testing. The research methods were replicable, but the unquantified co-contraction force applied through the arms and torso were unaccounted for. As a result, the use of this potential bracing means that the amount of isolation achieved in the measurement of neck strength is unknown.

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.10 Rugby-specific bespoke rig
(from Salmon et al., 2018)

Moreover, a study using a head harness and tension scale, similar to the GSA Analyser System™, was conducted with the primary aim of analysing two different testing postures – seated and standing – in the measurement of neck strength using a make test (Figure 4.11) (McDaniel et al., 2021). Due to the fixed-height chair and the lack of ability to prevent the participant from using their body mass to lean into the test, the seated position is not consistent between participants of differing heights. This meant that the potential contribution to the task of measuring neck force from body-bracing mechanisms, such as pushing through the ground with the feet, was inconsistent between participants and was unaccounted for in the test. In the standing test position, as the body is completely unrestrained, it is not possible to quantify the contribution made by the body leaning away from the load cell, making it difficult to account for this in the force measurement being attributed as neck strength. This means that the test position in this experiment cannot specifically measure neck strength in isolation from contribution from the body. Despite these limitations, the reported intra-rater (test–retest) reliability was found to be good to excellent

(ICC values of 0.78–0.97) for both test positions. However, the limited data analysis presented in this study of 31 participants only allowed for conclusions to be drawn regarding the reliability of the two testing positions, with no analysis conducted to investigate which of the test positions was preferable in allowing participants to produce their MVIC neck strength.

One way to overcome the unknown quantity of force contribution to the neck strength test from the upper and lower extremities was suggested in a study using a mounted HHD by Catenaccio et al. (2017). In this study, participants (untrained individuals) were strapped to the chair with a seat belt but had their feet placed on an empty cardboard box which they were instructed not to deform. They were also told to hold their arms at 90° shoulder abduction and 90° elbow flexion to avoid any bracing through the limbs (Figure 4.12). Reliability indices were recorded for only five men and five women. However, the neck strength peak MVIC for extension recorded a range of 30.6 kilogram-force (kgF) (mean = 22.8, SD = 7.05) for men and 18.3 kgF for women (mean = 14.1, SD = 3.96).

In a study by Ashall et al. (2021), in which the same HHD was used (microFet™) with 19 semi-professional rugby players, a mean MVIC for neck extension of 25.6 kgF (SD = 4.8) was reported, but not the range. The HHD in this study was also mounted, but no constraints were put in place to counter the bracing by the arms and legs (Figure 4.4). Therefore, despite these two studies appearing to complete the same test using the same equipment and with the same test position, raw force results from these two studies cannot be compared due to the differences in study populations and protocols adopted.

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.11 Fixed tension-scale instrumentation, seated and standing (from McDaniel et al., 2021)

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 4.12 Fixed MicroFet™ handheld dynamometer seated test using unsupported test position
(from Catenaccio et al., 2017)

As these examples show, the shortcomings of mainstream dynamometers in the measurement of neck strength necessitate the development of a bespoke instrument to meet the needs of clinicians. These tools have, like the commercial options evaluated in the previous section (Section 4.1.5.1), demonstrated good reliability in research settings, though there are limitations to these methods. Moreover, there is no evidence that any of these bespoke neck strength dynamometry tools have met widescale success or adoption. As such, none of these tools are currently appropriate for use in the development of a standardised neck strength measurement protocol due to the inability to control for the variables as stated.

As described, inconsistencies in protocols devised for these studies include the values recorded as either average MVIC (Farley et al., 2022; Versteegh et al., 2015) or peak MVIC (Geary et al., 2013; Hall et al., 2017; Hamilton et al., 2010; McDaniel et al., 2021; Salmon et al., 2015). A variable number of repetitions were recorded for each trial between studies, ranging from one (Salmon et al., 2018) to three (Farley et al., 2022; Geary et al., 2013; Hall et al., 2017; McDaniel et al., 2021; Versteegh et al., 2015) or four repetitions in the case of some of the subjects from the study by Hall et al. (2017). Other inconsistencies noted above include the isometric contraction duration, rest periods between contractions, and verbal encouragement versus no encouragement, all of which can impact the maximal force output of any MVIC test (McGuigan et al., 2013). Combined, these multiple barriers facing the current state of neck strength measurement in rugby indicate that current published data in this field suffers from inconsistencies in both testing equipment and protocols, negating the possibility of generating a useful normative database of neck strength and requiring the urgent need for a solution.

4.1.6 Rationale for methodological approach

4.1.6.1 Equipment options for measuring neck strength

The review of available mainstream (Section 4.1.5.1) and bespoke (Section 4.1.5.2) neck strength measurement instruments demonstrates that, for the quantification of neck force, there is currently no viable outcome measurement tool that meets each of the following criteria: that the tool be 1) used as a *universally accepted* measurement tool and protocol, which would allow for a large normative database of neck strength measurements to be generated regardless of location of test; 2) *reliable*, with quantified inter- and intra-rater reliability; 3) *portable*, with a load cell capacity sufficient for measuring the strength of a neck that is capable of producing such force as a rugby player can produce; and 4) able to *demonstrate face validity*, namely through incorporating a test position that can be consistently adopted and applied regardless of tester or location of test. This gap in the capacity of viable equipment must be understood in light of the evidence that supporting the development of a strong cervical spine could be advantageous in reducing both the frequency and intensity of concussion-related injuries sustained in contact sports such as rugby (Chéradame et al., 2021).

Furthermore, considering the growing awareness of the need for a reliable and valid method for testing neck strength across all levels of modern sport, including rugby (Section 2.6.1), it was therefore necessary to either create a new rig or to adapt existing equipment. The maturity of existing mainstream options (Section 4.1.5.1) is unquestionable; pragmatically, insights from what has been learned in their existing uses could be applied in an adaptive solution.

4.1.6.2 The ForceFrame (formerly GroinBar™) dynamometer

Three features made the ForceFrame (VALD Performance, Newstead, Queensland, Australia) suitable for adaptation and adoption into mainstream neck force testing. It was fully capable of meeting the identified criteria for adapting an existing piece of equipment (Section 4.1.6.1): its physical attributes, clinical applicability and widescale commercial production.

The ForceFrame had been tested for reliability with 18 professional Australian football players, and this study demonstrated a high level of reliability (ICC values of 0.87–0.96) of the adductor strength assessment system with a CV below 10% (Ryan et al., 2019). Moreover, it was already being adapted by clinicians to measure ankle, knee and shoulder strength (VALD Performance, n.d.). Such proofs of adaptation potential were attributed to the fact that the ForceFrame is a modular, portable and repeatable system for training and testing isometric muscle strength. These proofs also underscored the ForceFrame's suitability for adaptation to measuring neck strength. The ForceFrame had several perceived benefits and drawbacks when compared to other mainstream and laboratory-designed equipment (Table 4.1), which were taken into consideration when designing this study to assess its capability to reliably measure neck strength – something that had not yet been established. This phase of study therefore examined the ForceFrame modular frame isometric dynamometer's ability to measure cervical spine isometric strength.

Table 4.1 Summary of perceived advantages and disadvantages of the ForceFrame

Advantages	Disadvantages
➢ Adjustable modular frame ➢ Ability to store frame set-up data within the software, allowing replicability of participants' starting position on every testing occasion ➢ Maximum load cell sensor capacity of 1000 N per 100 kg (220 lb), exceeding the highest values obtained to date on rugby players necks by 700 N ➢ A safe overload value of 1500 N and a maximum overload per sensor of 2000 N (Resolution = 1 N) ➢ Load cells allow for isometric evaluation of Flex, Ext, LSF and RSF of the neck ➢ Lightweight (28 kg) and portable (dimensions of 1010 mm (L) by 1130 mm (W) by 960 mm (H)), and thus readily usable in both the laboratory and in the field ➢ Short set-up and dismantling time (no more than5 min)	➢ Does not allow for the measurement of rotation force ➢ Only measures isometric force ➢ Requires a Wi-Fi or mobile data connection in order to collect the data ➢ Standing arms were initially too short to test subjects over 1.95 m in height to maintain the neutral start position

Ext = extension; Flex = flexion; LSF = left side flexion; RSF = right side flexion

4.1.6.3 Testing position for the measurement of neck strength using the ForceFrame

The test position that must be adopted to use the ForceFrame for the measurement of neck strength is the quadruped position, with hands and knees in contact with the ground. This in turn ensures that the head is in contact with the load cells. One perceived benefit of using the quadruped test position is the stability it confers to the torso due to the four-point stable base. In addition, when the scapulae are retracted, this confers a rigidity to the thoracic spine (Cools et al., 2021), thereby circumventing the instability inherent in a test performed in standing with only a two-point base of support (e.g. McDaniel et al., 2021). Moreover, no extra equipment is introduced to the test set-up in this position, such as the chairs and plinths employed in other studies (e.g. Farley et al., 2022; Geary et al., 2013; Hamilton et al., 2010; McDaniel et al., 2021; Salmon et al., 2015; Versteegh et al., 2015). The test would have to be a make test, and lessons would be learnt from all the variables of previous studies in order to create and test an evidence-based protocol. However, due to the lack of previous investigation into the proposed quadruped test position for measuring neck strength, it would be desirable to investigate the effect of variables such as the exact positioning of the extremities on test subjects' ability to generate the MVIC of their neck. It would therefore be instructive to explore, for example, the impact of the placement of the hands, whether together or shoulder-width apart.

4.1.7 Aims, research questions, objectives and hypotheses

4.1.7.1 Aims

The main aims of this study were:

1) To establish the test–retest (intra-rater) and between-tester (inter-rater) reliability of the VALD ForceFrame for testing MVIC of the neck in four test directions;
2) To investigate the effect of using two different quadruped starting positions on participants' ability to generate maximal neck force; and
3) To investigate the association between MVIC of the neck and neck girth.

4.1.7.2 Research questions

RQ2 Can neck strength be reliably tested using existing equipment?

RQ2a Can reliability be achieved in terms of intra- and inter-rater response, participant sex and planes of motion?

4.1.7.3 Objectives

The main objectives of this study were:

1) To report test–retest (intra-rater) reliability of the VALD ForceFrame in measuring neck MVIC force in the test directions of Flex, Ext, LSF and RSF of male and female participants between two trials conducted at least 72 hours apart;
    a) To report the reliability of the VALD ForceFrame in measuring neck MVIC force between three repetitions within a single trial;
2) To measure the effect of sex and test direction on the participants' ability to generate maximal neck force;
3) To report the inter-rater reliability of the VALD ForceFrame in measuring neck MVIC force in the test directions of Flex, Ext, LSF and RSF between two trials conducted by two researchers;
4) To measure the effect of using two different quadruped testing positions on participants' ability to generate maximal neck force, with hands apart (HA) and hands together (HT); and
5) To measure the associations between MVIC of the neck and neck girth.

4.1.7.4 Hypotheses

The experimental hypotheses propose that: 1) there is good reliability between and within trials and 2) between testers; 3) that the use of two different testing positions will have an effect on neck MVIC force production capability; 4) there will be a greater MVIC neck force measured in males than females; 5) there will be a difference in neck MVIC force between the different planes of test directions, with Ext force being tested as greater than Flex, and LSF and RSF being equal; and 6) that there will be associations between MVIC of the neck and the anthropometric variable of neck girth.

4.2 Methods

4.2.1 Introduction

A double-session repeated measures intra-rater and inter-rater reliability study was performed.

4.2.2 Ethical considerations

Ethical approval was provided by the Coventry University Human Research Ethics Committee (P93801). Participants were informed about the study and gave written consent prior to participation.

4.2.3 Sample

A convenience sample of $N = 40$ participants ($n = 20$ male and $n = 20$ female) was recruited from the staff and student population at Coventry University. Recruitment was achieved through word-of-mouth. A required sample size of $n = 18$ was determined, with a potential 20% loss to follow up, based on *a priori* power analysis (effect size $f = 0.8$, $\alpha = 0.05$ and $\beta = 0.02$) (G*Power). The power level was set at 80% ($\rho = 0.8$), and the α error level at 0.05 to reduce the chance of a type I error, in which a true null hypothesis is rejected. The β value was set at 0.02 to reduce the likelihood of committing a type II error, in which a false null hypothesis is accepted. Due to the identified lack of previous research using the proposed protocol for the measurement of neck force (MVIC) with the VALD ForceFrame there was no data available for use to calculate the exact sample size required for this experiment. The study conducted using the VALD force frame for the measurement of hip adductor strength utilised 45 participants for a single measure (adduction strength) and a subgroup of 18 participants who reported groin pain. No power calculation was reported in this study (Ryan et al, 2019). The calculation used (figure 4.13) demonstrated that for a moderate effect size of between 0.4 – 0.8 a sample size of between 16 and 30 would be sufficient to reduce the chance of a type I error (figure 4.13).

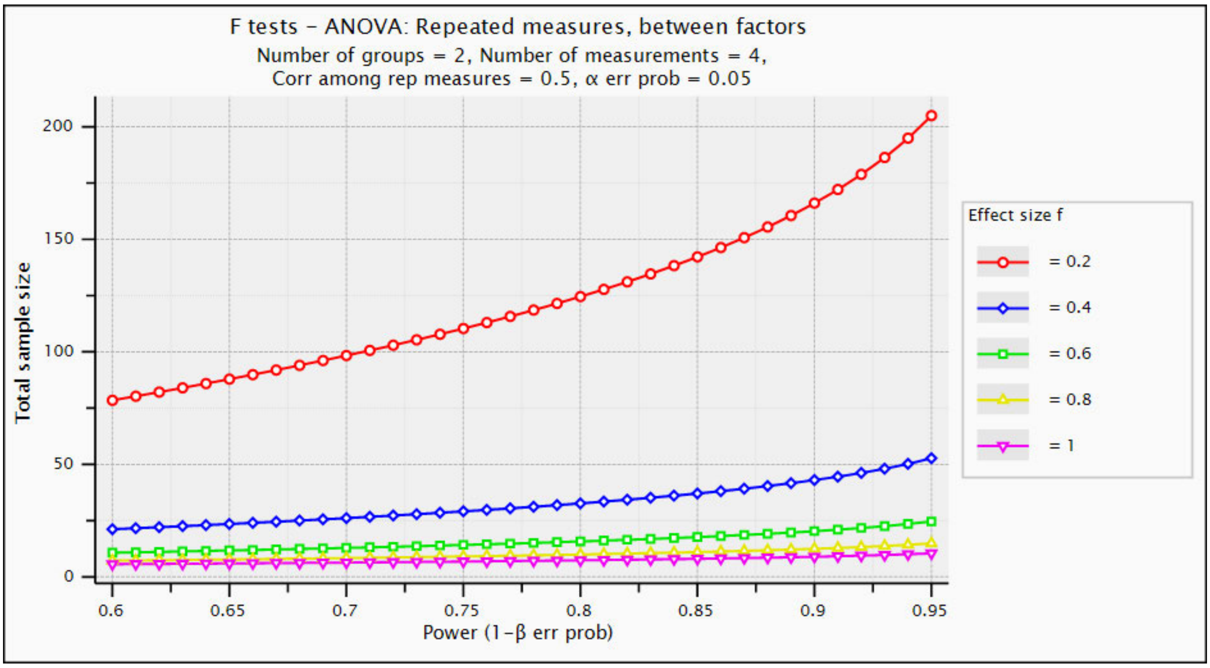


Figure 4.13 Power calculation with different effect sizes for comparison

Both males and females were recruited in order to assess reliability for both populations and to gather data of baseline measures on both populations for comparison. All participants were physically active and were subject to the inclusion and exclusion criteria shown in Table 4.2.

Table 4.2 Inclusion and exclusion criteria for participation in the reliability study

Inclusion Criteria	Exclusion Criteria
➢ Aged 18–50 years ➢ Able to safely perform neck exercises without pain ➢ Able to safely adopt the quadruped testing position without pain ➢ Able to understand the instructions ➢ Able to read and understand the participant information sheet ➢ Read and signed the informed consent form ➢ Able to return one week later for retest	➢ Any cervical spine injury resulting in an ongoing pain state ➢ Any upper or lower body neurological deficit ➢ Diagnosis of any neuromuscular condition that might be exacerbated by testing ➢ Heavy physical activity on day of test ➢ Imbibed alcohol on day of test

4.2.4 Trials

Participants were required to visit the testing laboratory on two occasions. On their first visit, all 40 participants were tested by Researcher 1 in the hands-apart (HA1) and hands-together (HT) positions to investigate the effect of testing position on MVIC of the neck. Of these 40, a random group of seven participants were further tested during Visit 1 by Researcher 2 in the hands-apart position (HA2) to investigate inter-rater reliability, with a minimum of 30 minutes' rest between the trials conducted by the two researchers. The order of the two or three trials in Visit 1 was fully randomised by the use of a computerised random number generator.

Of the 40 participants, 38 attended a second visit, at least 72 hours after their first. During Visit 2, all 38 participants were retested by Researcher 1 in the hands-apart position (HA3) to investigate intra-rater reliability. Of these 38, a random group of 14 participants (not including any of the seven tested in Visit 1) were further tested by Researcher 2 in the hands-apart position (HA2) to investigate inter-rater reliability, with a minimum of 30 minutes' rest between the trials conducted by the two researchers. The total number of participants in the inter-rater reliability study was therefore 21 (n = 16 male and n = 5 female). The order of the two trials conducted with these 14 participants in Visit 2 was again fully randomised using a computerised random number generator.

Along with the two participants who failed to attend Visit 2 (Participants 16 and 24, both male), two further male participants' data (Participants 2 and 9) was subsequently omitted from statistical analysis of intra-rater reliability (see Section 4.2.7.1), which was therefore performed on 36 participants (n = 16 male and n = 20 female) (Figure 4.13).

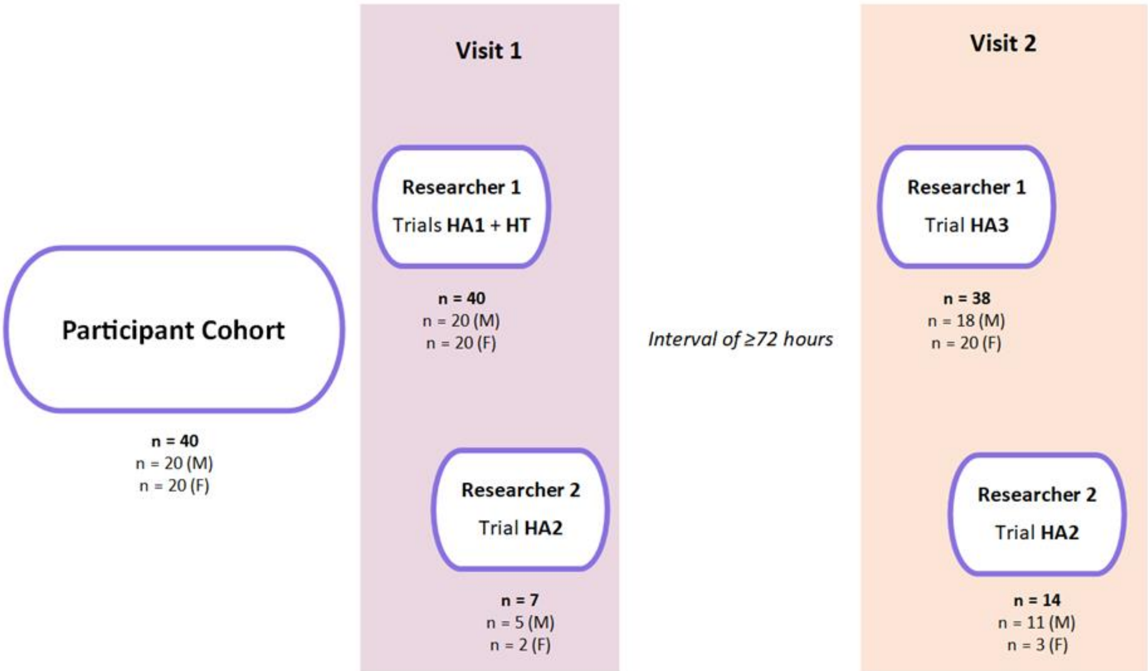


Figure 4.14 Participant involvement in each of the four trials conducted
(HA = hands apart; HT = hands together; M = male; F = female)

At the start of Visit 1, measurements were recorded of participants' height (to the nearest 0.5 cm; Leicester height stadiometer, SECA), body mass (to the nearest 0.5 kg; flat scales, SECA 877) and neck girth (to the nearest 0.5 cm; measuring tape, SECA 201), measured immediately cranial to the thyroid cartilage, with the participant instructed to look straight ahead (Table 4.3 to Table 4.5).

Table 4.3 Anthropometric data, height (cm), mass (kg), neck girth (cm) for all study participants (n = 40) (mean ± SD)

	***n* =**	**Age**	**Height (cm)**	**Mass (kg)**	**Neck girth (cm)**
Males	20	22.9 ± 4.4	181 ± 7	87.3 ± 11.1	40.7 ± 2.0
Females	20	24.5 ± 8.2	165 ± 6[a]	65.0 ± 12.9[a]	33.9 ± 2.2[a]
Total	40	23.7 ± 6.5	173 ± 10	75.6 ± 16.2	37.1 ± 4.0

[a] Significantly different from males ($p < 0.05$)

Table 4.4 Anthropometric data height (cm), mass (kg), neck girth (cm) for inter-rater reliability study participants (n = 21) (mean ± SD)

	***n* =**	**Age**	**Height (cm)**	**Mass (kg)**	**Neck girth (cm)**
Males	16	23.9 ± 4.9	180 ± 8	87.3 ± 11.7	40.5 ± 2.0
Females	5	32.4 ± 9.0	169 ± 9[a]	68.4 ± 14.0[a]	33.5 ± 2.3[a]
Total	21	26.0 ± 6.9	178 ± 9	82.8 ± 14.5	38.8 ± 3.7

[a] Significantly different from males ($p < 0.05$)

Table 4.5 Anthropometric data, height (cm), mass (kg), neck girth (cm) for intra-rater reliability study participants (n = 36) (mean ± SD)

	***n* =**	**Age**	**Height (cm)**	**Mass (kg)**	**Neck girth (cm)**
Males	16	23.1 ± 4.7	180 ± 8	86.5 ± 11.6	40.7 ± 2.2
Females	20	24.5 ± 8.2	165 ± 6[a]	65.0 ± 12.9[a]	33.9 ± 2.2[a]
Total	36	23.8 ± 6.6	173 ± 10	75.8 ± 16.3	37.3 ± 4.1

[a] Significantly different from males ($p < 0.05$)

4.2.5 The ForceFrame equipment

The ForceFrame equipment comprised an adjustable rig fitted with four independent and adjustable uniaxial load cells fitted to a fixed frame (Figure 4.15). The dynamometer component consisted of the four load cells which, when pushed against, generated a read-out in the VALD Dashboard software, attached wirelessly to a bespoke software program on a tablet through an app. The dynamometer position was customised within the frame to fit each participant by moving the bar up or down.

Figure 4.15 The ForceFrame (Groinbar™)
(from VALD Performance, n.d.)

4.2.6 Testing protocol

4.2.6.1 Initial set-up

Due to the lack of a bespoke cervical spine program at the commencement of the reliability study, a custom program was chosen from the software (VALD Performance, Newstead, Australia).

An initial practice run was performed with a single participant (excluded from analysis for the study) in order to determine the most suitable starting position, the load cells to be used for each test direction and the design of the custom software program used to record the measurements.

During this practice run, a dowel was placed on the participant's back to be in contact with the occiput, thoracic spine and sacrum (Figure 4.16). This was intended to ensure that the verbal instructions used to direct participants to adopt the correct testing position translated to a reproducible position every time.

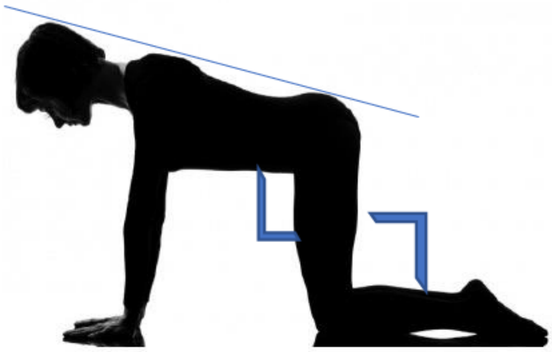


Figure 4.16 The testing position, quadruped, for all directions

The load cells were moved within the frame to enable the measurement of Flex, Ext, LSF and RSF (Figure 4.17).

4.2.6.2 Pre-test protocol

On entering the laboratory, participants were instructed to read the participant information sheet, were checked against the inclusion and exclusion criteria and were invited to sign and date the informed consent form (Appendix 4).

Each participant completed an isometric warm-up, which involved pushing their head against their own hand in each of the four test directions (Flex, Ext, LSF and RSF) with progressively increased force from 50% to 75% of their self-perceived maximal effort. This was repeated a further four times for each direction with a 10-s rest between each contraction.

Figure 4.17 Test position adopted for (A) flexion, (B) left side flexion and (C) extension for the assessment of isometric neck strength in the VALD ForceFrame

4.2.6.3 Testing positions

Participants were instructed to adopt one of two quadruped starting positions, HA or HT, with the head in proximity to the load cells of the ForceFrame (Figure 4.17). The load cell was in contact with the frontal bone just above the eyebrows for Flex, the occiput for Ext and the temporal bone just above the superior aspect of the helix of the ear for LSF and RSF. For the HA trials, participants placed their hands on the floor, shoulder-width apart, perpendicularly below the shoulder and elbow joints. For the HT trial, participants placed their hands on the floor directly below the manubrium sterni, with thumbs touching. Elbows were fully extended, scapulae retracted (fully drawn together), and hips and knees set at 90°, with knees therefore directly below the hips. Before commencing the first trial, participants became familiar with pushing against the load cell on the ForceFrame at an estimated 80% of their MVIC between one and three times until the participant was comfortable with the test procedure. The ForceFrame was zeroed after the warm-up and between each directional test.

4.2.6.4 Testing procedure

For the test, participants were required to perform three repetitions of their neck MVIC for 3 s per repetition, with a minimum of 10 s between each repetition, into the test directions of Flex, Ext, LSF and RSF in a randomised order, with 3 min taken between each test direction. The randomisation of test direction and testing position was achieved by assigning the numbers 1–8 to each of the tests (Flex HA, Flex HT, Ext HA, Ext HT, LSF HA, LSF HT, RSF HA and RSF HT) and using a computer program to randomise the order.

After force recording commenced, participants were instructed to inhale and exhale, and then, when ready, to push against the load cell as hard and as fast as they could (i.e. produce their MVIC) for 3 s (Salmon et al., 2015). Verbal encouragement was provided during each MVIC, in accordance with the protocol adopted in reliability testing undertaken by Ryan et al. (2019). Regarding the instructions given for the MVIC for the neck, in-keeping with evidence from work published for the measurement of mid-thigh pull (Haff et al., 2015), it was deemed essential to use the instruction to “push as hard and as fast as possible”, as this likely ensured a maximal effort during the performance of the MVIC, and a repeatable and easily understood instruction for the tester and the participant. The peak force recorded from the three repetitions in each of the four test directions was selected as the participant's MVIC for that test direction.

Force data from the ForceFrame was transferred at 50 Hz either to a personal computer through a USB connection, or wirelessly via a tablet to the VALD application using custom-made software (ForceFrame, VALD Performance, Newstead, Queensland, Australia), which produced numerical datasets and data visualisations (Figure 4.18). Data was subsequently uploaded to a private, institutional cloud account and exported into a customised Microsoft Excel 2008 spreadsheet for analysis.

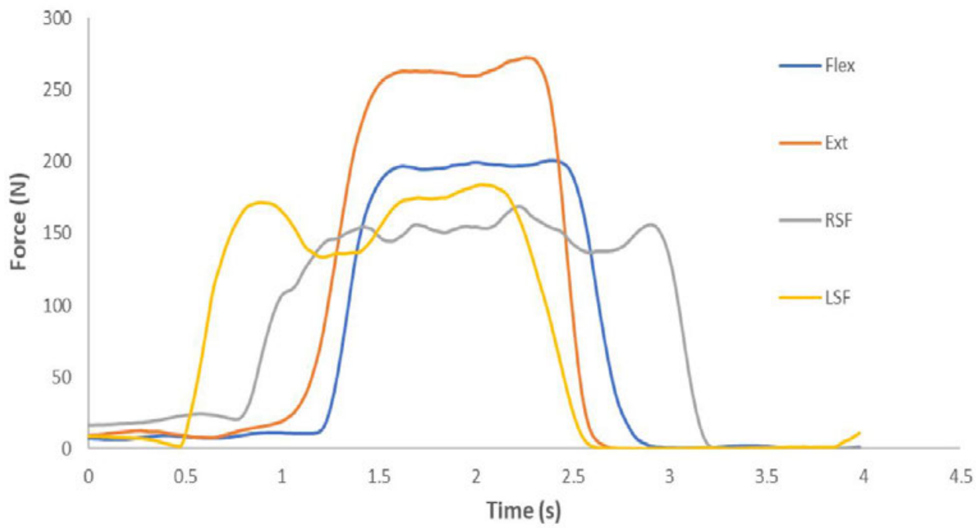


Figure 4.18 Example of the force–time curve for flexion (Flex), extension (Ext), left side flexion (LSF) and right side flexion (RSF) for a male participant

4.2.7 Analysis

4.2.7.1 Data analysis

Anthropometric data was collected for 40 participants (*n* = 20 male and *n* = 20 female; Table 4.3). Two male participants (Participants 16 and 24) were unable to return for the second testing session. In addition, two further male participants' data (Participants 2 and 9) was excluded from reliability analyses as the repeat measurements were more than three SD from the mean (Leys et al., 2013; Leys et al., 2018; Leys et al., 2019). Therefore, the double-session, repeated-measures, intra-rater reliability study involved a total of 36 participants (n = 16 male and n = 20 female; Table 4.4). For the inter-rater reliability study, 21 participants were recruited (n = 16 male and n = 5 female; Table 4.5), and data from two trials (one conducted by Researcher 1 and the other by Researcher 2) was analysed.

4.2.7.2 Statistical analysis

Statistical analysis was performed using SPSS version 26 (IBM Corp, Armonk, New York, USA), and the criterion for statistical significance was set at $p \leq 0.05$ *a priori*. The assumption of normality was assessed using a visual exploration of the Q-Q plot, box-plots, Shapiro–Wilk test of normality, and kurtosis and skewness values, with normal distribution being indicated between −1 and 1 (Kline, 2016, p. 78). Three variables were not normally distributed (LSF HA, LSF HT and RSF HA), and data was therefore transformed using the square-root function, generating kurtosis and skewness values that indicated a normal distribution.

An independent t-test was performed on the anthropometric data of the participants (age, height, mass and neck girth) to explore differences in these characteristics between sexes. Descriptive statistics (mean ± SD) were calculated for maximum force (N) in each of the four test directions.

One-way mixed model analysis of variance (ANOVA) was undertaken to establish whether there were significant differences between the three repetitions in each of the three trials, for each of the four directions, for both testing positions (HA and HT) and for each sex. Levene's test for homogeneity of variance demonstrated that there was no significant difference in variance ($0.537 \leq p \leq 0.999$) in all cases.

A paired samples *t*-test was performed to investigate the effect of using two different quadruped testing positions on participants' ability to generate maximal neck force, with hands apart (HA1) and hands together (HT); Cohen's *d* effect size was also reported.

Two-way ANOVA was used to compare peak isometric neck strength for each of the four directions and sex (male and female) as the fixed factors. Mauchly's test of sphericity was used to determine if sphericity was violated, and a Greenhouse-Geisser correction was used when this occurred. Where differences were noted in ANOVA, pairwise comparisons (Bonferroni-adjusted) were made to identify where significant differences occurred. Effect size for the ANOVA statistics was estimated using partial eta-squared (η^2_p) for analysis of variance (Ferguson, 2009).

To determine the relative reliability of the measures, two-way mixed model ICCs were calculated. A consistency definition for the inter-rater reliability tests was employed, and an absolute agreement definition for the intra-rater reliability tests (Koo & Li, 2016) for the maximum isometric force values from the three trials for each of the four directions was also employed. The ICCs were evaluated using the following criteria: poor ICC < 0.50, moderate ICC = 0.50–0.70, good ICC = 0.70–0.90, and excellent ICC > 0.90 (Koo & Li, 2016). The CV was calculated based on the mean square error of logarithmically transformed data (Hopkins, 2000). Acceptable reliability was then determined as an $ICC_{(3,1)} > 0.70$ and a CV < 15% (Beckham et al., 2013).

Absolute reliability of the peak isometric force for each direction and both sexes was determined using the standard error of measurement (SE_m), calculated using the formula $SE_m = SD \times \sqrt{1 - ICC}$, where the SD value was the combined SD value from Trial HA1 and Trial HA3, and the ICC values were the two-way mixed model single measure of consistency (Hopkins, 2000). The minimal detectable change (MDC) was determined using the formula

$MDC = 1.96 \times \sqrt{2} \times SE_m$ and calculated to the 95% confidence level (Beckerman et al., 2001).

A bivariate Pearson correlation coefficient was calculated to establish the level of association and the direction of any correlation between anthropometric data of neck girth and strength with $p \leq 0.05$, set *a priori*.

4.3 Results

4.3.1 Anthropometric data for all participants

Height, body mass and neck girth were all significantly lower in females than males ($p < 0.001$). Height was 9% lower: $t(39) = 6.28$; mass 26% lower: $t(39) = 4.70$; and neck girth 17% lower: $t(39) = 11.2$ (Table 4.5).

4.3.2 Peak maximum voluntary isometric contractions of the neck in flexion, extension, left and right side flexion

The key findings from the measurements of peak MVIC neck force (N) in all four directions (Flex, Ext, LSF and RSF) for all 40 participants (n = 20 males, n = 20 females) are reported in Table 4.6.

Table 4.6 Mean ± SD values for female and male maximum isometric neck force all four directions – flexion, extension, left side flexion and right side flexion – in hands apart

		Trial HA1 (R1)		Trial HA2 (R2)		Trial HA3 (R1)	
Test direction	**Group**	***n* =**	**MVIC force (N)**	***n* =**	**MVIC force (N)**	***n* =**	**MVIC force (N)**
Flex	Female	20	127 ± 22	5	134 ± 15	20	134 ± 19
	Male	20	231 ± 42	16	214 ± 36	16	239 ± 37
	Total	40	179 ± 62	21	195 ± 47	36	184 ± 61
Ext	Female	20	131 ± 37	5	134 ± 32	20	136 ± 30
	Male	20	271 ± 74	16	258 ± 65	16	273 ± 61
	Total	40	201 ± 91	21	228 ± 79	36	203 ± 84
LSF	Female	20	95 ± 29	5	111 ± 33	20	105 ± 26
	Male	20	157 ± 55	16	156 ± 46	16	178 ± 44
	Total	40	126 ± 52	21	145 ± 47	36	139 ± 55
RSF	Female	20	90 ± 21	5	102 ± 26	20	102 ± 24
	Male	20	131 ± 48	16	157 ± 42	16	167 ± 40
	Total	40	126 ± 52	21	144 ± 45	36	133 ± 46

Flex = flexion; Ext = extension; LSF = left side flexion; RSF = right side flexion; HA = hands apart; MVIC = maximal voluntary isometric contraction; R1 = Researcher 1; R2 = Researcher 2

4.3.3 Reliability of neck strength measurement in all four neck test directions (Flex, Ext, LSF and RSF) for three repetitions in each of three trials (hands apart (HA1 and HA3) and hands together (HT))

One-way mixed model ANOVA demonstrated no significant difference for any test directions at the $p < 0.05$ level, for the peak force recorded between three repetitions in all cases for Trial HA1: $F(2, 117) \geq 0.039$, $p \geq 0.899$; for Trial HT: $F(2, 117) \geq 0.001$, $p \geq 0.838$; for Trial HA2: $F(2, 60) \geq 0.006$, $p \geq 0.592$; and for Trial HA3: $F(2, 111) \geq 0.015$, $p \geq 0.808$ (Figure 4.19).

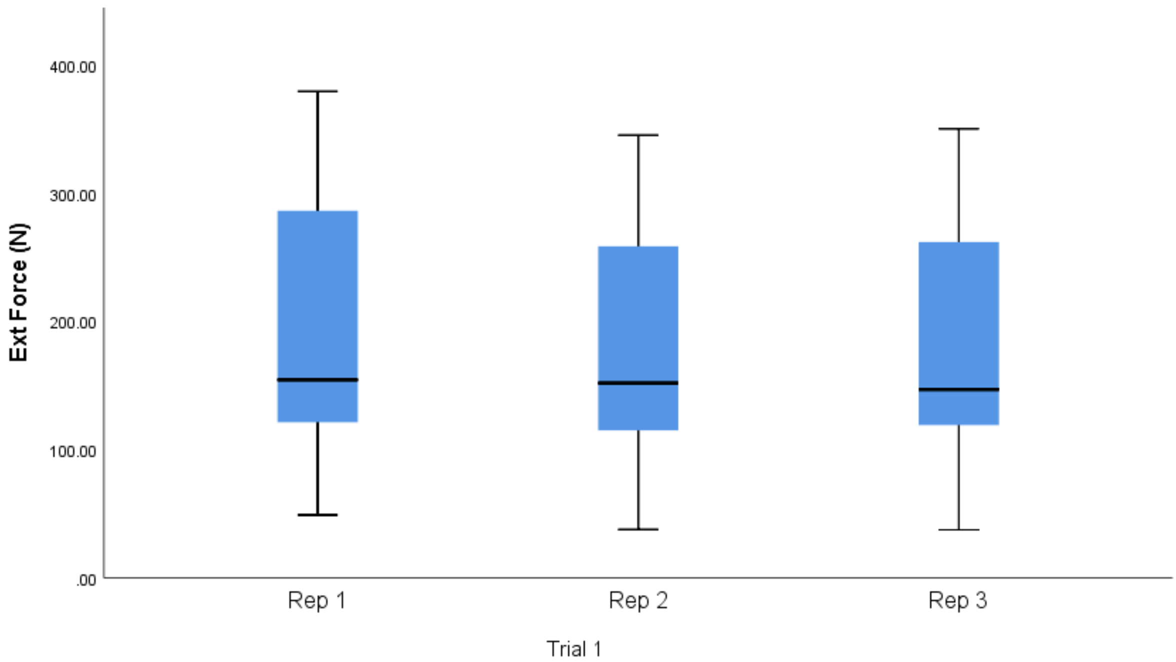


Figure 4.19 Example of box plots to demonstrate three repetitions for Trial HA1 (hands apart) extension for all participants (n = 40)
(Rep = repetition; Ext = extension)

4.3.4 Comparison of neck strength tested in two different quadruped positions: hands apart (HA1) and hands together (HT)

The results indicated that for Flex in Trial HA1 (mean = 179; SD = 62) and Trial HT (mean = 177; SD = 62), there was no significant difference: $t(39) = 0.721$, $p = 0.475$; and the effect size was small (Cohen's d = 0.11). For Ext in Trial HA1 (mean = 201; SD = 91) and Trial HT (mean = 195;

SD = 89), there was no significant difference: $t(39) = 1.46$, $p = 0.152$; and the effect size was small (Cohen's $d = 0.231$). However, for both LSF and RSF, the resultant neck MVIC force measurement was significantly greater in Trial HA1 than Trial HT ($p < 0.001$) in both cases: for LSF, HA1 was 16% greater than HT; and for RSF, HA1 was 20% greater than HT. For LSF, Trial HA1 (mean = 126; SD = 53) and Trial HT (mean = 109; SD = 42) were significantly different: $t(39) = 6.04$, $p = < 0.001$; with a large effect size (Cohen's $d = 0.955$). For RSF, Trial HA1 (mean = 126; SD = 52) and Trial HT (mean = 105; SD = 42) were significantly different: $t(39) = 6.46$, $p < 0.001$; with a large effect size (Cohen's $d = 1.02$).

4.3.5 Test–retest (intra-rater) reliability

Results from Trial HA1 (Researcher 1, Visit 1) and Trial HA3 (Researcher 1, Visit 2) from the single measure absolute $ICC_{(3,1)}$ were good to excellent across all directions (ICC > 0.87, CV < 14% for both males and females) (Table 4.7). The highest SE_m occurred in Ext among male participants (25 N), whereas the lowest variation occurred in Flex and RSF among female participants ($SE_m = 6$ N).

Inter-rater reliability results from Trial HA1 or HA3 (Researcher 1, Visit 1 or 2) and Trial HA2 (Researcher 2, Visit 1 or 2) from the single measure consistency $ICC_{(3,1)}$ were excellent: 0.96 (CV 11.1%) for Ext, 0.97 (CV 7.6%) for Flex, 0.97 (CV 9.7%) for LSF, and 0.97 (CV 10.7%) for RSF.

Table 4.7 Mean ± SD values and CV % for male (n = 16) and female (n = 20) maximum isometric neck force and intra-rater reliability values for all four test directions

					ICC			MDC		CV	
Direction	**Group**	**Trial HA1 (N)**	**Trial HA3 (N)**	**Total (N)**	**$ICC_{(3,1)}$**	**95% CI**	**SE_m (N)**	**Absolute (N)**	**% of mean**	**(%)**	**95% CI**
Flex	Female	127 ± 22	134 ± 19	130 ± 21[a]	0.92	0.81–0.97	6	16	12	5.2	3.9–7.7
	Male	231 ± 47	239 ± 39	235 ± 43	0.87	0.68–0.95	15	43	18	6.8	5.0–10.8
	Total	173 ± 63	180 ± 61	176 ± 61[b]							
Ext	Female	131 ± 37	135 ± 30	133 ± 34[a]	0.87	0.69–0.94	12	34	26	10.4	7.8–15.6
	Male	270 ± 77	268 ± 62	269 ± 69	0.87	0.66–0.95	25	69	26	11.1	8.1–17.7
	Total	193 ± 90	194 ± 81	193 ± 85							
LSF	Female	95 ± 29	105 ± 26	100 ± 26[a]	0.86	0.69–0.94	10	27	27	11.0	8.2–16.4
	Male	156 ± 55	177 ± 47	167 ± 51	0.90	0.74–0.96	16	45	27	10.5	7.6–16.6
	Total	123 ± 51	137 ± 51	130 ± 51[bc]							
RSF	Female	90 ± 21	102 ± 24	96 ± 23[a]	0.94	0.85–0.97	6	16	17	8.3	6.2–12.3
	Male	159 ± 53	166 ± 43	163 ± 47	0.83	0.58–0.94	20	54	33	14.0	10.2–22.5
	Total	121 ± 52	130 ± 46	125 ± 49[bc]							

ICC = intraclass correlation coefficient; 95% CI = confidence interval for the $ICC_{(3,1)}$ single measure; CV = coefficient of variance; SE_m = standard error of measurement; MDC = minimal detectable change; Ext = extension; Flex = flexion; LSF = left side flexion; RSF = right side flexion; HA = hands apart

[a] Significant difference between males and females ($p \leq 0.05$)

[b] Significant difference between Ext with Flex, LSF and RSF ($p \leq 0.05$)

[c] Significant difference between Flex with LSF and RSF ($p \leq 0.05$)

Isometric neck strength showed a significant main effect for sex: $F(1,31) = 92.1$, $p \leq 0.001$, (η^2_p) $p = 0.75$. Over the four directions, males produced greater MVICs than females: 81% greater in Flex, 102% greater in Ext, 67% greater in LSF and 70% greater in RSF (Table 4.7). There was a significant main effect for direction: $F(2.17, 67.1) = 103.62$, $p \leq 0.001$, (η^2_p) $p = 0.77$ (Table 4.7). Over the four directions, Ext was greater than Flex by 10%, LSF by 48% and RSF by 54%. Flex was greater than LSF by 35% and RSF by 41%.

4.3.6 Associations between neck strength and neck girth

There was no relationship between neck strength and neck girth ($p \leq 0.05$) for female or male participants for any test direction ($r < 0.35$ and $p > 0.14$ in each case) (Table 4.8).

Table 4.8 Association between neck girth and maximum voluntary isometric contraction of the neck in all test directions

Test direction	**Group**	**Pearson correlation coefficient**	**Significance (*p* value)**
Flex	Female	0.28	0.23
	Male	0.13	0.59
Ext	Female	0.34	0.15
	Male	0.15	0.54
LSF	Female	0.09	0.70
	Male	−0.02	0.94
RSF	Female	0.29	0.21
	Male	0.05	0.85

Flex = flexion; Ext = extension; LSF = left side flexion; RSF = right side flexion

4.4 Discussion

This study examined the reliability of the ForceFrame (VALD performance, Newstead, Queensland, Australia) to measure maximal isometric neck strength via a make test. The main outcomes were good-to-excellent test–retest reliability in both test conditions (intra- and inter-rater reliability), indicating that the ForceFrame is a viable, commercially available option for measuring neck force in young and healthy males and females aged between 18 and 42. The results demonstrated high similarity in MVIC neck force production to values previously reported for both male and female participants. The ForceFrame was found to demonstrate similar test–retest (intra-rater) reliability for the measurement of neck strength to an earlier model of the equipment (Groinbar™) when tested for the measurement of hip strength (Ryan et al., 2019).

4.4.1 Reliability

The results from this study demonstrated intra-rater ICC results that ranged between 0.83 and 0.94, with a CV between 5.2% and 14% (Table 4.7). The inter-rater reliability ranged from 0.96 to 0.97, with CV between 7.6% and 11.1%. Data produced in the analysis of isometric mid-thigh pull, a gold-standard test for muscle force production research, supports a minimal acceptable threshold of ICC > 0.7 and CV < 15% (Haff et al., 2015). Therefore, this indicates that the protocol used in this study has good-to-excellent intra- and inter-rater reliability for testing neck strength in all four directions tested. All inter-rater reliability testing was performed on the same day, potentially accounting for the greater reliability recorded compared with the intra-rater testing, where there was a minimum of 72 hours apart between tests. These findings for the reliability of using the ForceFrame to measure maximal isometric neck strength are similar to previously reported ICC values for both intra- and inter-rater reliability of a custom-made device: 0.90–0.97 (Salmon et al., 2015); and for other commercially available FFD devices: 0.96–0.99 (Hall et al., 2017) and 0.85–0.97 (Peolsson et al., 2007)).

The absolute reliability (SE_m) findings ranged from 5.63 (female RSF) to 24.8 (male Ext) and are similar to previously reported SE_m values of 19 in Flex, 16 in Ext, 16 in LSF and 14 in RSF by Almosnino et al. (2010), who used a custom-made device. The difference in values for Ext may be explained by differences in the testing positions adopted by the two studies. In this study, MDC values ranged from 16 N to 34 N for females and from 43 N to 69 N for males (Table 4.7), indicating the levels at which meaningful clinical change in MVIC values can be detected. Moreover, in terms of the percentage of the mean, MDC values in the present study were broadly consistent across sexes (Table 4.7). This is important to consider when using measurements to inform and measure effective training programmes designed to improve neck strength.

Consistent with previous studies, the protocol used here was found to be more reliable for testing in Flex and Ext than for the two SF test directions. It may be proposed that in the quadruped testing position with the scapulae retracted, the torso provides greater stability to the neck through the sagittal plane, parallel to the thoracic spine, than for neck movement through the frontal plane, which is orthogonal to the thoracic spine. This hypothesis is considered further in Chapter 5 (Section 5.4.3).

Previous studies have not included complete analysis of the reliability values recorded (Section 4.1.5). The failure of these studies to report CV values impedes a full understanding of the reliability of the instrumentation and protocols for measuring neck strength that they investigated and limits the ability to make comparisons with the present research. The CV values reported here point to the robustness of the findings of good-to-excellent reliability indicated by the ICC data, further enhancing confidence in the reporting of the research using the ForceFrame.

The findings of this study have significant implications for further development of research into neck strength. This is the first study to test the reliability of a portable and commercially available FFD for the measurement of isometric neck strength. This work strengthens the argument for the use of the VALD ForceFrame in both clinical and sporting contexts where an objective measurement of neck strength is required.

4.4.2 Use of three repetitions

In-keeping with previous studies that have assessed isometric neck strength testing reliability (Selistre et al., 2021), three repetitions were conducted in each trial in order to facilitate participants' generation of their maximum voluntary contraction. As the ANOVA calculations demonstrated that there was no significant difference between the three repetitions (Section 4.3.3), the single measure ICC calculated from the highest of the three forces recorded by each participant could be used with confidence in assessing the reliability of measuring participants' MVIC, rather than using the weaker measure of taking the mean values of the three repetitions. These findings align with the evidence published by Salmon et al. (2015) that only a single repetition is required and that, in cases where recording a single trial is preferable for reasons of time constraint or test subjects' preference, reliability is not compromised, provided that the warm-up is correctly completed so that the maximum force can be recorded on the first and only attempt.

4.4.3 Use of two testing positions

The two different testing positions (HA and HT) were compared in order to establish the effect of hand placement on participants' ability to produce their MVIC. The HT condition produced significantly lower results ($p = 0.001$) for neck strength in both LSF and RSF. This indicates that the optimal testing position for measuring MVIC of the neck involves the placement of the hands directly below the shoulder rather than closer together, as the latter will reduce the peak force production from the neck. It may be hypothesised that the HA position produces higher values of neck force as the torso provides greater stability to the neck in this position; there is evidence to suggest that a stable base of support for the body enables muscles to generate greater MVIC than when acting with a less stable base of support (Behm & Anderson, 2006). As acceptable intra- and inter-rater reliability has been established for the HA position, but not the HT position, the HA position will be adopted for future tests.

4.4.4 Force data

The ForceFrame recorded the MVIC force from the neck in the four directions of Flex, Ext, LSF and RSF, as measured in several previous studies (Table 2.3). It could not measure rotation due to the load cells only being adjustable for the sagittal and frontal planes. Previous studies, with the exception of Versteegh et al. (2015) and Farley et al. (2022), have also omitted rotation from their testing protocols. The pattern of strength and the values obtained for all participants align with those reported by previous studies involving both athletes and normal healthy participants: Ext was found to be the largest maximal force recorded, followed by Flex, with LSF and RSF being similar to each other but both lower than the sagittal plane movement directions (Chavarro-Nieto et al., 2021; Collins et al., 2014; Farley et al., 2022; Hrysomallis, 2016; Salmon et al., 2015; Versteegh et al., 2015). The greater values found in

Ext for both males and females may be explained by the larger cross-sectional area of the cervical extensor muscles (multifidus, erector spinae and trapezius) in relation to the flexors (sternocleidomastoid, deep neck flexors) and the side flexor muscles (scaleni and levator scapulae) (Franco & Herzog, 1987). The male participants produced an average peak force of 269 N, which was similar to: the 278 N reported by Hall et al. (2017), in which participants were measured in a lying position (Figure 4.7 and Figure 4.8); the 235 N previously recorded for healthy males in a similarly horizontal testing position, with the torso supported by a bench (Figure 4.10) (Salmon et al., 2018); the 252 N recorded in a seated position (Almosnino et al., 2010); and the 224 N recorded by Catenaccio et al. (2017). However, the HHD used by Versteegh et al. (2015) recorded an Ext force for males of 664 N, which is almost 2.5 times greater than the peak force recorded in this study and is inconsistent with all previously reported findings regarding peak force. This adds further support for the argument that, in order for practitioners to generate a database of normative neck force values, a single piece of equipment is required with a specified protocol.

Male participants recorded greater force values than females in this study, which is similar to all previously reported results in which both males and females were included (Garces et al., 2002; Hall et al., 2017; Peek, 2022; Selistre et al., 2021). These findings, relating to differences in force produced between sexes, offer practitioners valuable insights when measuring baseline neck strength in different populations.

Other studies measuring neck strength have reported ratios of Ext to Flex as an important indicator of potential imbalances, despite not stating what a “healthy” balance might be (Salmon et al., 2018; Versteegh et al., 2015). Within sport science, despite ratios such as quadriceps-to-hamstring strength having long been explored in relation to knee injury (specifically anterior cruciate ligament injury) and muscle injury (specifically hamstring strains) (Chavarro-Nieto et al., 2023a), the ratio of strength between the four neck movement directions cannot currently be predicted from existing literature. However, this specific calculation might be instrumental in linking injury audits to strength measurements within sport as a potential predictor of head and neck injury. In the present study, average peak force in Flex (176 N) was 91% of that in Ext (193 N) across the 36 participants. In males, the disparity was greater, with Flex only representing 87% of Ext; whereas in females, Flex and Ext were much closer to a 1:1 ratio, with Flex representing 98% of Ext. Comparing these findings to ratios calculated in other studies involving the measurement of neck force in both males and females reveals the wide range of reported values. Versteegh et al. (2015) reported Flex representing 55% of Ext for females and 63% for males, though the raw peak force results for females were also very high (210 N for Flex, 381 N for Ext) compared to this study (130 N for Flex, 133 N for Ext). The wide disparities in the results published in previous studies (Section 4.1.5) do not afford many useful comparisons, either between those studies or with the present research. The lack of a normative database for neck strength force is a notable omission within the strength-and-conditioning (S&C) and medical literature, which could be attributed to the lack of consistency within the field of research into standardised procedures for the measuring and recording of neck strength.

4.4.5 Association between neck girth and neck strength

Greater neck girth has previously been cited as a predictor for greater neck strength during Ext in rugby players (Salmon et al., 2015), most likely as a result of higher muscle mass. In contrast, this study of non-rugby players found no significant correlation between neck girth and neck strength (Table 4.8). This finding indicates that the size of the neck cannot therefore be used indiscriminately as an indicator of neck strength without taking into consideration the demographic profile of the individual. This may be because neck girth measurement is an overly simplistic indicator for the size of the neck muscles, as it takes no account of the difference between muscle mass and body fat.

4.4.6 Adaptation of equipment

The testing procedure adopted in this study offers practitioners a simple protocol in comparison to existing options. The procedure showed high clinical applicability due to the low equipment burden for test completion (Ashall et al., 2021; Geary et al., 2013; Salmon et al., 2015). After the study's completion, certain limitations of the ForceFrame were identified and conveyed to VALD, who made adjustments to the frame and to the software program. Completion of tests in all four test positions required time to be taken removing the crossbar from the frame and turning it over to enable Flex to be measured (Ext and both SFs were measured with the crossbar in the downward position, and Flex with the crossbar in the upward position). Following feedback on this, VALD developed a rotational arm for the ForceFrame, which considerably simplified and reduced testing time. Furthermore, specific programs for measuring neck strength were developed and included in the software provided by VALD, obviating the need to make use of the custom program function, which required more time and attention and posed greater risk of potential researcher error.

The quadruped position minimised the potential variability afforded by the requirement of external restraints such as seats and seatbelts (Table 2.3). In the quadruped position, stability was achieved by requiring participants to fully retract their scapulae and to fully engage their thoracic muscles, enabling a standardised, stable and highly reproducible test position. This position is particularly relevant to various sports which involve free, unrestrained body postures, including rugby.

4.4.7 Practical applications

The benefits of proving the strong intra- and inter-rater reliability of the ForceFrame are numerous. The instrument is not only commercially available but easily portable, with a mass of 28 kg, eliminating the burdens of previously tested laboratory-based equipment. Furthermore, the demonstrated inter-rater reliability and the reproducibility of the testing procedure reduce the need for specialist tester knowledge. Moreover, the combination of reliability, availability and ease of use allows for an increased equity of provision of neck strength measurement between stakeholders across the fields of healthcare and sports.

4.4.8 Limitations

This study was subject to a number of limitations. All participants were university staff or students, resulting in an age range (18 to 42, with a median 21 and a mean of 24) narrower than that of the general population. However, as this age range was representative of the sporting population for which this testing protocol is ultimately designed, it may be considered appropriate.

A further limitation was that the inter-rater reliability arm of the study recruited only 21 participants. While this number was greater than the minimum number of 18 participants required by the power calculation, only five of the 21 were female, with the result that analysis of the data by sex could not be conducted. The reduced number of individuals participating in the inter-rater reliability arm of the study was due to the availability of the second tester.

4.5 Conclusion

This study has demonstrated that the commercially available VALD ForceFrame provides a reliable measure of maximal isometric force for the neck flexors, extensors and side flexors when testing is performed in a quadruped position with hands perpendicularly below the shoulder in a population of healthy males and females. In light of the current drive to better understand the impact of head injuries in sport, and the hypothesised links between a strong neck and the mitigation of these injuries, this study provides practitioners with a reliable piece of commercially available equipment with which to measure neck strength. The normative values that have been presented enable comparison of neck strength in young, healthy adults of both sexes. The ability to reliably measure neck strength allows neck health to be tracked and for comparisons to be made across sports and populations, which will in turn enhance understanding of the relevance of neck strength in considerations of performance and injury prevention in sport.

Chapter 5: Assessment of the test position in terms of force distribution through the extremities

5.1 Context

5.1.1 Introduction

The previous chapter (Chapter 4) asserted the reliability of the ForceFrame (VALD, Newstead, Australia) in the measurement of neck muscle strength of 40 normal, healthy participants. Intra- and inter-rater reliability were shown to be measurable with intraclass correlation coefficient (ICC) values of good to excellent (0.83 to 0.97), and a coefficient of variation (CV) of <15% for both males and females in the four directions of testing: flexion (Flex), extension (Ext), left side flexion (LSF) and right side flexion (RSF) in two different quadruped start positions: hands-apart (HA) and hands-together (HT) (see Section 4.2.6.3). This data enables clinicians to be confident that they can trust the ForceFrame to produce acceptably *reliable* results for measuring neck strength. However, certain aspects of both the reliability of the test position (quadruped), and therefore the ecological and face *validity* of the test protocol, have yet to be demonstrated in relation to testing neck strength. Knowledge of the distribution of force from the extremities at both commencement of the test and at the point of peak neck strength would serve to provide detail around how this test can be compared to other neck strength tests suggested in the literature (Daly et al., 2021; Selistre et al., 2021).

There is a plethora of methods for measuring neck strength that have emerged in recent literature, as explored in the literature review (see esp. Section 2.6.2) (Selistre et al., 2021). However, despite the number and variety of studies using different devices such as handheld dynamometers (HHDs) (Ashall et al., 2021; Collins et al., 2014; Farley et al., 2022; Geary et al., 2014; Versteegh et al., 2015) or bespoke research lab-based equipment (Salmon et al., 2015), there is still no single method which has been universally accepted and adopted by the clinical or sporting community as a “gold standard”. Practitioners need to have confidence in the test method being used to assess their athletes or patients, which is usually gained through rigorous testing of both the equipment and the method of testing for both reliability and validity.

In the social and medical sciences, testing for validity – defined here as the assessment of the ability of a test method to achieve accurate results (Gold et al., 2010) – is multifaceted (Andrade, 2018). The major considerations are face, ecological, criterion and construct validity (Andrade, 2018). *Ecological* validity (external) is the generalisability and usefulness of the results obtained in research settings when being applied in the field. *Face* validity (internal) concerns whether the protocol appears to test what it purports to be measuring, which is instrumental to practitioners believing in the test and therefore adopting it in practice (Lemeunier et al., 2020). *Criterion* validity (how accurately the test reports the outcome it was intended to measure), along with face validity and *content* validity (concerning whether the output from the instrument can deliver all the required content for the variable being measured), all combine to generate *construct* validity, an important aspect to consider when assessing how the proposed equipment and the test itself might be received in a sporting setting (Heale & Twycross, 2015).

In order for the test proposed in this thesis to gain widespread adoption, and therefore to address the unmet need for a test that addresses both ecological and face validity as well as reliability, it is important that the start position (quadruped) can be justified through an in-depth exploration of the whole test. One of the major omissions in previously published testing protocols is the consideration of distribution of force through the body during the neck test, and therefore the reliability of the test position itself.

A key observation from previous isometric neck strength tests is the lack of detail pertaining to standardisation of the test position and quantification of force distribution through the body during the neck test, which may violate both the face and ecological validity of such methods (Selistre et al., 2021). To explore the validity of a test, it is important to assess how closely the results of the proposed technique align with those produced by the test currently considered the gold standard (Gold et al., 2010). Often this gold-standard test is a more sophisticated or expensive method, against which the accuracy of a more field-based, accessible method that is not confined to the research laboratory can be assessed. According to McDaniel et al. (2021), fixed-frame dynamometry is widely recognised as the gold standard for measuring neck strength. However, McDaniel et al. added no detail with which to substantiate this assertion, and no articles were cited suggesting which positions were being assessed during that gold-standard testing.

As a consequence, the challenge is to create a test that can be trusted to be reliable and that has face and ecological validity, in turn promoting its universal acceptance by practitioners in the field.

5.1.2 Rationale

5.1.2.1 Existing approaches for the testing of neck strength and analysis of test position

Examples of fixed-frame dynamometers (FFDs) include the ForceFrame (VALD, Newstead, Australia) and KangaTech (North Melbourne, Australia). Studies exploring the reliability of techniques and equipment to measure neck strength have indicated the use of a variety of test positions. However, the focus of previous studies was the measurement of reliability of the equipment used, with little or no regard to the assessment of the specified test position adopted by the participant and its role in the neck force generated. Test positions adopted have been varied and include participants being seated (Ashall et al., 2021; Geary et al., 2013); standing unsupported (McDaniel et al., 2021; Versteegh et al., 2015); lying (Hall et al., 2017); and forward-supported leaning on a bench, bracing with a handle in each hand (Salmon et al., 2015) (Figure 4.10).

However, these previously reported neck strength tests have not attempted to measure the contribution to the force measured of the bracing procedure adopted by the participant within the restraints provided. To give an example, Salmon et al. (2015) used seat belts in the seated position and the plinth in the forward lean position. This could have been achieved through the use of force transducers – for example, in the handles of the equipment used – which would have been able to quantify the force exerted through the upper limbs during a neck strength test. The rig described by Salmon et al. allowed bracing through the forearms and trunk, ground reaction force (GRF) through the feet, and the participant could also pull or push through the handles (Figure 4.10). The implications of these external forces and their potential impact on the reliability of the neck strength measurements are currently unknown.

In tests performed in a seated position, such as that undertaken by Ashall et al. (2021), participants have been unrestrained. Ashall et al. reviewed the concurrent validity of using an HHD, either in the hand of the researcher or fixed through wall-mounting, with the participant's spine against the chair and feet on the floor. In their study, the height of the chair was not standardised, and neither was it altered in relation to the height of the participant being tested, meaning that the start position differed depending on the height of each participant. Muscular co-contraction via the spine and pelvis being in contact with the chair, together with the consequent GRF through the feet at the time of neck force production (Hildenbrand & Vasavada, 2013), may have led to the participant's height and posture accounting for some of the reported differences in neck strength. As evidenced by Rezasoltani et al. (2005), the level of thoracic support afforded by a chair used for the test position in the measurement of cervical spine isometric strength affects the maximum isometric force produced by the neck. This research suggests that in order to standardise cervical spine strength measurements taken in the seated position, the length of the lever arm between the top of the chair's back and the neck represents an important variable that should also be standardised.

Other studies have compared the reliability of seated and standing test positions. For example, McDaniel et al. (2021) attached a tension-scale instrument to a fixed wall bar to assess the difference in neck strength tests between standing unsupported or seated unsupported. The reliability of testing in both positions was shown to be good to excellent, with the seated position being rated as slightly more reliable than the standing position. This led the researchers to conclude that an increased ability to brace contributed to increased stability, thereby producing a more reliable measure. The neck force values recorded were not significantly different from each other in either the seated or the standing position, and it was noted that the participants reported similarities between the two start positions in terms of being able to "us[e] their body to produce more force" (McDaniel et al., 2021, p. 569). The conclusion from this study was that while the two techniques were reliable, further research was needed to examine the start positions and their influence on neck strength results.

Conversely, in an earlier study by Strimpakos et al. (2004), forces recorded in the seated position were significantly higher than in the standing position. However, the standing position was reported as a more reliable test. The participants in this study reported using their trunk and legs to generate more neck force when seated, whereas due to the standing position being next to the dynamometer, they could not lean into the device, and this component removed the ability of using co-contraction strategies to increase neck force.

The other commonly used method for measuring neck strength (as determined by the survey in Section 3.3.2) is the use of the GSA Analyser™ system for testing isometric neck strength via eccentric muscle activity by means of a *break test* (Figure 5.1). Again, there is no published methodology specific to this test that has been reviewed for reliability in which the start position has been standardised or analysed for its impact on the neck strength data collected by the load cell. More recent amendments to the protocol include the addition of bracing the forearms against a plinth for the measurement of Ext (see Figure 4.1). However, standardised positioning during GSA Analyser™ measurement protocols has not been described or assessed for reliability within the peer-reviewed literature to enable comparison of results across cohorts. Moreover, external forces – such as those exerted through the seat, the feet, the height of the seat, the angle of pull on the harness or the bracing effect of the forearms – have neither been quantified nor accounted for.

Figure 5.1 GSA Analyser™ systems isometric neck test system
(from Hamilton & Gatherer, 2014)

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Figure 5.2 Handheld dynamometer testing
(from Versteegh et al., 2015)

5.1.2.2 Use of force plates to account for distribution of force throughout the body

These findings serve to demonstrate that neck force measurements from different studies often cannot be reliably compared due to unmeasured differences in the kinetic chain that occur due to the adoption of different test positions. Within any force assessment of the body, it is important to recognise that a single area of the body cannot work in isolation (Verdera et al., 1999). Any part of the body that is being assessed for its force production capacity is co-dependent on stability in other areas of the body producing an equal and opposite bracing force to enable the maximal voluntary contraction at the region of interest (Geary et al., 2013). Due to the lack of quantification of forces acting through the body and the differing amounts of body bracing possible during previous studies, existing results cannot reliably be considered together to generate a larger database of information.

One method to quantify the forces acting through the body during a test of neck strength would be to adopt methods from sports science whereby force plates have been used to measure GRFs during activities such as walking, countermovement jump and mid-thigh pull (Lake et al., 2018). The data gleaned from force platforms affords the measurement of force, velocity, power, displacement and left and right symmetry (Bishop et al., 2021).

In-ground laboratory-based force plates are considered the gold standard in the force plate equipment market (Lake et al., 2018). However, portable, dual-plate systems have compared favourably in previous reliability and validity tests (Lake et al., 2018). This may provide a useful solution in cases where in-ground technology cannot be used in conjunction with a fixed-frame dynamometer (FFD).

The assessment of symmetry through the extremities is common practice when using force plate data within tests such as the mid-thigh pull, the squat and countermovement jumps (Bishop et al., 2017). Data from force plates collected during strength tests can be used to analyse asymmetry, which may be a predictor of injury or could lead to a reduction in performance. Moreover, if previous injury has occurred to the extremities such as the anterior cruciate ligament, which is a common injury in rugby (PRISP, 2022), asymmetry could be identified through the force plate measurement of GRF (Moya-Angeler et al., 2017; Read et al., 2020).

During neck strength measurement, force plates could be placed under the feet to record force distribution through the lower extremities during the test. This has not been attempted in existing research. The quantification of such forces during a neck strength test would enable researchers to better interpret the neck strength results and work towards evidence-based proposals for more reliable test positions.

To give one example of neck strength measuring protocols, when adopting the quadruped neck strength test position, the participant acts as their own brace control, as there is only the floor against which to brace. In addition, stabilisation of the thoracic spine through the engagement of the scapulothoracic muscles during the test creates a reproducible starting test position.

5.1.2.3 Adopting the quadruped position

In this thesis, several factors were considered regarding the testing of isometric neck force using the VALD ForceFrame (Newstead, Australia) in terms of their potential to impact the reliability of the test–retest data collected (see also Section 4.1.5.1). The quadruped test position, adopted for use with an FFD, was the position chosen for this study to remove the operator involvement error inherent in handheld dynamometry, as well as the potential impact of bracing error common to seated or prone positions when testing on a plinth.

In Chapter 4, the test–retest, intra-rater reliability of the ForceFrame rig was determined during measurement of neck force maximum voluntary isometric contraction (MVIC) (see Section 4.3.5). However, it was also considered important to quantify the distribution of force across the extremities in contact with the ground during the test in order to assess the adopted test position in terms of its efficacy. This has not been recorded in any previous studies, which reduces their impact in this emerging field of research (Peek, 2022). One of the benefits of adopting the quadruped position for the test protocol in this study was the ability to further study the influence of the distribution of force recorded through the addition of force plates to the test, thereby allowing for measurement of the distribution of force through the upper and lower extremities. This would allow for a richness in the interpretation of the neck force data with the additional force distribution data from the limbs engaged in the test position. Other factors considered included the reproducibility of the initial position adopted within the frame, the wording of the verbal instructions given to the participants and the inclusion of verbal encouragement during the test (Haff et al., 2015). Not all of these variables have been described in previous studies, thus rendering protocols unclear and violating the reliability claims of previous publications.

As demonstrated in Chapter 4 (Section 4.3.2), the HA position allowed for a higher maximal neck force to be produced in all directions. This finding was statistically insignificant when testing Flex (p = 0.475) and Ext (p = 0.152) but statistically significantly different from the HT test when testing both LSF and RSF (p = 0.001), with lower strength being recorded for the HT position. This may be linked to research suggesting that the stabilisation of the torso during neck strength testing is important (McDaniel et al., 2021; Rezasoltani et al., 2005). However, more data is needed to account for these differences in order to determine which start position should best be adopted. In order to confer face validity on the test, the closest representative test position for the sport being investigated would be preferrable. This could include sitting for motorsport, standing for running sports and football (soccer), lying for sledding sports and quadruped for sports where neck strength is required at its maximum in that position – for example, in rugby scrums (Peek, 2022; Salmon et al., 2018).

5.1.2.4 Rationale for measuring force distribution through extremities

To extend the findings of Chapter 4, force data is collected in the present study, which enables the quantification of agreement and level of bias between the mean differences of the recordings from the four force plates to be assessed (Giavarina, 2015). As the force plates recorded the individual forces exerted by each of the four extremities, it was deemed necessary to analyse these differences in detail. If all four limbs record identical forces, the differences will clearly be insignificant. However, if they are not identical, calculating the limits of agreement (LoA) will inform understanding of the relative magnitudes of these disparities. This information can then be used to determine whether the force exerted through the limbs is relatively consistent and, if not, should be considered as an influencing factor in the measurement of neck strength.

Another important reason for measuring extremity forces was to consider the set-up position objectively. By determining the percentage distribution of force recorded through each extremity at baseline during the set-up for each neck force direction test, it is possible to deduce whether the test instructions were clear for a standardised start position. These measurements also allow the researcher to observe how the participant accomplishes the neck force output during the force test. This information can in turn serve to clarify the verbal instructions required for reliable testing, thereby enhancing the credibility of the test.

In sum, while the neck cannot be measured in isolation, a deeper understanding of force distribution across the areas of the body that have a potential impact on the test results – e.g. the four extremities in contact with the ground when adopting a quadruped position – will afford greater understanding of potential confounding factors when measuring neck strength. Acknowledging the impact of these external forces on the test may facilitate consistent standardisation of the start position, knowledge about body symmetry during the test and the impact of the verbal instructions given pre-test and during the test to ensure consistency in approach. Finally, using force plates to measure wider bodily force distribution through the extremities ensures that both internal and external validity will be accounted for (Peek, 2022).

5.1.3 Aims, research questions and objectives

5.1.3.1 Aims

The overall aim of this chapter was to determine the distribution of force across the four extremities in the quadruped test position at both the commencement of the test, prior to the neck strength test commencing and at the time of peak neck force produced in all four neck strength tests (Flex, Ext, LSF and RSF) when measuring an MVIC at the neck using the ForceFrame.

5.1.3.2 Research questions

RQ2 Can neck strength be reliably tested using existing equipment?

RQ2b Can test position reliability be achieved?

5.1.3.3 Objectives

The main objectives of this study were:

1) To measure the percentage force distribution across the four extremities – hereafter denoted as left knee (LK), right knee (RK), left hand (LH) and right hand (RH) – at the commencement of the neck force test (baseline) and at the time of peak neck MVIC for the two HA trials and the HT trial in all four neck test positions (Flex, Ext, LSF and RSF);
2) To determine the force distribution symmetry through the extremities for each neck test direction, as calculated between:
    a) Left and right sides, and
    b) Front and back;
3) To determine reliability of force distribution of all four extremities between:
    a) Trial HA1 (Visit 1, Researcher 1) and Trial HA3 (Visit 2, Researcher 1), and
    b) Trial HA1 and Trial HT (both Researcher 1).

5.2 Methods

5.2.1 Introduction

An experiment to investigate the distribution of force exerted through the extremities during neck strength testing was performed. Data for this study was collected alongside the neck strength measurement reliability study described in Chapter 4. Greater detail regarding the recruitment of participants and the overall experimental procedure is provided in Chapter 4 (Section 4.2). What follows is a summary of those procedures, as well as a detailed description of the specific methods employed in this part of the study.

5.2.2 Ethical considerations

Ethical approval was provided by the Coventry University Human Research Ethics Committee (P93801). Participants were informed about the study and gave written informed consent prior to participation (Appendix 4).

5.2.3 Sample

A convenience sample of n = 40 participants (n = 20 male and n = 20 female) was recruited. A required sample size of n = 18 was determined, with a potential 20% loss to follow-up based on *a priori* power analysis (effect size f = 0.8, α = 0.05 and β = 0.02) (G*Power). The power level was set at 80% (ρ = 0.8) and the α error level at 0.05 to reduce the chance of a type I error, in which a true null hypothesis is rejected. The β value was set at 0.02 to reduce the likelihood of committing a type II error, in which a false null hypothesis is accepted. All participants were aged 18 or over and met all inclusion and exclusion criteria (see Table 4.2).

5.2.4 Trials

Participants were required to visit the testing laboratory on two occasions. On their first visit, all 40 participants in the cohort were tested in the hands-apart (HA1) and hands-together (HT) position to investigate the effect of testing position on force distribution through the four extremities in contact with the ground in the quadruped position during an MVIC neck force test. The order of the two trials in Visit 1 was fully randomised through the use of a computerised random number generator.

Of the 40 participants in the cohort, 38 attended a second visit, at least 72 hours after their first. During Visit 2, all 38 participants were retested in the hands-apart position (HA3) to investigate the reliability of this testing position, both at set-up and during the MVIC neck force test (see Figure 4.16). (Hands-apart trial HA2 was conducted by a second researcher as part of the inter-rater reliability study described in Chapter 4 and is not relevant to this chapter.)

Along with the two participants who failed to attend Visit 2 (Participants 16 and 24, both male), a further three participants (Participants 22, 23 and 27, two males and one female) were excluded from statistical analysis due to partially missing data (Section 5.2.7.1). Statistical analysis was therefore performed on 35 participants ($n = 16$ male and $n = 19$ female).

At the start of Visit 1, measurements were recorded of participants' height (to the nearest 0.5 cm; Leicester height stadiometer, SECA) and body mass (to the nearest 0.5 kg; flat scales, SECA 877) (Table 5.1).

Table 5.1 Anthropometric data for force plate study participants (mean ± SD)

	***n* =**	**Age**	**Height (cm)**	**Mass (kg)**
Males	16	22.4 ± 3.6	182 ± 8	86.8 ± 11.6
Females	19	24.7 ± 8.3	166 ± 6[a]	65.6 ± 13.0[a]
Total	35	23.7 ± 6.6	173 ± 11	75.3 ± 16.2

[a] Significantly different to males ($p < 0.05$)

5.2.5 Equipment

Neck force testing was conducted using the VALD ForceFrame (see Section 4.2.5). Data on the GRFs produced through the upper and lower extremities (hands and knees, respectively) was recorded by four Pasco force plates (PS-2141, PASPORT Force Platform) using the Capstone software package. These portable, uniaxial Pasco force plates – each measuring 35 cm by 35 cm and equipped with a single axis load cell that measures vertical axis downward force – were employed due to the test requiring portable force plates that could fit onto the base of the ForceFrame. These force plates had a sampling frequency of 200 Hz, which is consistent with previous research (Chen et al., 2021). They had a force measuring capacity between −1.1 kN and 4.4 kN, with overload protection up to 6.6 kN, and were calibrated prior to use using a known weight of 10 kg. The force plates were zeroed before contact with each participant, as per the manufacturer's instructions, using a software function.

5.2.6 Testing protocol

The testing procedure for the neck MVIC force study is described in Chapter 4 (Section 4.2.6). What follows is a description solely of the elements of the testing procedure that apply to the force plate study.

5.2.6.1 Testing positions

Participants adopted one of two quadruped starting positions: HA, wherein each hand and knee was placed on a separate force plate; or HT, wherein both hands were placed on a single force plate, with the knees on separate force plates (Figure 5.3). This follows the protocol for using force plates to measure GRF during an upper-body activity set out by Koch et al. (2012).

For the HA trials, participants placed their hands a shoulder-width apart and perpendicularly below the shoulder and elbow joints, with elbows fully extended and scapulae retracted (fully drawn together). The hands were placed on two separate force plates in this position, each of which recorded a separate value throughout the test. Hips and knees were set at 90°, with knees therefore directly below the hips and each on a separate force plate. Two of the four force plates were placed on the ForceFrame platform under the measurement arm of the frame, one at the front for a hand and one at the back for a knee (Figure 5.3). As the platform was not wide enough to accommodate all four force plates, the remaining two force plates were placed on a mat to the side of the platform, matching the height of the force plates on the platform (Figure 5.3).

For the HT trial, participants placed their hands directly below the manubrium sterni, with thumbs touching, elbows fully extended and scapulae retracted. Both hands were placed on a single force plate, which recorded a single, combined value for both hands throughout the test. Hips and knees were set at 90°, with knees therefore directly below the hips and each on a separate force plate. The single plate for both hands was placed directly under the load cell of the ForceFrame, and the two rear force plates were situated in the same positions as described for the HA test.

5.2.6.2 Testing procedure

For the test, participants were required to perform three repetitions of their neck MVIC for 3 s per repetition, with 10 s between each repetition. These were conducted in all test directions (Flex, Ext, LSF and RSF) in a randomised order, with 3 min taken between each test direction. The randomisation of test direction and testing position was achieved by assigning the numbers 1–8 to each of the tests (Flex HA, Flex HT, Ext HA, Ext HT, LSF HA, LSF HT, RSF HA and RSF HT) and using a computer program to randomise the order.

Figure 5.3 Four Pasco force plates in position to measure ground reaction force (GRF) during the flexion (Flex) hands-apart (HA) test

(The force plates under the participant's right hand (RH) and right knee (RK) are supported by the base plate on the fixed-frame dynamometer (FFD), and the force plates under the participant's left hand (LH) and left knee (LK) are supported by mats.)

After force recording commenced, participants were instructed to inhale and exhale, allowing time for the recording of their baseline force distribution across the four force plates – LK, RK, LH and RH – in the HA position or three force plates – LK, RK and combined hands (LHRH) – in the HT position. Participants were then instructed, when ready, to push against the ForceFrame load cell as hard and as fast as they could (i.e. produce their MVIC) for 3 s (Salmon et al., 2015) (Figure 5.4). Meanwhile, the force plates collected data synchronously to quantify the forces produced by the upper and lower extremities during the MVIC of the neck (Figure 5.5).

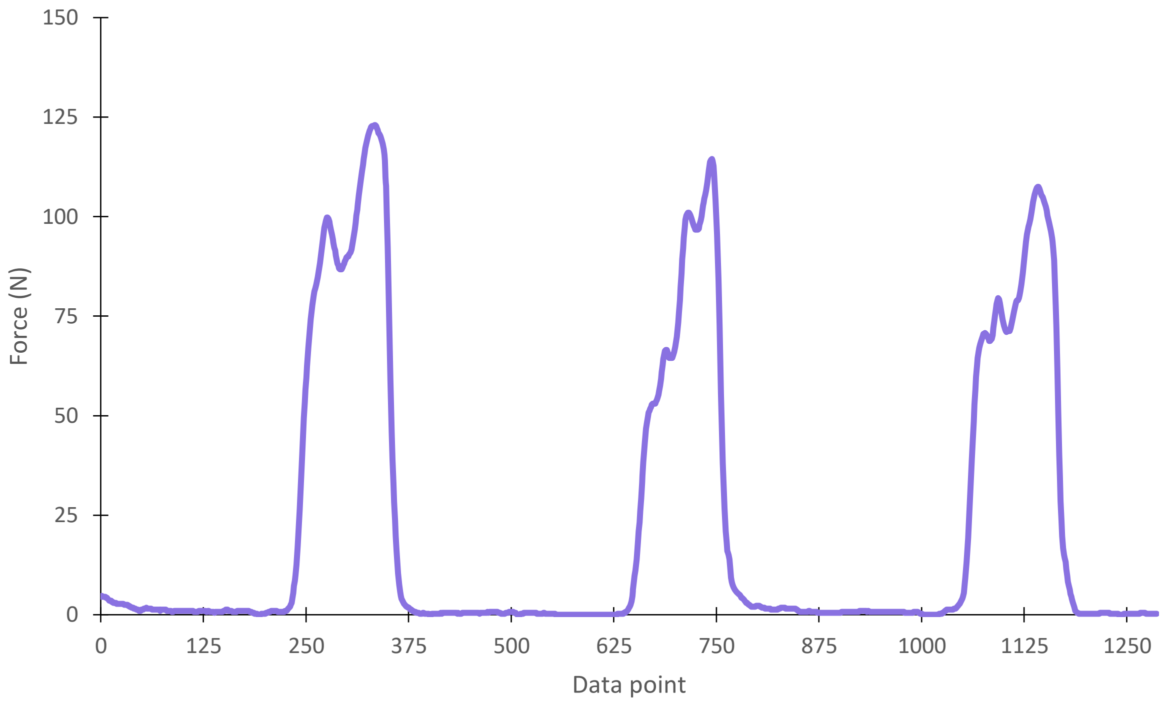


Figure 5.4 Example of ForceFrame traces produced during hands-apart trial HA1 into extension (Ext) (Participant 34, right hand (RH))

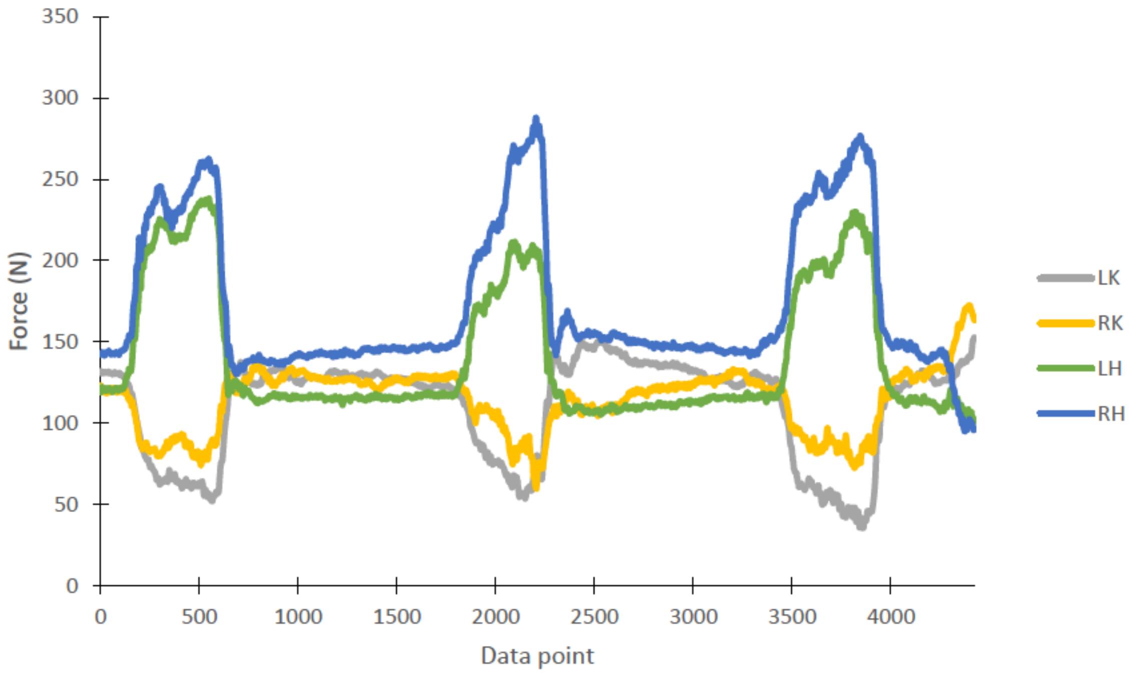


Figure 5.5 Example of force plate traces produced during hands-apart trial HA1 into extension (Ext) (Participant 34, all extremities)

Force data from the force plates was transferred at 200 Hz to a personal computer through a USB connection using the Capstone software package. Data was subsequently uploaded to a private, institutional cloud account and exported into a customised Microsoft Excel 2008 spreadsheet for analysis.

5.2.7 Analysis

5.2.7.1 Data analysis

Extraction of Pasco force plate data (PS-2141, PASPORT Force Platform) was completed for 40 participants for all four neck test directions (Ext, Flex, LSF and RSF). This was undertaken for Trial HA1 and Trial HT, which created a total of 320 traces, each containing four force plate readings for HA (LK, RK, LH and RH) and three force plate readings for HT (LK, RK and LHRH). Two male participants (Participants 16 and 24) were unable to return for the second testing session, so a follow-up was completed on 38 participants (*n* = 18 male and *n* = 20 female), who were each retested in the HA test position in all four neck force test directions (Trial HA3), creating a further 152 traces.

All data sets were processed using Microsoft Excel which synchronised time to the neck force MVIC data recorded by the ForceFrame through visual analysis of the two sets of data and subsequent alignment of the time during the test of the peak neck force recording. Force data was collated from each of the four (HA) or three (HT) force plates. This produced a total of 472 traces to be analysed.

Before statistical analysis, the assumption of normality was confirmed. This revealed some extreme outliers, leading to a visual inspection of the data and all traces being quality-checked for errors. The common errors checked for were either missing data (where the force plate had suffered an omission of recording) or operator recorder error (where the researcher had made a mistake in data transfer). Following this close quality check, five participants were removed from the analysis. These included the two participants (Participants 16 and 24), who had failed to attend Visit 2. In addition, the third was Participant 27 (female), for whom it was established that data for Trial HA3 Ext was missing, potentially due to operator error, as all four force plates failed to demonstrate an output. The fourth was Participant 22 (male), for whom it was discovered that data for LHRH during Trial HT in both Flex and RSF was missing. The fifth was Participant 23 (male), for whom data was missing for RH in Trial HA3 Ext. Despite data for these last three participants being only partially missing, the participants nevertheless showed as extreme outliers when the data was processed for normality, skewness and kurtosis. It was therefore considered appropriate to remove them from the analysis. Therefore, further data and statistical analysis was only performed on 35 participants (*n* = 16 male and *n* = 19 female; Table 5.1).

The absolute peak force (N) measured at each force plate was extracted from the force plate data traces and adjusted to account for body mass in the following way: baseline force from each of the four (HA) or three (HT) force plates was established by calculating the median force applied to each force plate over a period of five seconds prior to MVIC production, during which the participant rested on the force plates. Following this, during the time of recording of peak neck force applied to the ForceFrame (as described in Chapter 4, Section 4.2.6.4), the absolute force measured by each of the four (HA) or three (HT) force plates was recorded. The baseline force for each plate was then subtracted from the absolute peak force to give the relative force exerted through each extremity (or combination, in the case of LHRH) during neck MVIC production.

The distribution of force across the four (HA) or three (HT) force plates was calculated and expressed as a percentage of the total force at baseline, at the point of peak neck force, and as the percentage change this represented from baseline to peak force for all four neck test directions in all three trials.

5.2.7.2 Statistical analysis

Statistical analysis was performed using SPSS version 26 (IBM Corp, Armonk, New York, USA) and the criterion for statistical significance was set at $p \leq 0.05$ *a priori*. The assumption of normality was assessed on the difference between Trial HA1 and Trial HA3, and between Trial HA1 and Trial HT, using a visual exploration of the Q-Q plot, box plots, Shapiro–Wilk test of normality, and kurtosis and skewness values, with normal distribution being indicated between −1 and 1 (Kline, 2016, p. 78). All data was found to be normally distributed and met the assumptions for the statistical tests as described.

The difference in peak force measured through the force plate between two trials (HA1 vs HA3 and HA1 vs HT) for each of the four neck test directions (Flex, Ext, LSF and RSF) for each extremity (LH, RH, LK and RK) were assessed using a paired-sample t-test.

$ICC_{(3,1)}$, two-way mixed model single measure of consistency (Hopkins, 2000), were calculated for reliability of the two trials (HA1 vs HA3 and HA1 vs HT) for each of the four neck test directions (Flex, Ext, LSF and RSF) for each extremity (LH, RH, LK and RK) and evaluated using the following criterion measures: values <0.5 indicated poor reliability, values 0.5–0.75 indicated moderate reliability, values 0.75–0.9 indicated good reliability and values >0.9 indicated excellent reliability (Koo & Li, 2016).

The absolute reliability of the force plate measurements (N) was determined using the standard error of measurement (SE_m), calculated using the formula

$$SE_m = SD \times \sqrt{1 - ICC}$$

where the standard deviation (SD) value was the combined SD value from Trial HA1 and Trial HA3.

The minimal detectable change (MDC) was determined using the formula

$$MDC = 1.96 \times \sqrt{2} \times SE_m$$

and calculated to the 95% confidence level, giving a value that defines the acceptable limits of error of the test (Beckerman et al., 2001).

The 95% LoA ($mean\ [\text{of the differences}] \pm 1.96 \times SD$) were calculated (Bland & Altman, 1999) to assess the agreement between force plate readings for all extremities between the two tests (HA1 and HA3). It was inferred that bias was present if the 95% confidence interval (CI) of the mean of the differences did not include the ratio of 1.00, and to examine the bias a paired t-test was used (Bland & Altman, 1999).

5.3 Results

5.3.1 The quadruped testing position at baseline for all tests

The distribution of force across all four force plates (HA) or three force plates (HT) at baseline for all neck strength test directions (Flex, Ext, LSF and RSF) demonstrated no significant difference ($t(34) < 0.45$, $p > 0.001$ in all cases) at initial set-up (baseline) between Trial HA1 Trial HA3 and Trial HT (Figure 5.6 to Figure 5.13).

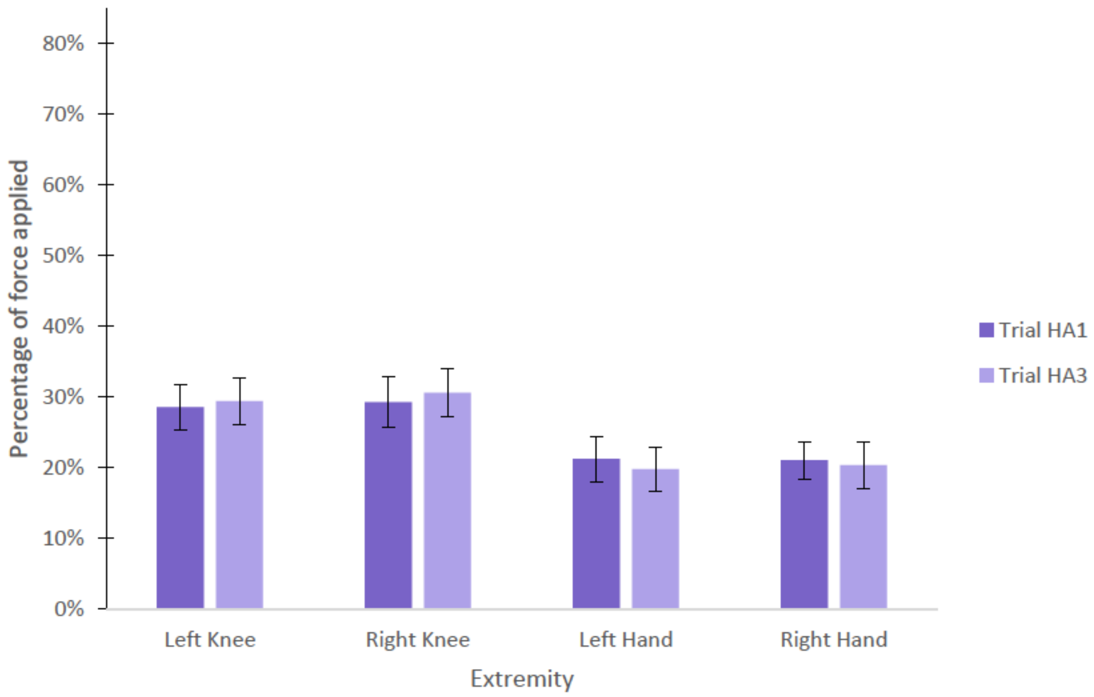


Figure 5.6 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (n = 35) for flexion (Flex)

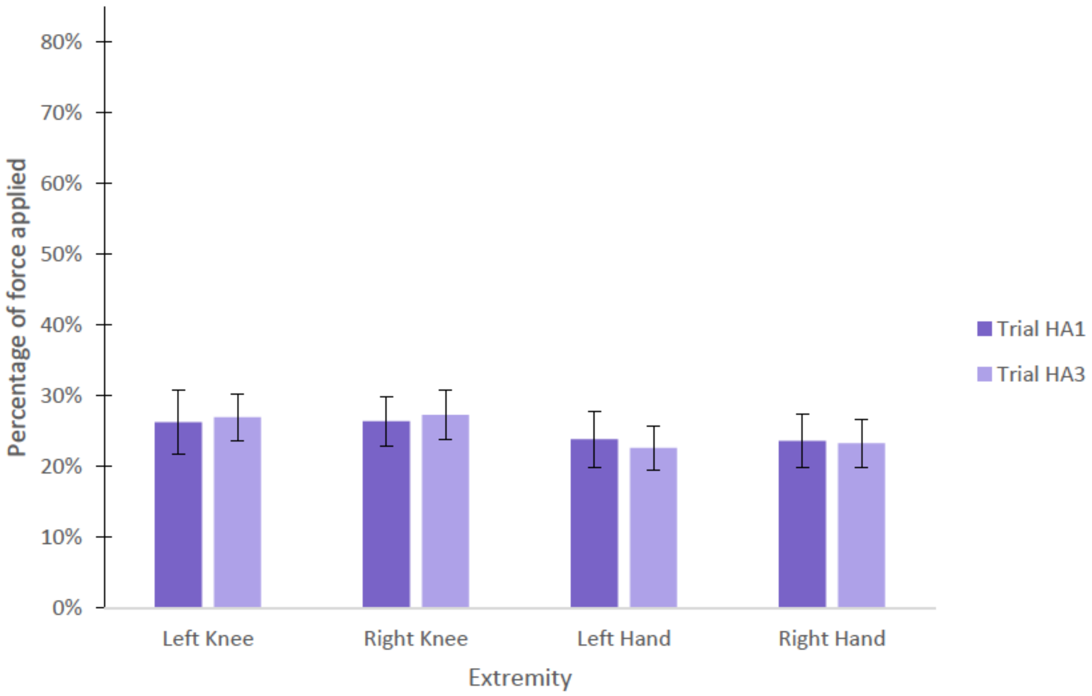


Figure 5.7 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (n = 35) for extension (Ext)

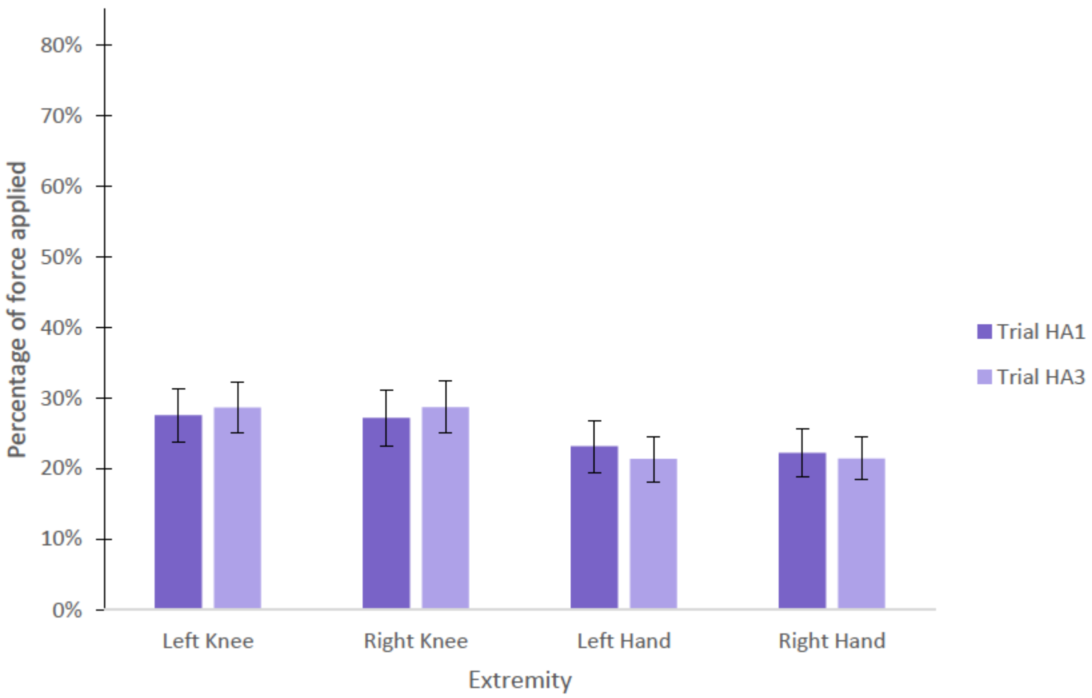


Figure 5.8 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (n = 35) for left side flexion (LSF)

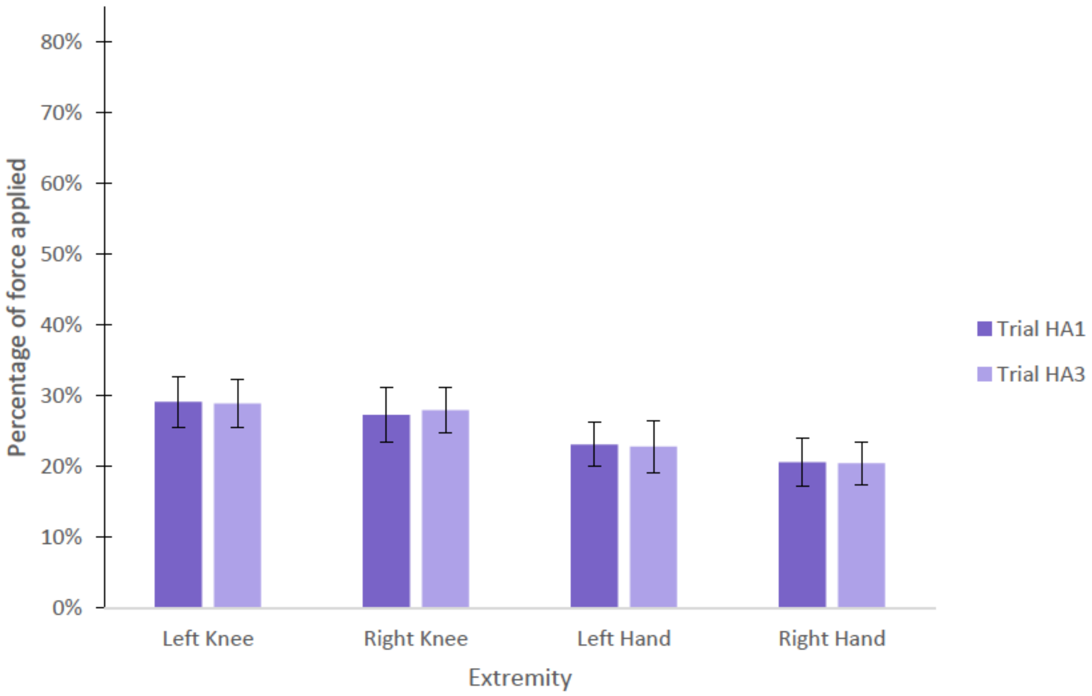


Figure 5.9 Force distribution by extremity at baseline between two hands-apart trials (HA1 and HA3) for all participants (*n* = 35) for right side flexion (RSF)

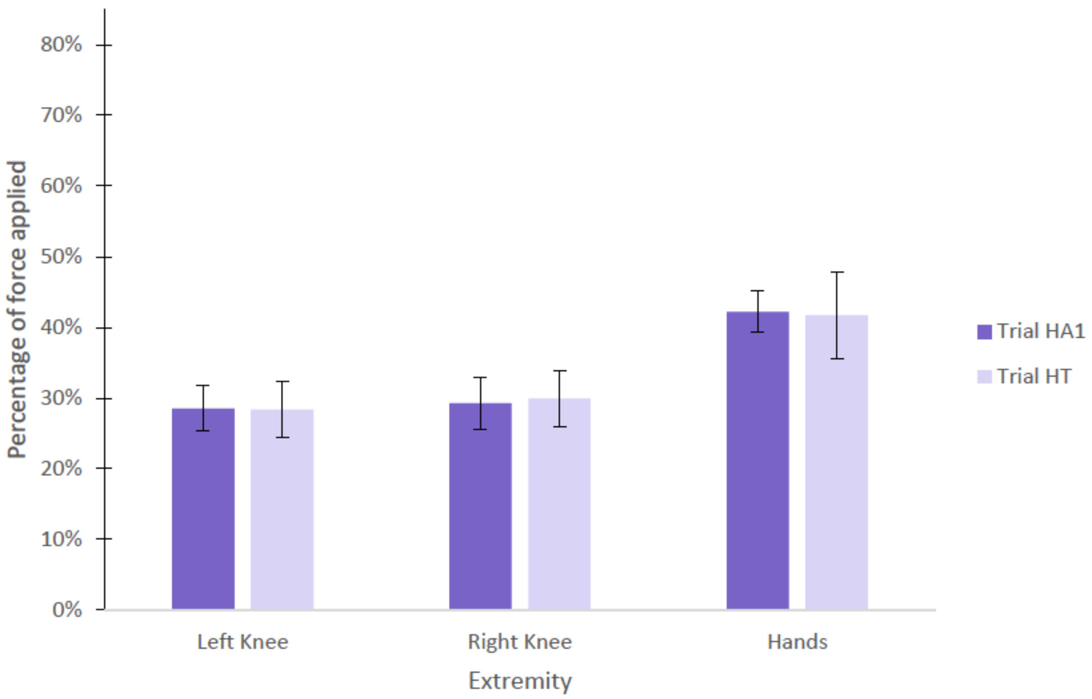


Figure 5.10 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (*n* = 35) for flexion (Flex)

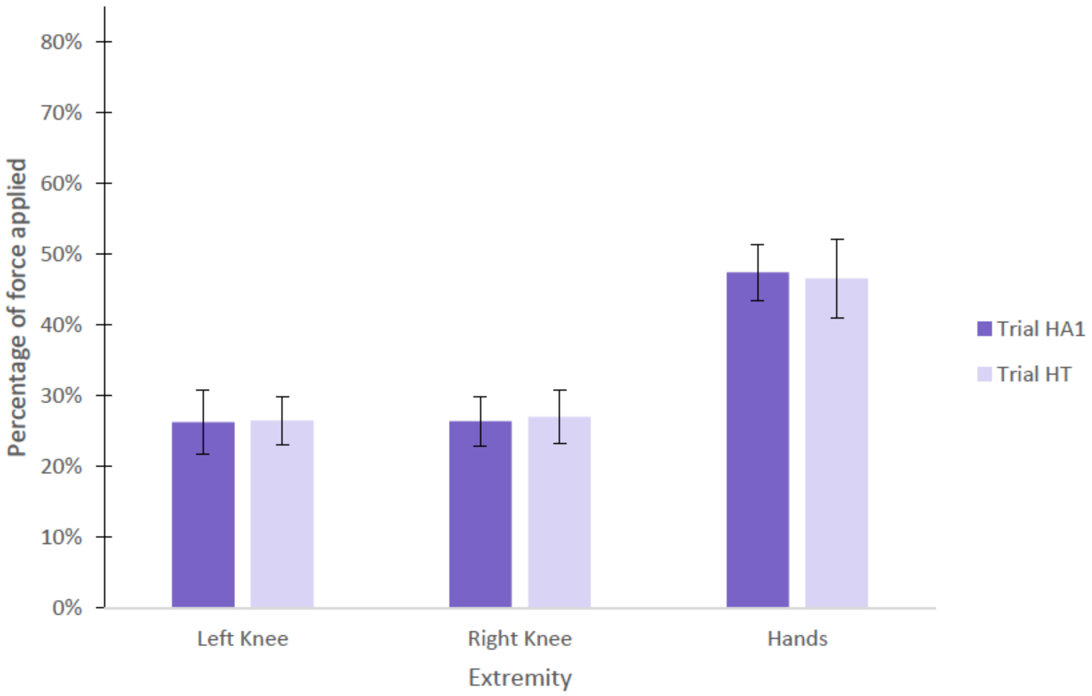


Figure 5.11 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) for extension (Ext)

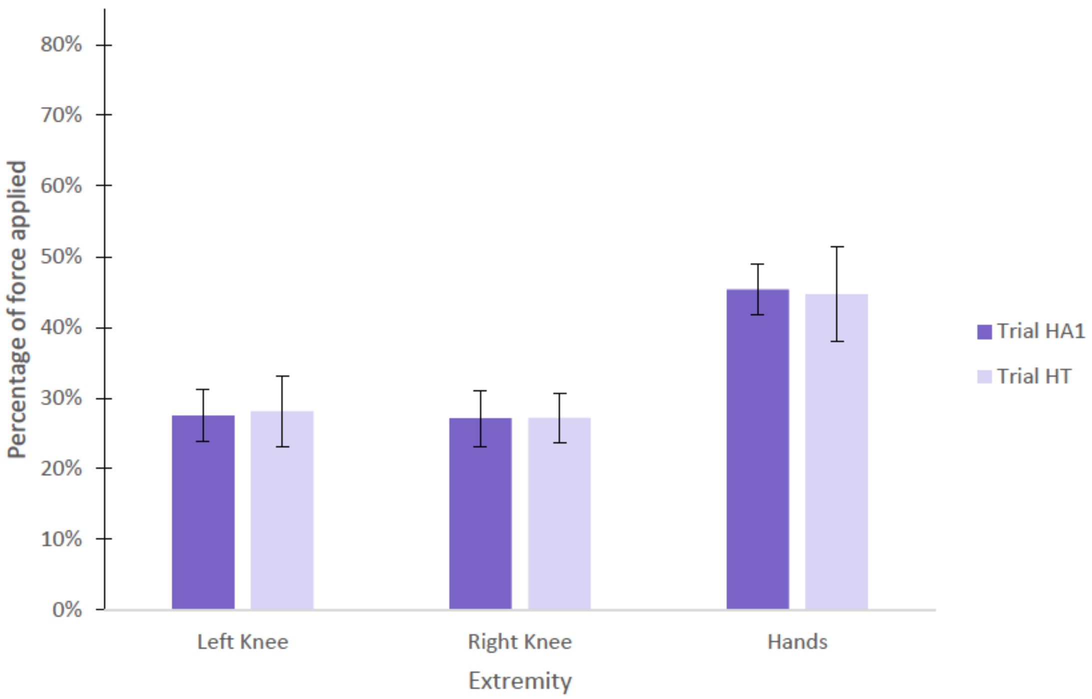


Figure 5.12 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) for left side flexion (LSF)

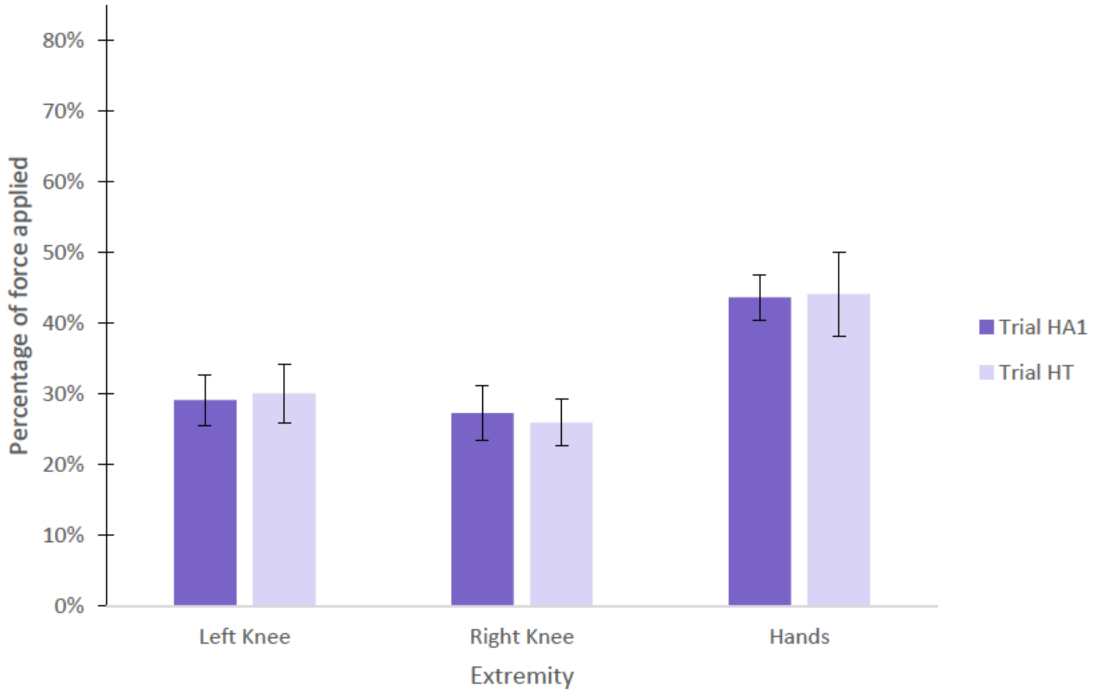


Figure 5.13 Force distribution by extremity at baseline between hands-apart and hands-together trials (HA1 and HT) for all participants (*n* = 35) for right side flexion (RSF)

5.3.2 Two trials in the hands-apart testing position (HA1 and HA3)

The distribution of force across all four force plates was compared to determine differences, via a paired samples *t*-test, between the two hands-apart test conditions (HA1 and HA3) conducted by Researcher 1 during neck strength tests in all four test directions (Flex, Ext, LSF and RSF) and are reported below by extremity (Figure 5.15 to Figure 5.19 and Table 5.2).

5.3.2.1 Rear-left force plate (left knee)

The force recorded through the rear-left force plate (LK) in Trial HA1 and Trial HA3 was not significantly different in the Flex, Ext or RSF neck test directions ($t(34) < 1.55$, $p > 0.13$ in each case) but was significantly higher in LSF HA3 than HA1 ($t(34) = 2.61$, $p = 0.013$) (Figure 5.14 and Table 5.2).

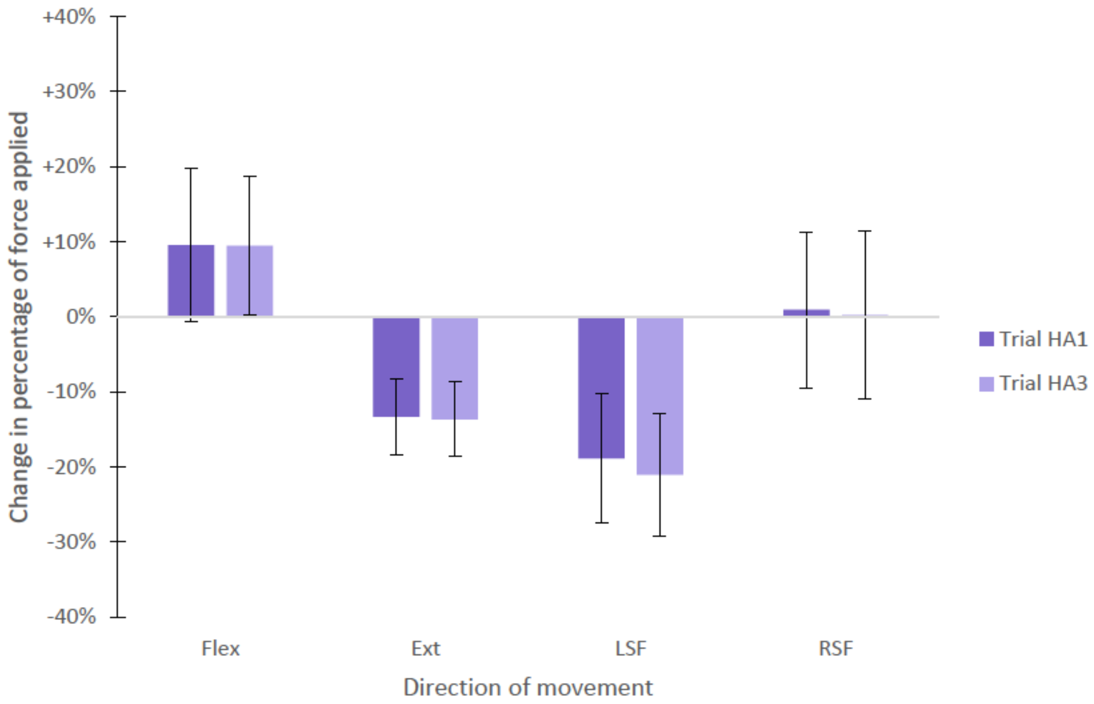


Figure 5.14 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (n = 35) by direction of movement for the left knee (LK)

5.3.2.2 Rear-right force plate (right knee)

The force recorded through the rear-right force plate (RK) in Trial HA1 and Trial HA3 was not significantly different in the Ext or Flex neck test directions ($t(34) < 0.42$, $p > 0.68$ in each case) but was significantly higher in LSF HA3 than HA1 ($t(34) = -2.03$, $p = 0.05$) and significantly lower in RSF HA3 than HA1 ($t(34) = 3.17$, $p = 0.003$) (Figure 5.15 and Table 5.2).

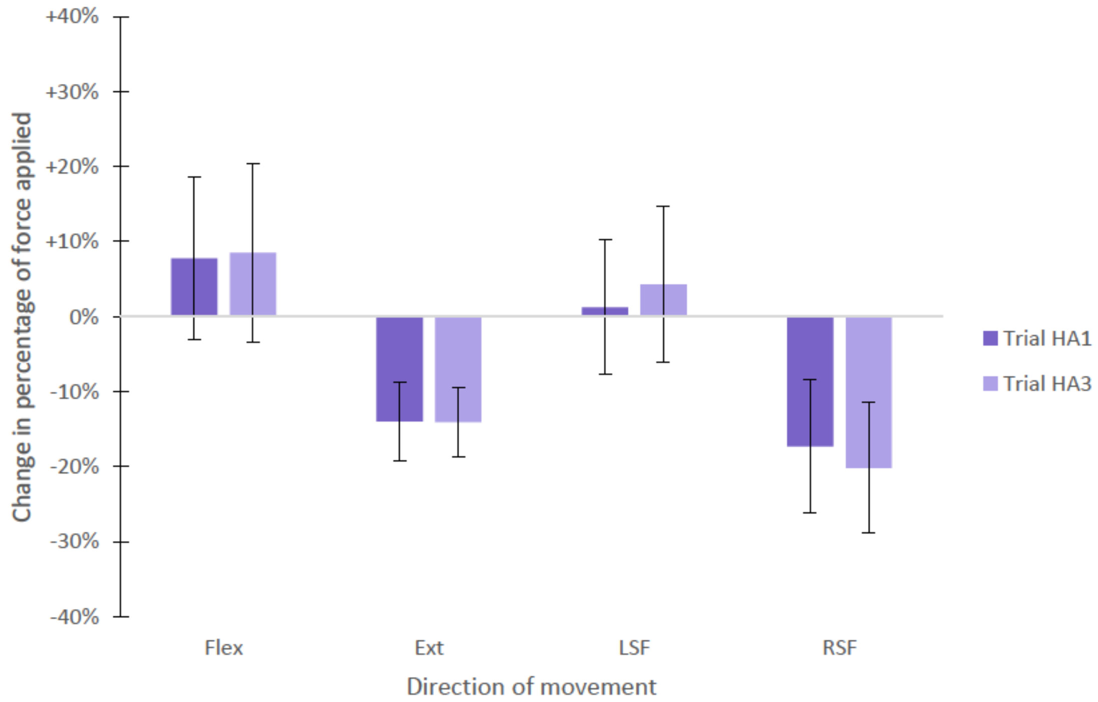


Figure 5.15 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (n = 35) by direction of movement for the right knee (RK)

5.3.2.3 Front-left and front-right force plates (left hand, right hand)

The forces recorded through the front two force plates (LH and RH) in Trial HA1 and Trial HA3 were not significantly different in any of the neck test directions of Flex, Ext, LSF or RSF ($t(34) < -1.82$, $p > 0.08$ in each case for LH, and $t(34) < 0.83$, $p > 0.42$ in each case for RH) (Figure 5.16 and Figure 5.17 and Table 5.2).

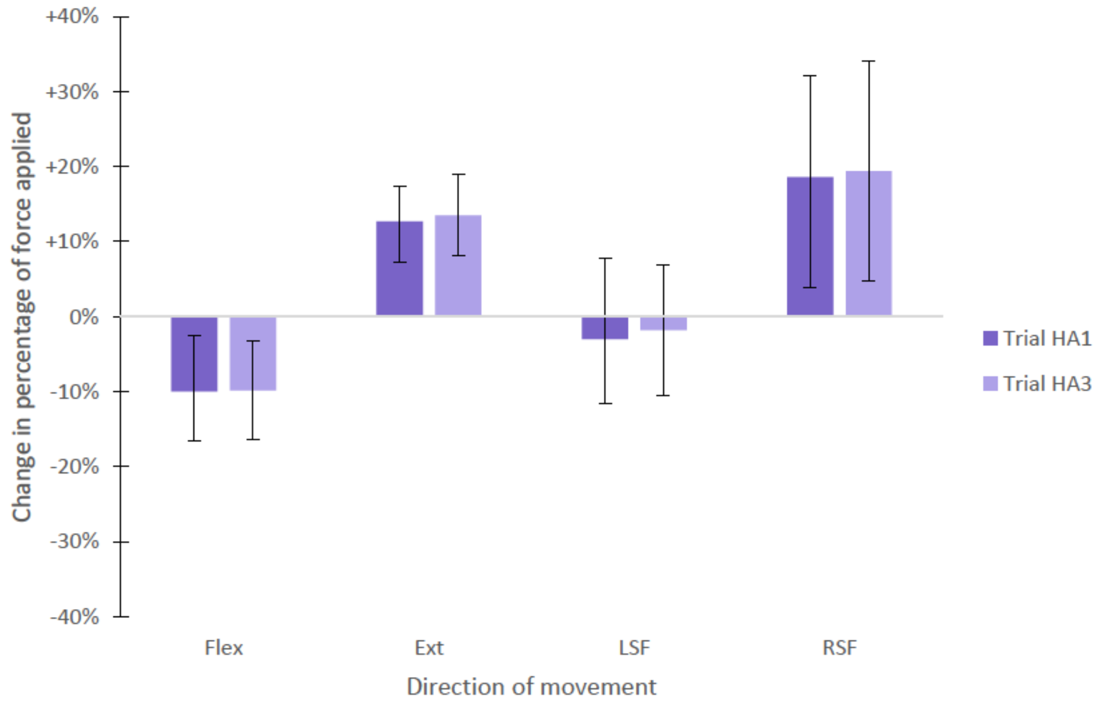


Figure 5.16 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (*n* = 35) by direction of movement for the left hand (LH)

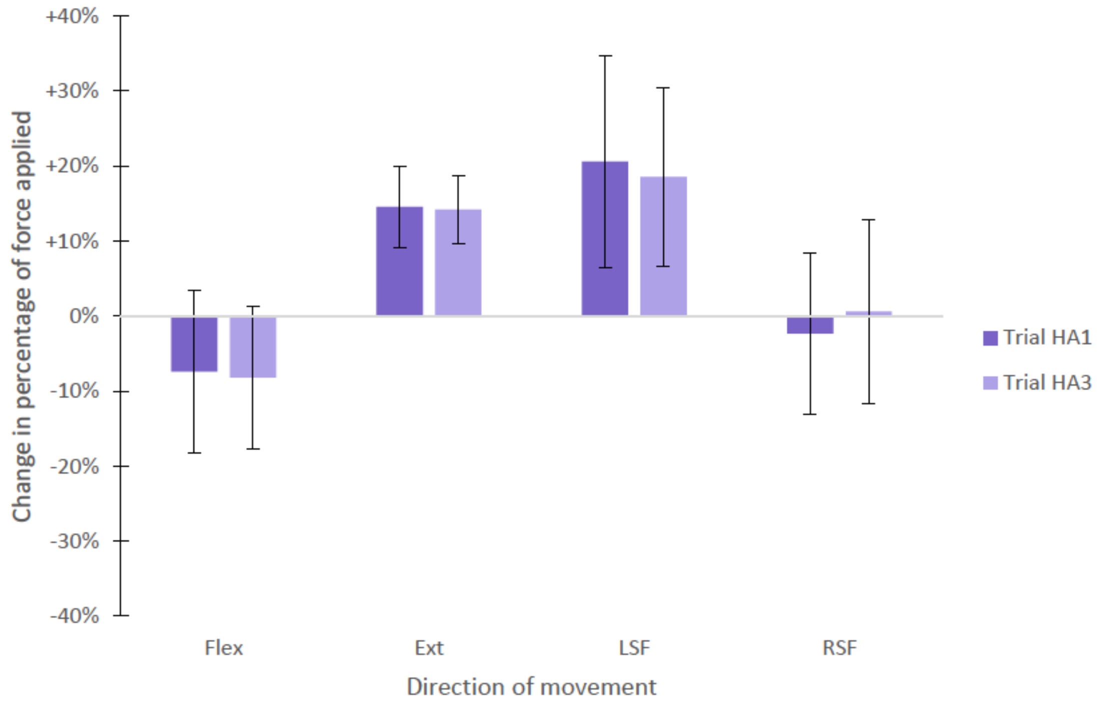


Figure 5.17 Change in force distribution between two hands-apart trials (HA1 and HA3) for all participants (*n* = 35) by direction of movement for the right hand (RH)

5.3.3 Two trials in different hand testing positions (Trial Hands Apart 1 and Trial Hands Together)

5.3.3.1 Rear force plates (left knee and right knee)

The forces recorded through the rear force plates between the two trials (HA1 and HT) for the LK and RK, conducted on Visit 1 by Researcher 1, were not statistically significantly different for Flex or Ext ($t(34) < 0.99$, $p > 0.15$ in each case) but were significantly different for both LSF and RSF ($t(34) < 3.97$, $p \leq 0.001$ in each case) (Figure 5.18 and Figure 5.19).

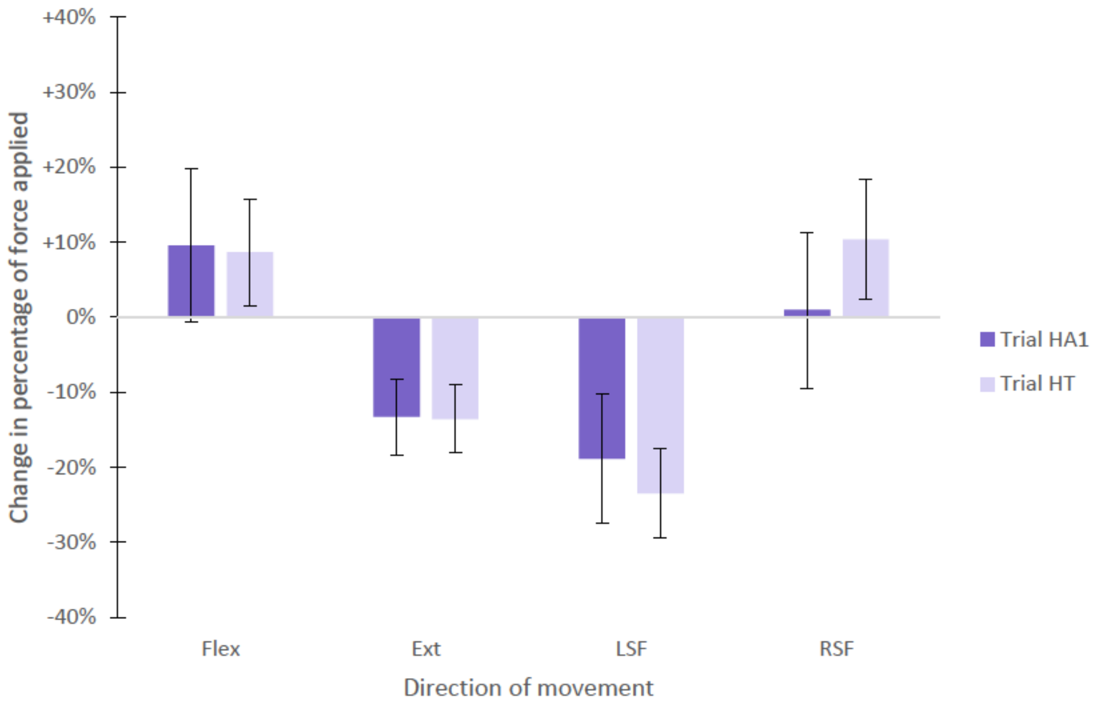


Figure 5.18 Change in force distribution between hands-apart and hands-together trials (HA1 and HT) for all participants (n = 35) by direction of movement for the left knee (LK)

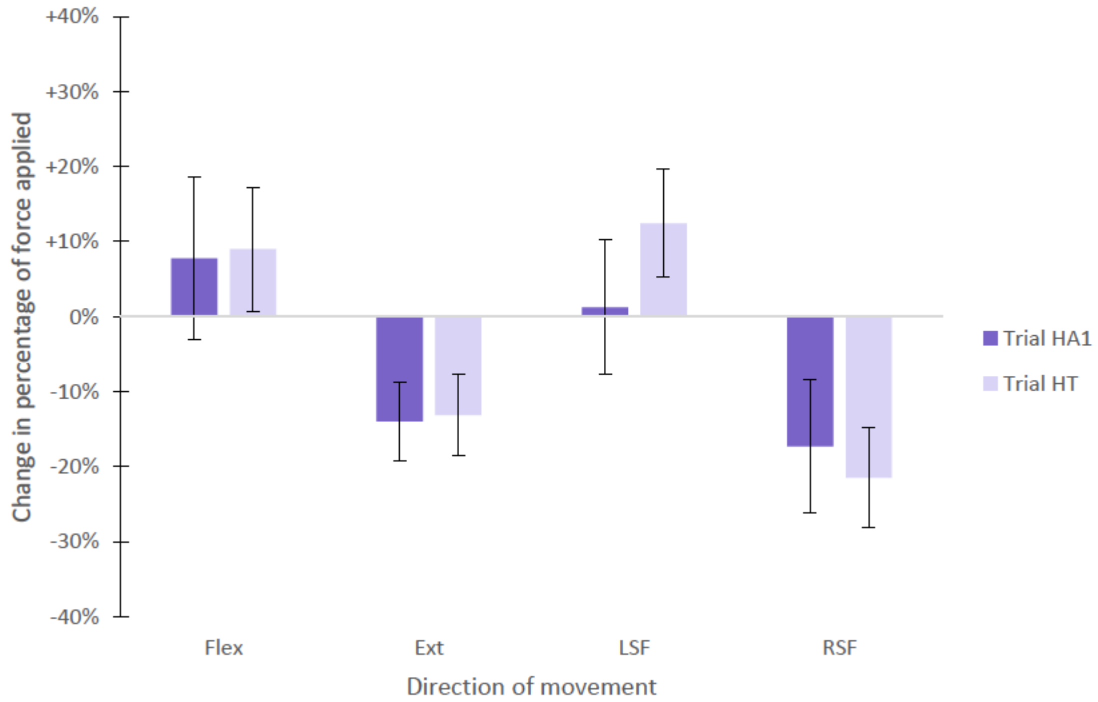


Figure 5.19 Change in force distribution between hands-apart and hands-together trials (HA1 and HT) for all participants (*n* = 35) by direction of movement for the right knee (RK)

5.3.3.2 Front force plates (left hand, right hand and both hands)

The combined force recorded through the force plates for both the LH and the RH in Trial HA1 and the force recorded through the single force plate for LHRH in Trial HT were not significantly different for all neck test directions of Flex, Ext, LSF or RSF ($t(34) < 1.1$, $p > 0.30$ in each case) (Figure 5.20).

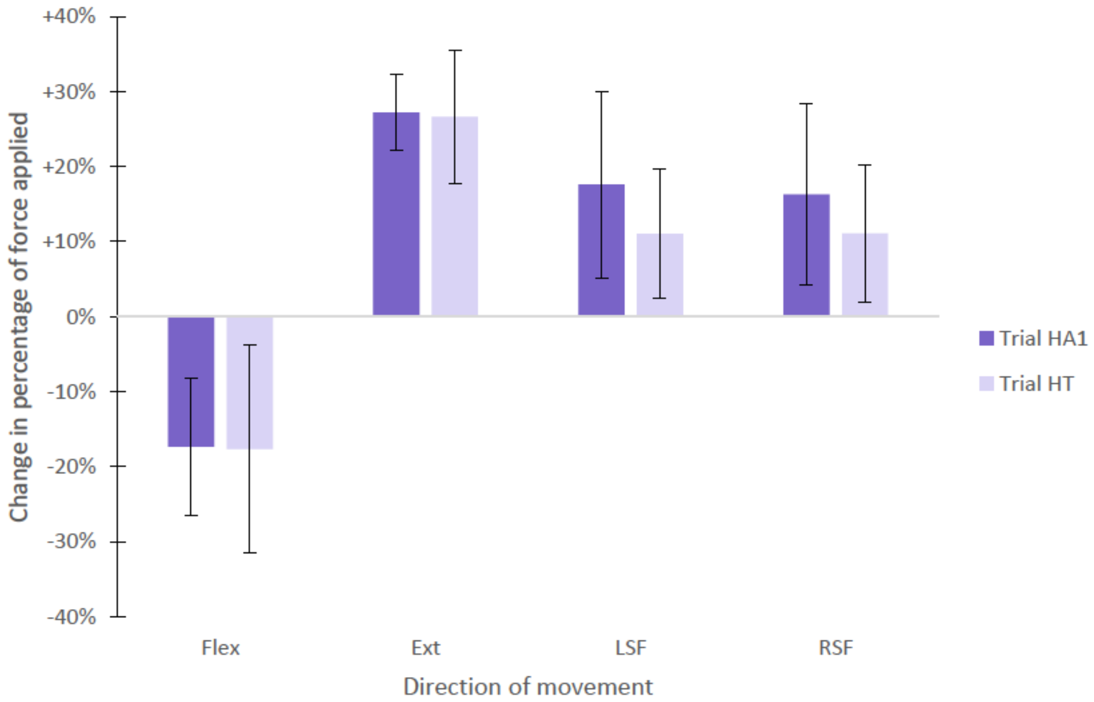


Figure 5.20 Change in force distribution between hands-apart and hands-together trials (HA1 and HT) by direction of movement for the left hand + right hand (LH+RH) and single plate left hand and right hand together (LHRH)

5.3.4 Reliability analysis (Trial Hands Apart 1 and Trial Hands Apart 3)

Reliability data for the two HA trials demonstrated good $ICC_{(3,1)}$ values (≥0.75) for all four extremities in the neck test direction of Flex. For Ext, excellent $ICC_{(3,1)}$ values (≥0.9) were recorded for the three extremities of LK, LH and RH, while reliability for the RK was good ($ICC_{(3,1)} = 0.89$). In LSF, reliability was excellent for the RH ($ICC_{(3,1)} = 0.90$), good for the LK and LH ($ICC_{(3,1)}$ values of 0.87 and 0.82, respectively) and moderate for the RK ($ICC_{(3,1)} = 0.68$). Finally, in RSF, good reliability ($ICC_{(3,1)}$ ≥0.75) was found for all four extremities (Koo & Li, 2016). The highest SE_m was recorded in the RK for LSF (44.2 N) and in the LK for RSF (36.7 N), indicating that the highest level of variability was in the two test directions of side flexion (SF) in the knee opposite to the direction of neck movement. When MDC was compared with the overall mean for each direction, the highest value was 123 N for the RK in the test direction of LSF, and the lowest was 29.4 N for the LK in the test direction of Ext (Table 5.2).

Table 5.2 Mean ± SD for change in participants' (*n* = 35) force plate values and reliability values for all four neck test directions

						ICC			
Direction	**Force plate**	**Trial HA1 (N)**	**Trial HA3 (N)**	**Mean (N)**	**Difference between trials (N)**	**$ICC_{(3,1)}$**	**95 % CI**	**SE_m (N)**	**MDC (N)**
Ext	LK	−76.1 ± 44.1	−78.7 ± 42.1	−77.4 ± 43.1	2.55	0.94	0.88–0.97	10.6	29.4
	RK	−80.9 ± 42.8	−80.5 ± 44.0	−80.5 ± 43.2	0.41	0.89	0.79–0.95	14.3	39.7
	LH	159 ± 74.8	168 ± 84.5	163 ± 79.3	8.94	0.95	0.90–0.97	17.7	49.2
	RH	176 ± 85.6	172 ± 74.6	174 ± 79.8	4.48	0.96	0.92–0.98	16.0	44.2
Flex	LK	−7.32 ± 67.2	−19.2 ± 68.7	−13.2 ± 67.8	11.8	0.87	0.75–0.94	24.4	67.7
	RK	−19.8 ± 75.4	−24.3 ± 75.9	−22.1 ± 75.2	4.52	0.78	0.56–0.89	35.3	97.7
	LH	−101 ± 36.8	−96.1 ± 39.7	−98.4 ± 38.1	4.53	0.87	0.74 –0.93	13.7	38.0
	RH	−93.3 ± 33.0	−92.9 ± 37.2	−93.1 ± 34.9	0.41	0.77	0.55–0.89	16.8	46.4
LSF	LK	−135 ± 63.6	−155 ± 69.6	145 ± 66.9	20.2[a]	0.87	0.74–0.93	24.1	66.9
	RK	−0.79 ± 72.0	25.4 ± 82.8	12.3 ± 78.1	26.2[a]	0.68	0.37–0.84	44.2	123
	LH	−31.4 ± 66.4	−15.2 ± 67.7	−23.3 ± 67.1	16.3	0.82	0.64–0.91	28.5	78.9
	RH	111 ± 78.8	106 ± 66.7	108 ± 72.5	5.12	0.90	0.80–0.95	22.9	63.6
RSF	LK	6.71 ± 73.7	−1.41 ± 83.5	2.65 ± 78.2	8.12	0.78	0.56–0.89	36.7	102
	RK	−127 ± 70.1	−151 ± 70.6	−139 ± 70.8	23.6[a]	0.89	0.78–0.95	23.5	65.1
	LH	113 ± 75.2	122 ± 67.3	118 ± 71.0	9.20	0.85	0.71–0.93	27.5	76.2
	RH	−20.4 ± 68.7	−17.7 ± 65.8	−19.1 ± 66.8	2.73	0.87	0.75–0.94	24.1	66.8

ICC = intraclass correlation coefficient; 95% CI = confidence interval for the $ICC_{(3,1)}$ single measure; CV = coefficient of variance; SE_m = standard error of measurement; MDC = minimal detectable change; Ext = extension; Flex = flexion; LSF = left side flexion; RSF = right side flexion; HA = hands apart; LK = left knee; RK = right knee; LH = left hand; RH = right hand [a] Significant difference between Trial HA1 and Trial HA3 ($p < 0.05$).

5.3.5 Limits of agreement between force plates

To assess agreement between the forces recorded by the force plates, the differences between measures recorded from baseline to peak neck force and between Trials HA1 to HA3 and HA1 to HT were used to calculate an estimate of the LoA between trials (Table 5.3).

Table 5.3 Bias and 95% limits of agreement for all force plates (left knee, right knee, left hand and right hand) in all neck test directions

Direction	Force plate(s)	Bias	Significance (*p* value)	SD	Lower 95% limit	Upper 95% limit	*r* (mean vs abs diff)
	LK and RK (HA1)	−5.18	0.636	64.2	−131	121	−0.241
	LH and RH (HA1)	−3.23	0.583	34.6	−71.0	64.5	0.075
Flex	LK + LH and RK + RH (HA1)	1.95	0.861	65.1	−126	130	−0.228
	LK + RK and LH + RH (HA1)	146	0.001	157	−162	453	0.401
	LHRH (HT) and LH + RH (HA1)	5.94	0.363	38.1	−68.8	80.7	−0.129
	LK and RK (HA1)	3.44	0.450	26.6	−48.7	55.6	−0.176
	LH and RH (HA1)	−4.12	0.586	44.3	−91.0	82.8	0.194
Ext	LK + LH and RK + RH (HA1)	−0.690	0.936	50.4	−99.5	98.1	0.278
	LK + RK and LH + RH (HA1)	−497	0.001	230	−949	−45.5	0.841
	LHRH (HT) and LH + RH (HA1)	−8.60	0.360	54.8	−116	98.9	0.342
	LK and RK (HA1)	−134	0.001	91.7	−314	45.5	0.184
	LH and RH (HA1)	−121	0.001	123	−363	121	−0.010
LSF	LK + LH and RK + RH (HA1)	−276	0.001	147	−565	12.1	−0.461
	LK + RK and LH + RH (HA1)	−215	0.001	144	−497	67.2	−0.831
	LHRH (HT) and LH + RH (HA1)	−6.09	0.456	47.8	−99.7	87.5	0.115
	LK and RK (HA1)	134	0.001	113	−87.5	356	0.185
	LH and RH (HA1)	134	0.001	120	−101	369	0.107
RSF	LK + LH and RK + RH (HA1)	268	0.001	171	−67.8	603	−0.095
	LK + RK and LH + RH (HA1)	−213	0.001	150	−507	80.7	−0.129
	LHRH (HT) and LH + RH (HA1)	−26.0	0.020	63.2	−150	97.8	0.763

LoA = limit of agreement; Flex = flexion; Ext = extension; LSF = left side flexion; RSF = right side flexion; LK = left knee; RK = right knee; LH = left hand; RH = right hand; LHRH = left hand and right hand together; HA1 = Trial Hands Apart 1; HT = Trial Hands Together

5.3.5.1 Test direction: flexion

For Flex, the absolute LoA calculated for the change in the force measured between the baseline and the recording of peak force were found not to be significantly different ($p > 0.36$ in all cases) between the two rear force plates in Trial HA1 (Figure 5.21), the two front force plates in Trial HA1 (Figure 5.22), the two combined left force plates and the two combined right force plates in Trial HA1 (Figure 5.23), and the two combined front force plates in Trial HA1 and the single front force plate in Trial HT (Figure 5.24). The LoA for the change in the force measured between the baseline and the peak force was found to be significantly different ($r = 0.401$, bias 146, $p \leq 0.001$) between the two combined rear force plates and the two combined front force plates for Flex in Trial HA1 (Figure 5.25).

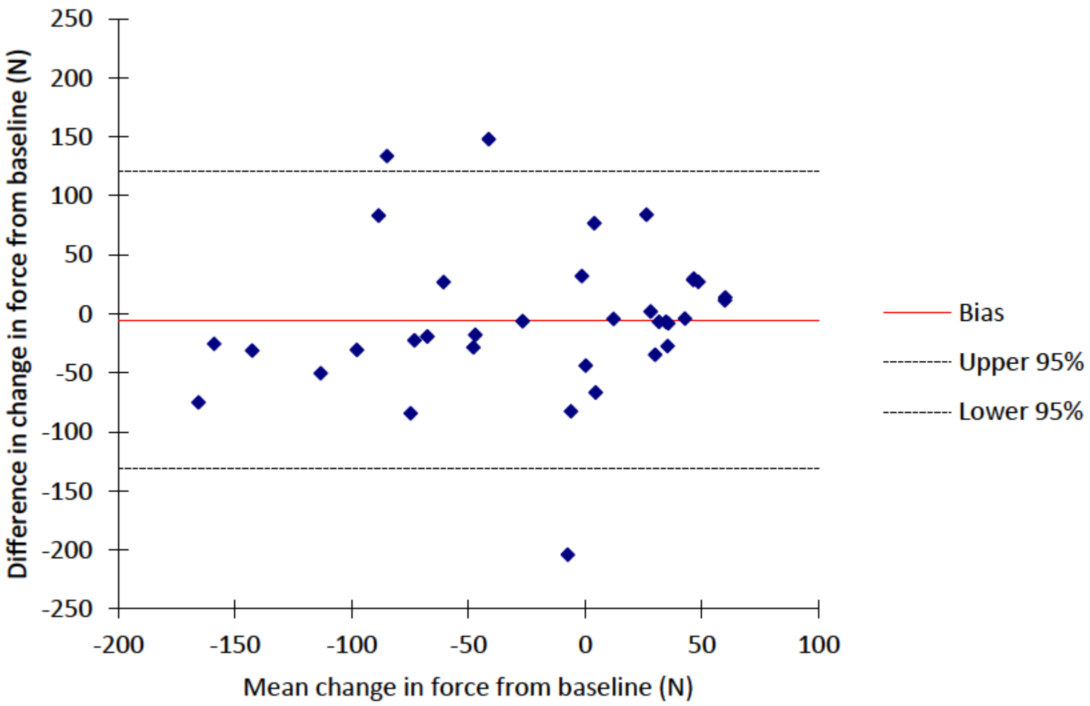


Figure 5.21 Bland–Altman plot for left knee (LK) and right knee (RK) in flexion (Flex) hands apart (HA1)

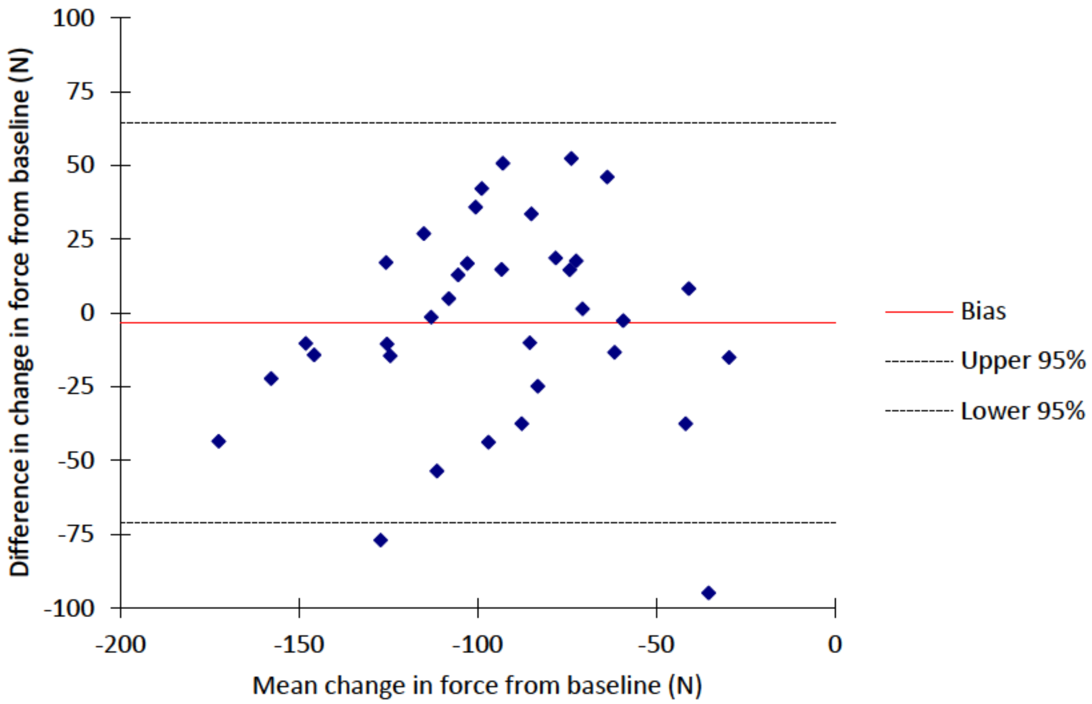


Figure 5.22 Bland–Altman plot for left hand (LH) and right hand (RH) in flexion (Flex) hands apart (HA1)

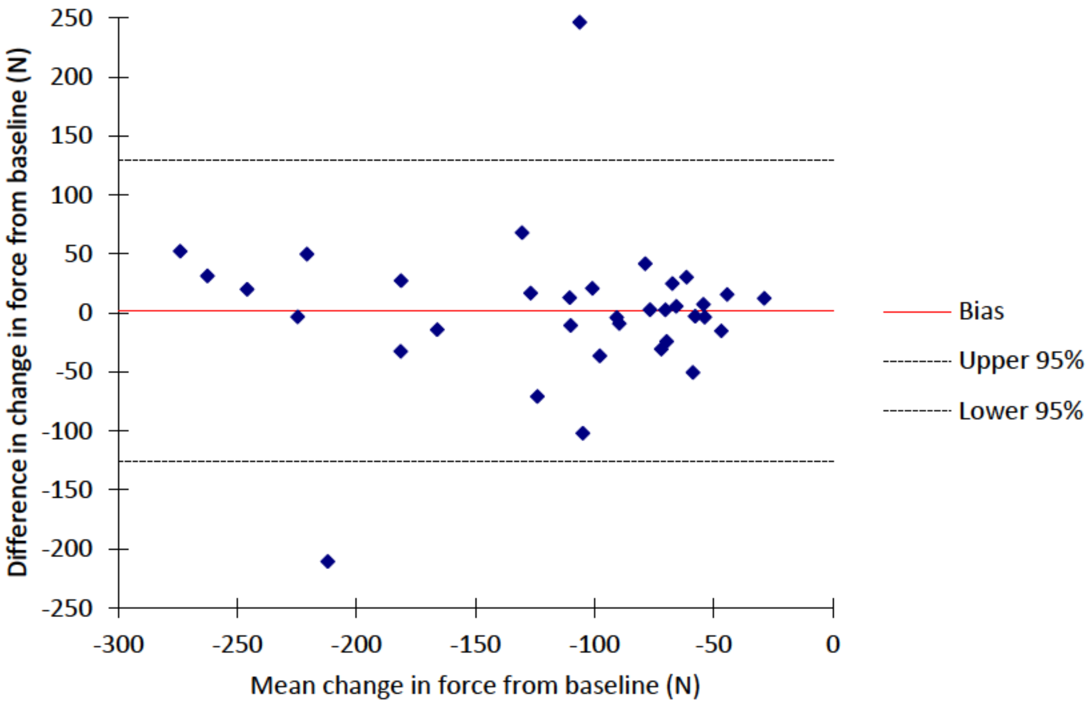


Figure 5.23 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in flexion (Flex) hands apart (HA1)

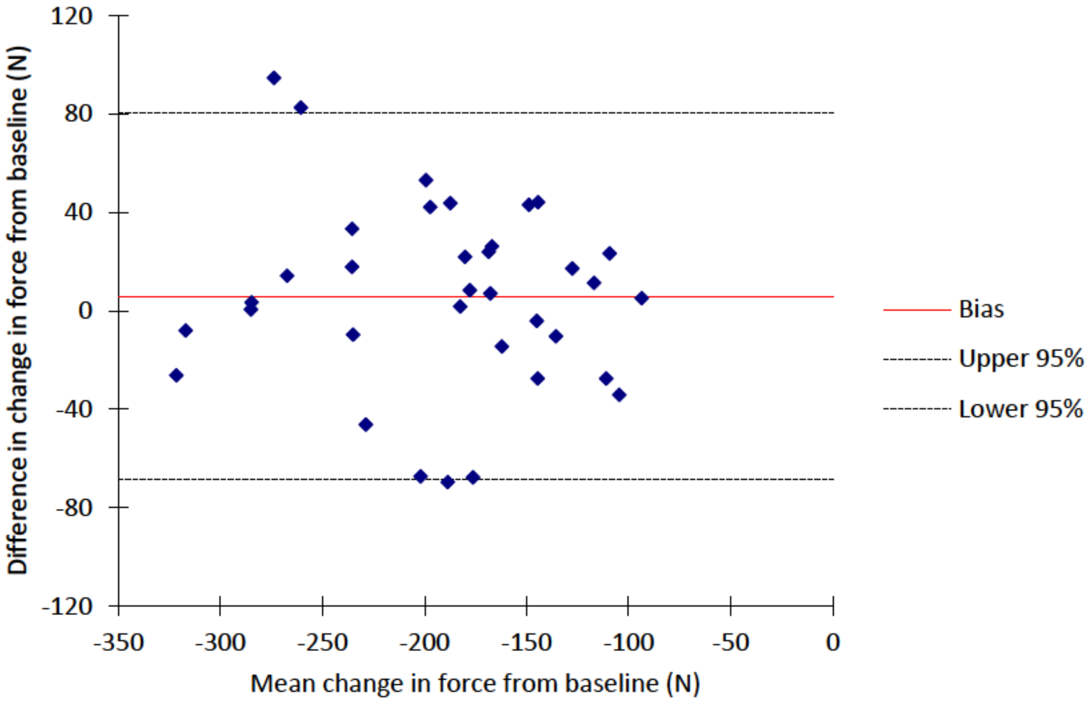


Figure 5.24 Bland–Altman plot for both hands (LHRH) in flexion (Flex) hands together (HT) and left hand (LH) + right hand (RH) in flexion (Flex) hands apart (HA1)

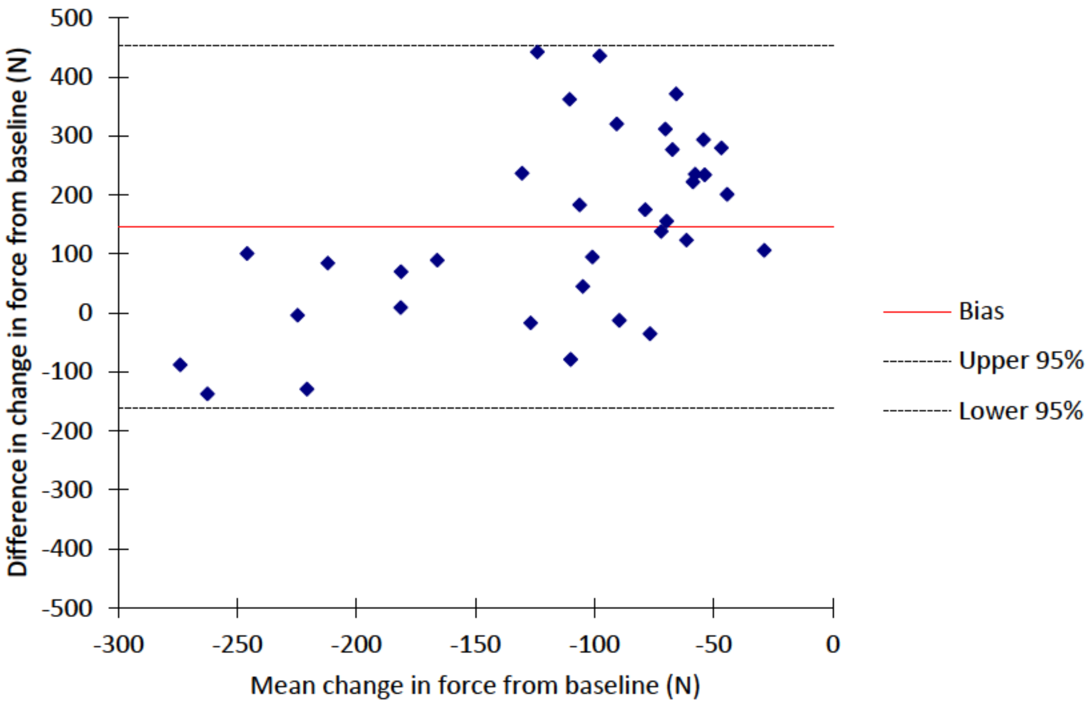


Figure 5.25 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in flexion (Flex) hands apart (HA1)

5.3.5.2 Test direction: extension

For Ext, the LoA calculated for the change in the force measured between the baseline and the peak force recorded were found not to be significantly different ($p > 0.45$ in all cases) between the two rear force plates in Trial HA1 (Figure 5.26), the two front force plates in Trial HA1 (Figure 5.27), the two combined left force plates and the two combined right force plates in Trial HA1 (Figure 5.28), and the two combined front force plates in Trial HA1 and the single front force plate in Trial HT (Figure 5.29). The LoA for the change in the force measured between the baseline and the peak force was found to be significantly different ($r = 0.841$, bias −497, $p \leq 0.001$) between the two combined rear force plates and the two combined front force plates for Ext in Trial HA1 (Figure 5.30).

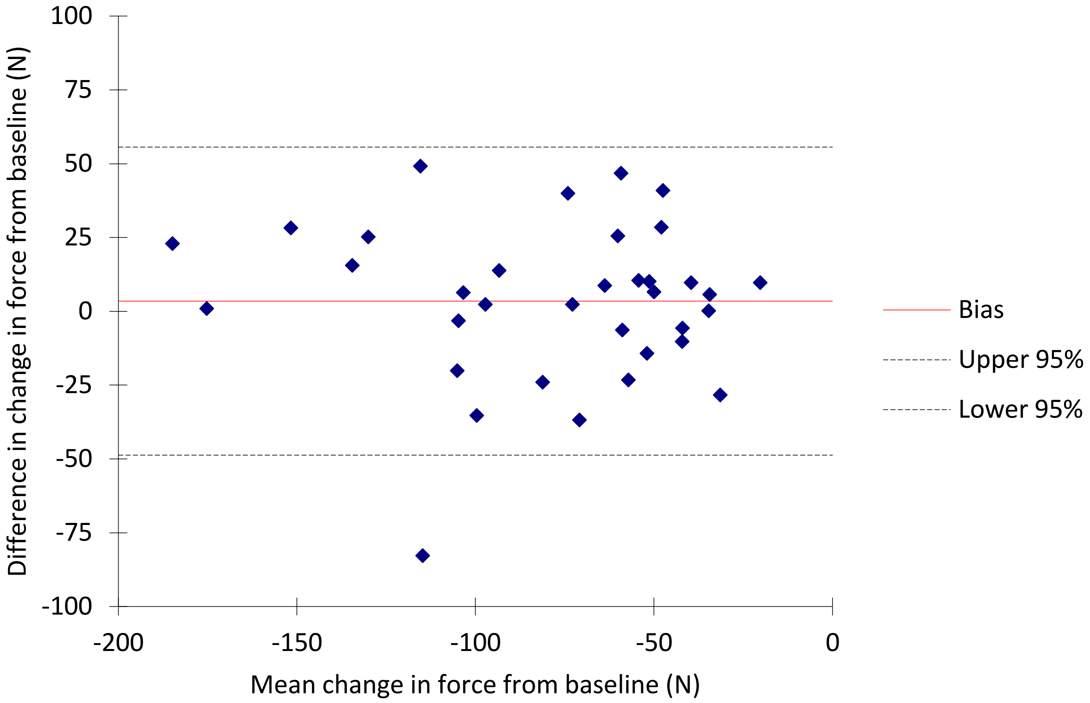


Figure 5.26 Bland–Altman plot for left knee (LK) and right knee (RK) in extension (Ext) hands apart (HA1)

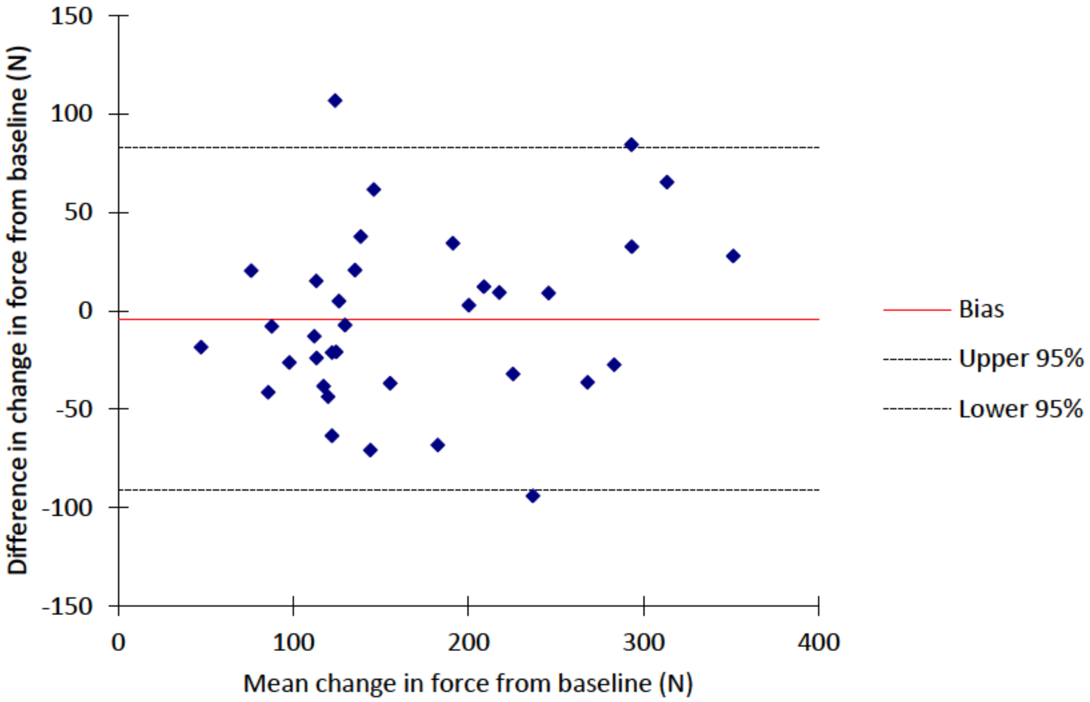


Figure 5.27 Bland–Altman plot for left hand (LH) and right hand (RH) in extension (Ext) hands apart (HA1)

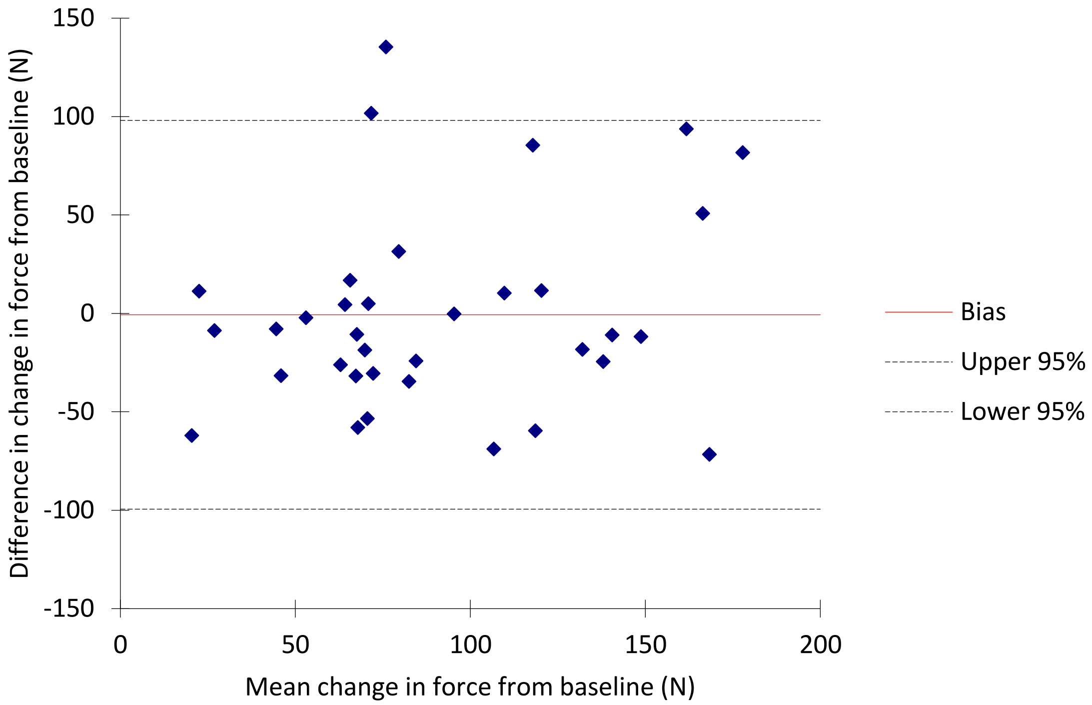


Figure 5.28 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in extension (Ext) hands apart (HA1)

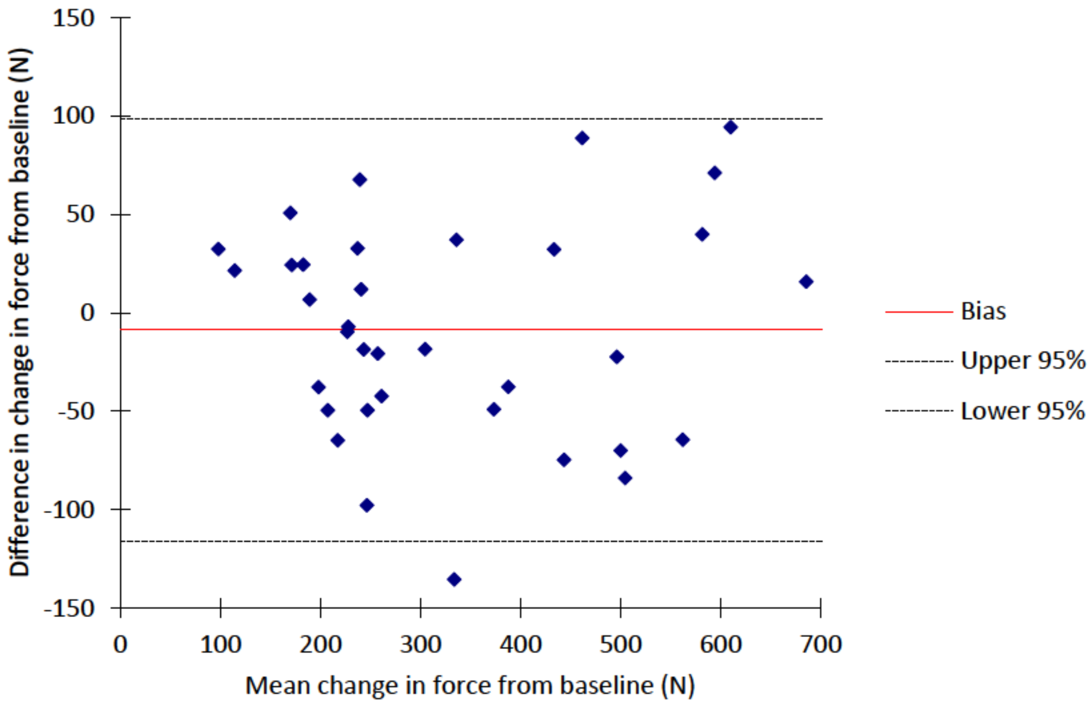


Figure 5.29 Bland–Altman plot for both hands (LHRH) in extension (Ext) hands together (HT) and left hand (LH) + right hand (RH) in extension (Ext) hands apart (HA1)

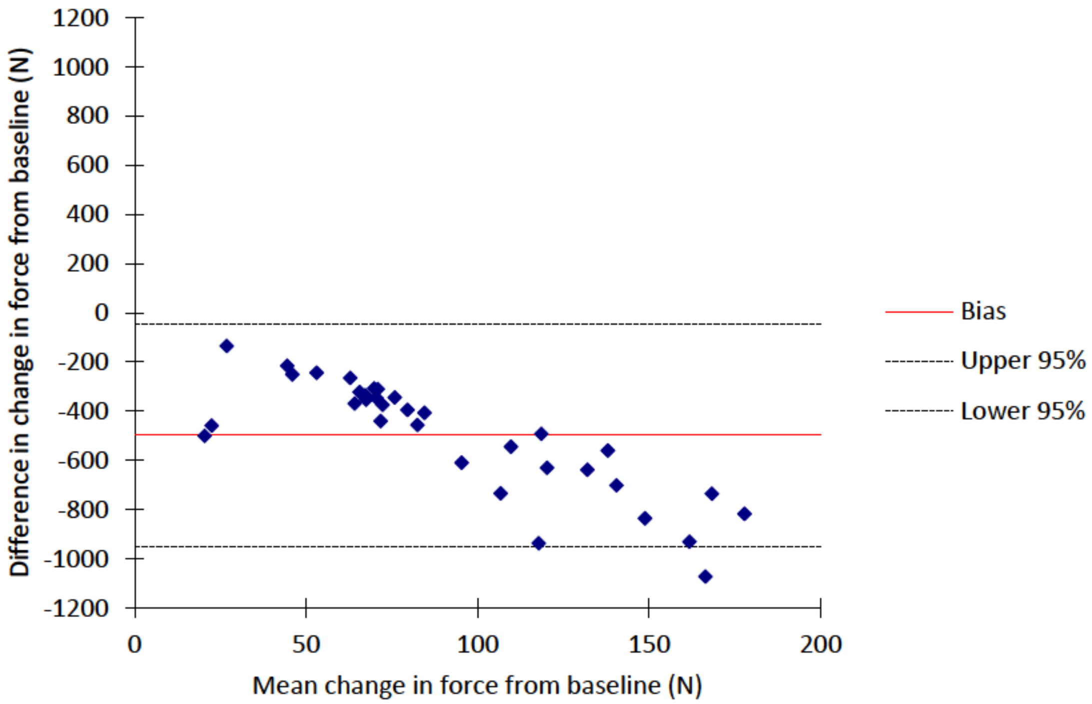


Figure 5.30 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in extension (Ext) hands apart (HA1)

5.3.5.3 Test direction: left side flexion

For LSF, the LoA calculated for the change in the force measured between the baseline and the peak force recorded were found to be significantly different ($p \leq 0.001$) between the two rear force plates in Trial HA1 (Figure 5.31), the two front force plates in Trial HA1 (Figure 5.32), the two combined left force plates and the two combined right force plates in Trial HA1 (Figure 5.33), and the two combined rear force plates and the two combined front force plates in Trial HA1 (Figure 5.34). The LoA for the change in the force measured between the baseline and the peak force was found not to be significantly different ($p = 0.46$) for LSF between the two combined front force plates in Trial HA1 and the single front force plate in Trial HT (Figure 5.35).

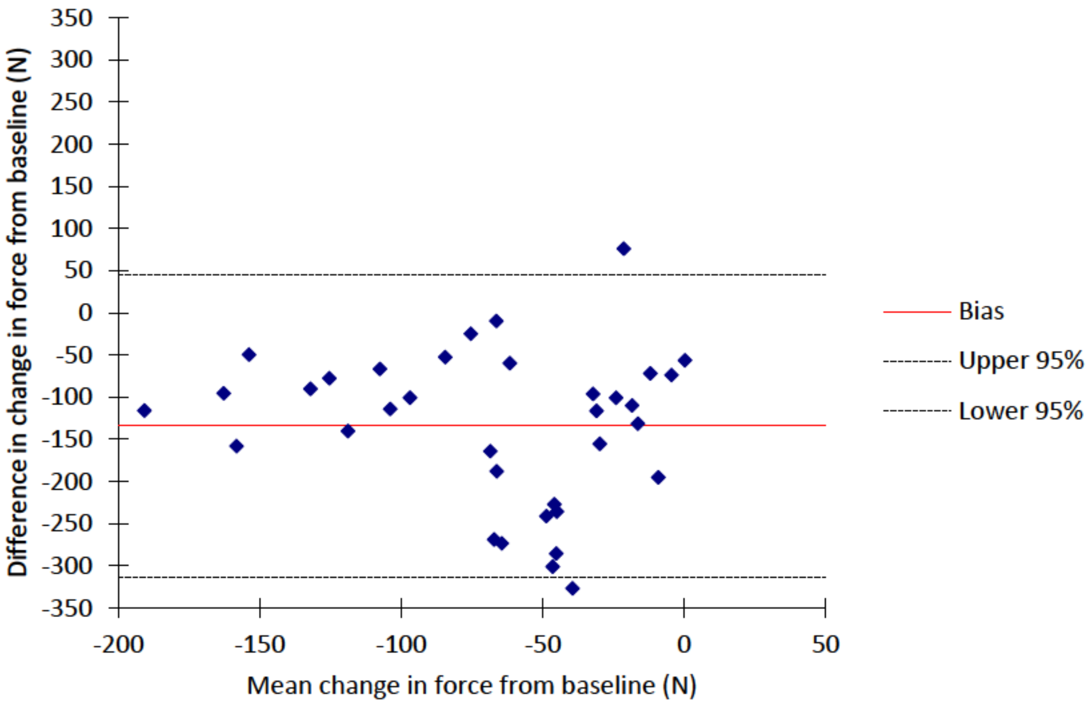


Figure 5.31 Bland–Altman plot for left knee (LK) and right knee (RK) in left side flexion (LSF) hands apart (HA1)

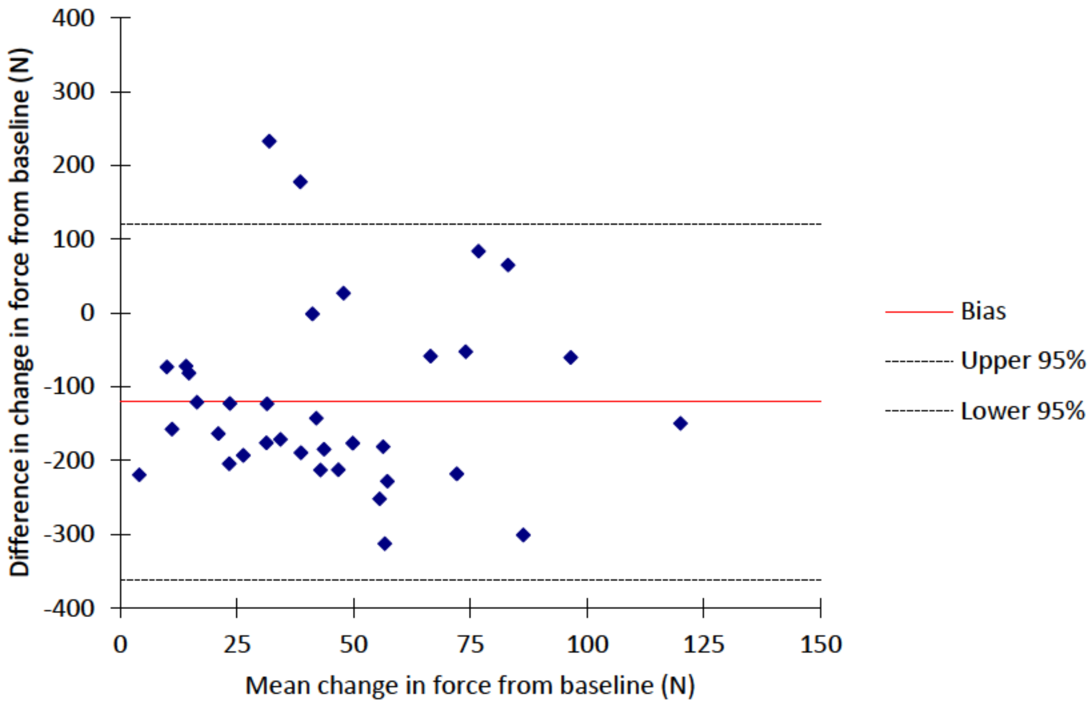


Figure 5.32 Bland–Altman plot for left hand (LH) and right hand (RH) in left side flexion (LSF) hands apart (HA1)

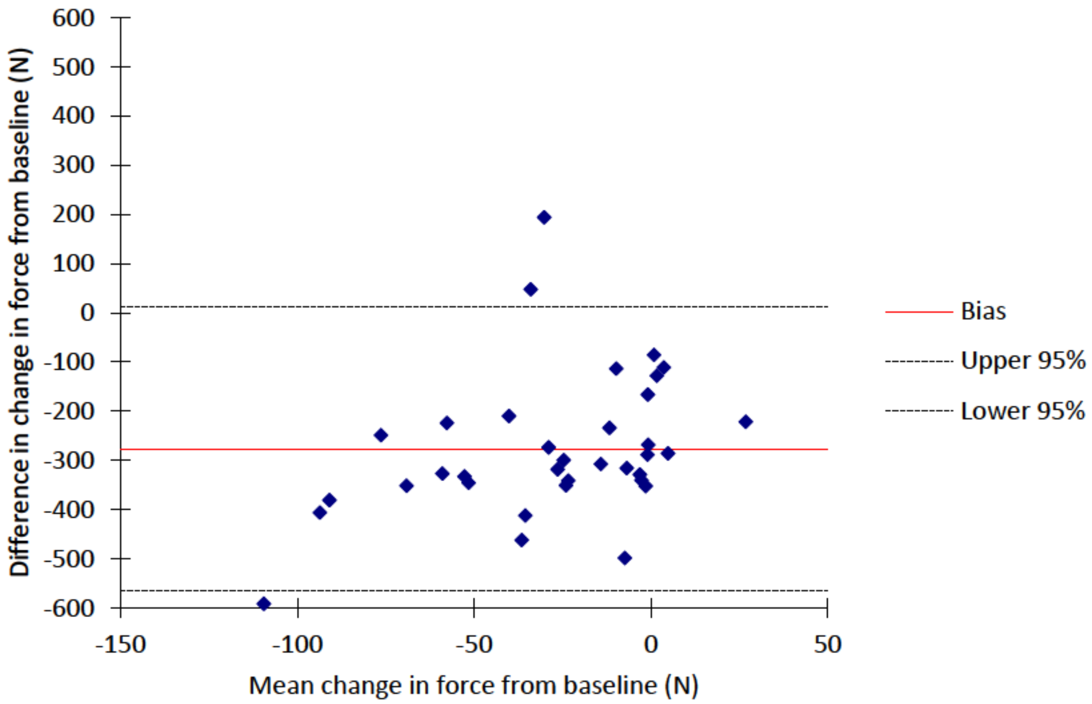


Figure 5.33 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in left side flexion (LSF) hands apart (HA1)

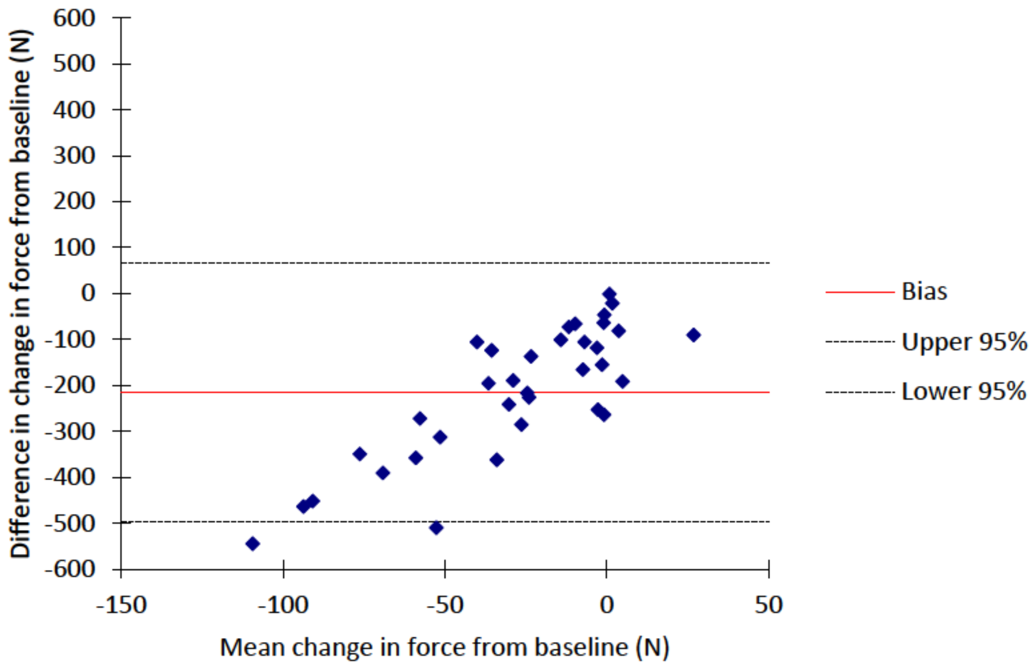


Figure 5.34 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in left side flexion (LSF) hands apart (HA1)

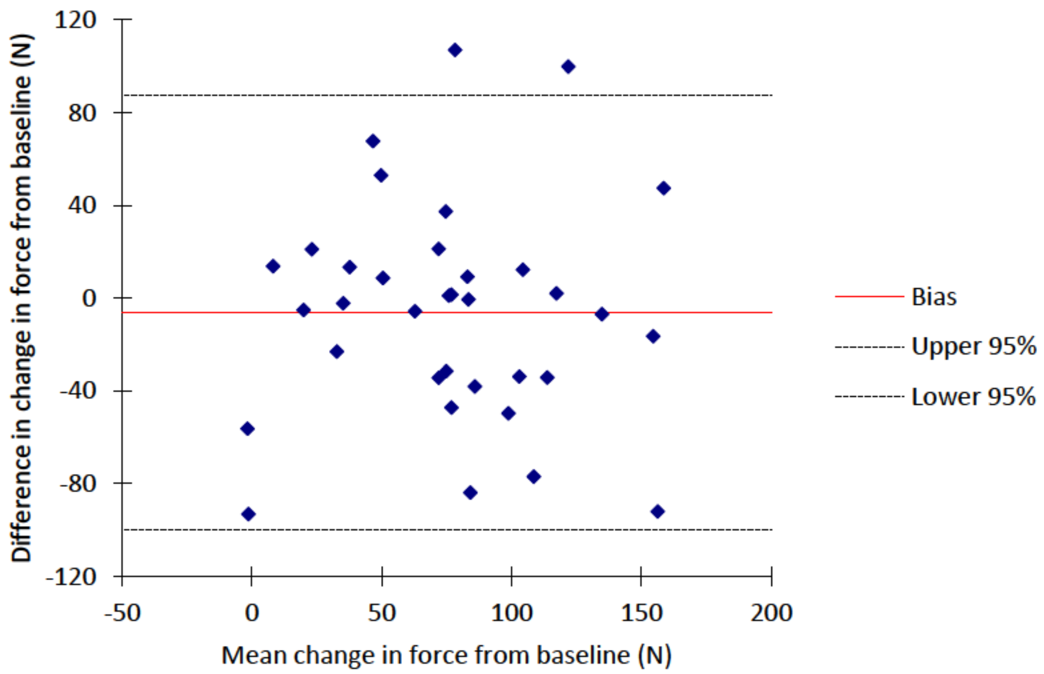


Figure 5.35 Bland–Altman plot for both hands (LHRH) in left side flexion (LSF) hands together (HT) and left hand (LH) + right hand (RH) in left side flexion (LSF) hands apart (HA1)

5.3.5.4 Test direction: right side flexion

For RSF, the LoA calculated for the change in the force measured between the baseline and the peak force recorded were found to be significantly different ($p \leq 0.001$) between the two rear force plates in Trial HA1 (Figure 5.36), the two front force plates in Trial HA1 (Figure 5.37), the two combined left force plates and the two combined right force plates in Trial HA1 (Figure 5.38), and the two combined rear force plates and the two combined front force plates in Trial HA1 (Figure 5.39). The LoA for the change in the force measured between the baseline and the peak force was found to be not significantly different ($p = 0.02$) for RSF between the two combined front force plates in Trial HA1 and the single front force plate in Trial HT (Figure 5.40).

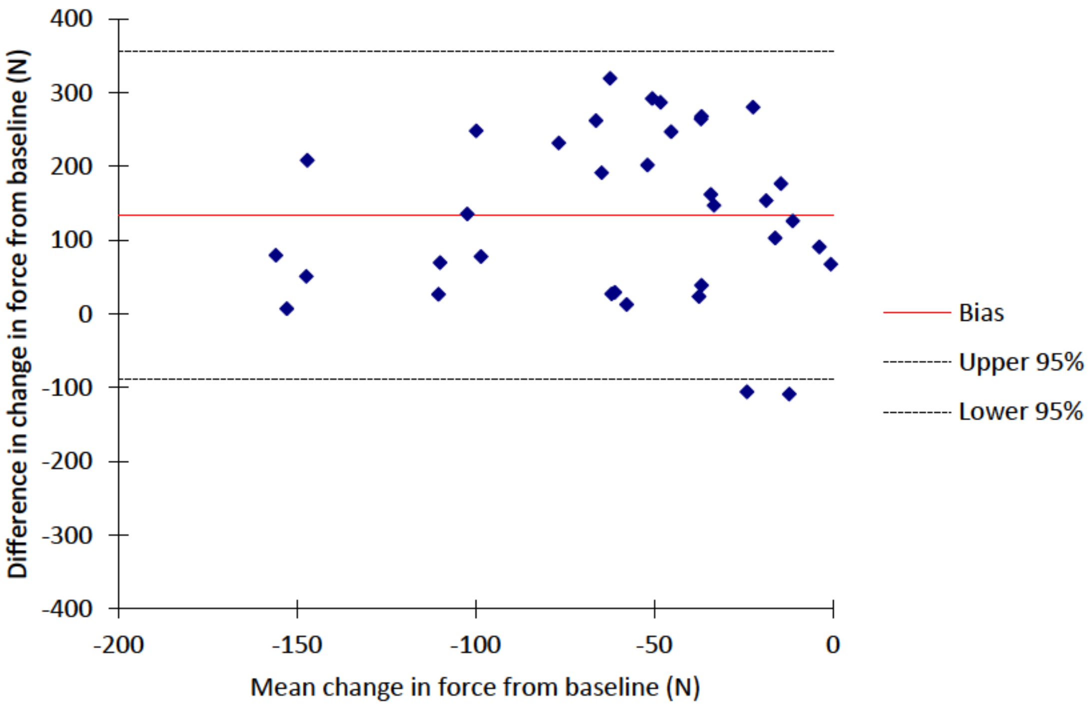


Figure 5.36 Bland–Altman plot for left knee (LK) and right knee (RK) in right side flexion (RSF) hands apart (HA1)

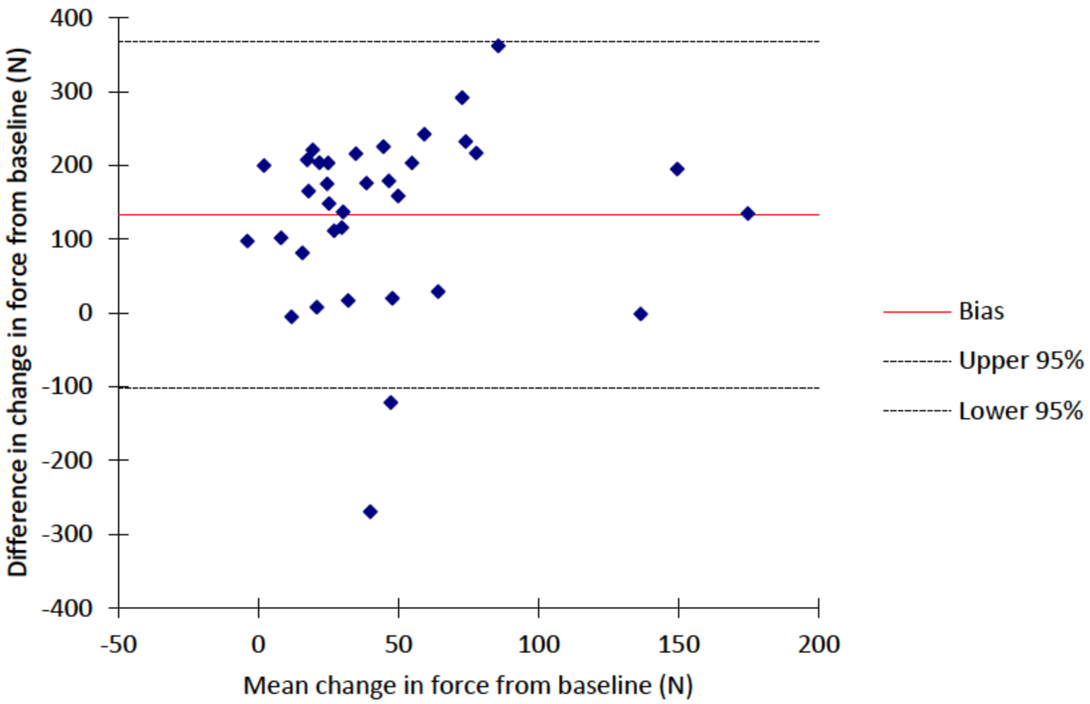


Figure 5.37 Bland–Altman plot for left hand (LH) and right hand (RH) in right side flexion (RSF) hands apart (HA1)

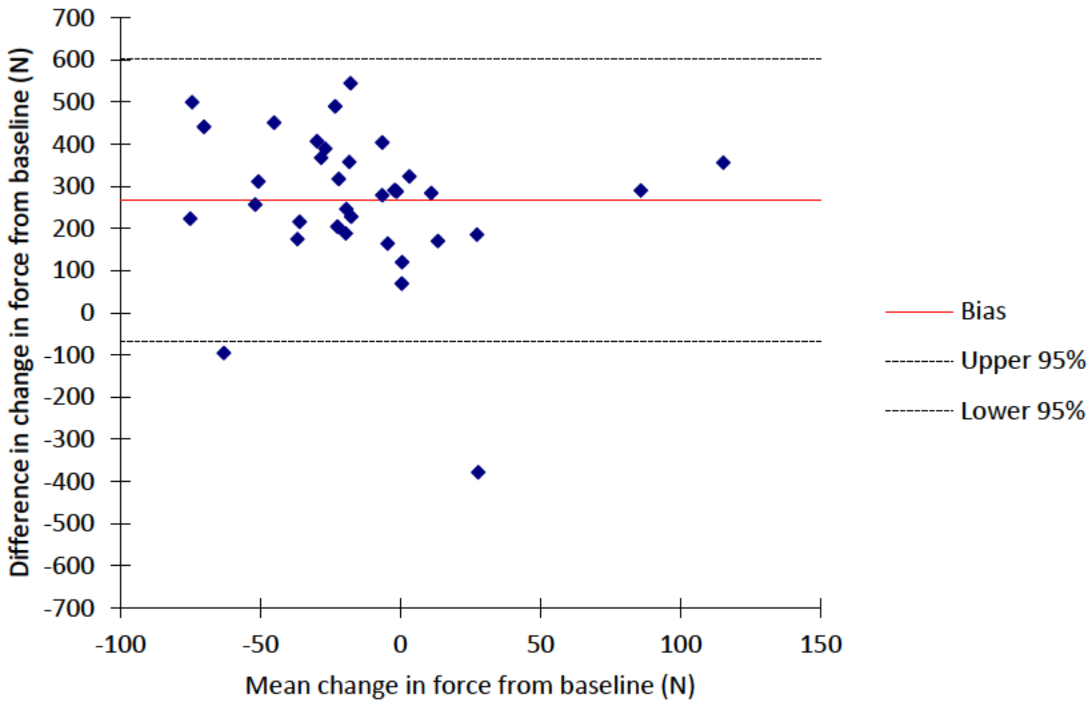


Figure 5.38 Bland–Altman plot for left knee (LK) + left hand (LH) and right knee (RK) + right hand (RH) in right side flexion (RSF) hands apart (HA1)

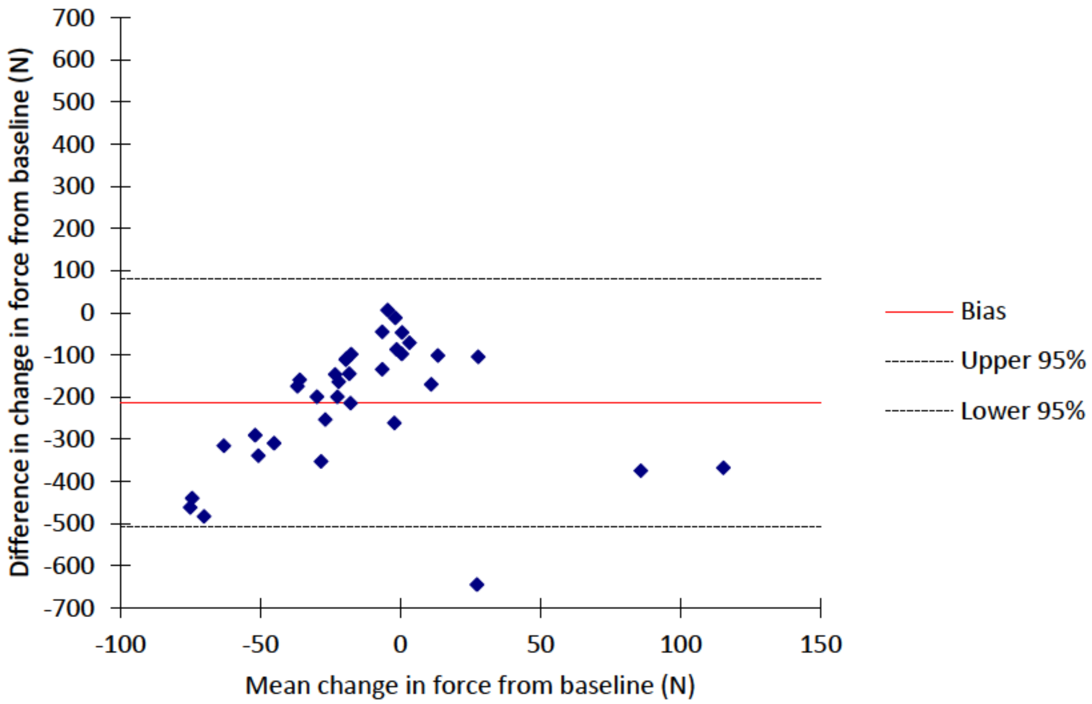


Figure 5.39 Bland–Altman plot for left knee (LK) + right knee (RK) and left hand (LH) + right hand (RH) in right side flexion (RSF) hands apart (HA1)

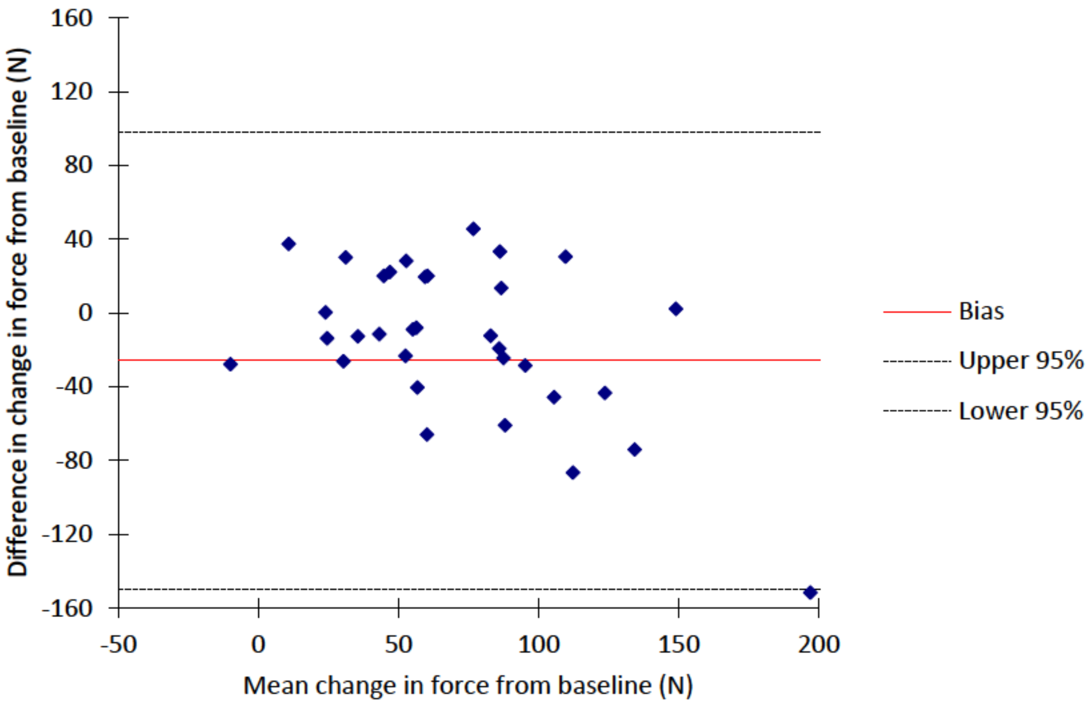


Figure 5.40 Bland–Altman plot for both hands (LHRH) in right side flexion (RSF) hands together (HT) and left hand (LH) + right hand (RH) in right side flexion (RSF) hands apart (HA1)

5.4 Discussion

The aim of this study was to establish best practice with regard to the set-up position of the body for the test protocol proposed for measuring neck strength using the ForceFrame. This was achieving through verifying that the proposed quadruped stance used in Chapter 4 produce repeatable GRFs. This was possible due to the quadruped test position allowing optimally for the measurement of the resultant GRF distribution exerted through the extremities by the addition of force plates to the testing procedure.

The measurements taken using the first force plate were compared with the measurements taken using the same force plate in subsequent trials conducted by Researcher 1 (HA1, HA3 and HT), as well as with each of the three other force plates during MVIC of neck

Flex, Ext, LSF and RSF (Bland & Altman, 1999; Lake et al., 2018). This has given depth to the analysis in this novel study beyond that which has been possible in previous studies (Selistre et al., 2021). Gathering this data is important as it aids in verifying that the start position and force patterns produced during the neck strength test are repeatable and therefore reliable.

This study also used three different statistical approaches to test the reliability of the force plate data between the two trials: paired *t*-test, $ICC_{(3,1)}$ and LoA. These three sets of results together afforded robust understanding of what was happening during the neck force test, specifically by attending closely to force distribution across the body. In this way, the results go beyond simple description of neck force data to account for wider bodily force distribution, meaning that the findings extend beyond those reported in previous neck strength testing studies.

The main findings were that the neck strength tests of Flex and Ext in the sagittal plane demonstrated no variability in body force distribution between any of the testing positions (HA1, HA3 or HT), but that there was more variability for the two side flexion tests LSF and RSF, more especially in the HT test position. As a result, the evidence suggests that the hands-apart quadruped stance should be adopted as the test position of choice for measuring neck strength in the frontal plane.

5.4.1 Testing position

The forces exerted through all four extremities (LK, RK, LH and RH) were measured throughout all four directional tests for neck strength (Flex, Ext, LSF and RSF) to assess the effect of body position prior to the start of the application of maximal neck force (see Figure 5.6 to Figure 5.13). The data demonstrates that participants began the test with a mean of

28.1% distribution of force through each lower extremity for the HA trials, and 27.9% through each lower extremity for the HT trial. These almost identical figures indicate that the positioning of the hands does not affect the force exerted through the knees in the baseline resting position. Similarly, for the combined upper extremities, participants exerted a mean of 43.8% distribution of force for the HA tests and 44.2% (the total force exerted through the single force plate) for the HT tests, again demonstrating no significant difference ($t(34) < 0.45$, $p > 0.05$ in all cases) between the percentage distribution of forces exerted through the four limbs at baseline across the trials despite the two different start positions. This data can be used to reassure both practitioners and athletes that this test can demonstrate a reliable starting test position, which in turn confers face validity onto the test.

5.4.2 Force distribution measured by the four force plates (left hand, right hand, left knee and right knee)

5.4.2.1 Force distribution through all four extremities at peak neck flexion

At peak neck Flex, there was no difference in the force distribution seen between the four extremities between the two HA trials (HA1 and HA3) (Figure 5.6). However, the data showed a change in force distribution between the upper and lower extremities in the opposite direction to those recorded for Ext. The knees increased in force distribution at the time of peak Flex neck strength by 8.5% (LK) to 37.5% (Figure 5.14), and by 7.5% (RK) to 37% (Figure 5.15). At the same time, the hands decrease in force distribution by 9.5% (LH) to 11% (Figure 5.16), and by 6.5% (RH) to 14% (Figure 5.17). This can readily be explained in light of Newton's third law, which states that for every action (force), there is an equal and opposite reaction

(Newton, 1846). In this way, when the neck is pushing into Flex (towards the floor), the upper extremities reduce in force distributed through the force plates under the hands.

The paired *t*-test results between the two trials for Flex HA were not significantly different for any of the four extremities. For the HT trial for Flex, there was a change of force from baseline to peak of a decrease from 41% (LHRH) to 24% through the force plate that recorded both hands, an increase from 28% (LK) to 37%, and an increase from 31% (RK) to 39%. This is an identical pattern of force distribution and force change to the HA condition. The paired *t*-test again showed no significant difference for the hands ($p = 0.364$), the LK ($p = 0.328$), or the RK ($p = 0.703$) between Trial HA1 and Trial HT, demonstrating that for Flex, the quadruped position is a reliable test position. The $ICC_{(3,1)}$ values displayed good-to-excellent reliability scores for repeatability for all four force plates – LK (0.87), RK (0.78), LH (0.87), and RH (0.77) – between the two HA trials.

The LoA tests and Bland–Altman plots (Figure 5.21 to Figure 5.25) in Flex showed a mean bias between the left and right knees of −5.18 N and LoA that were not statistically significant ($p = 0.636$). In addition, there was a mean bias between the left and right hands of −3.23 N, which was not statistically significant ($p = 0.583$). This demonstrates agreement between the two rear and the two front force plates at the time of peak Flex force for each participant, giving the clinical users of the test confidence that the neck test into Flex is reliable. For HT tests involving a single force plate, the force distribution was compared to RH and LH as measured on two separate force plates (in HA tests) added together, resulting in a mean bias of 5.94 N, which again was not significantly different ($p = 0.583$). The differences from left to right were also not significantly different ($p = 0.861$), showing that for force measurements of the neck through the sagittal plane, there were no significant differences between force distribution left to right, or force distribution with HT or HA, signifying that the test can be trusted as reliable. The fact that there was a difference between the plates at the front (under the upper extremities) and those at the rear (under the lower extremities) ($p < 0.001$) simply reflects the pattern already described of a reduction in force through the upper extremities and an increase in force through the lower extremities during the test.

5.4.2.2 Force distribution at peak extension

During the test to record peak neck force into Ext, the forces recorded at the extremities demonstrated a reduction in force on the rear plates (LK and RK) and an increase on the front two plates (LH and RH). Again, this is to be expected when applying Newton's third law (Newton, 1846). However, a key finding was that there was no significant difference recorded between trials for any of the extremities for the HA tests (HA1 compared with HA2) or between Trial HA1 and the Trial HT (Figure 5.11). This suggests that for this test into Ext, the exact placement of the hands does not change the body force distribution, reducing the need for absolute replication of the start test position for each test for the purposes of maintaining excellent test reliability.

The force decreased on average between the two trials to a 13% distribution per knee, a reduction of 14% from baseline, and increased by 13.5% to 37% through LH and by 15% to 38% through RH (Figure 5.14 to Figure 5.20). This is the opposite force distribution for the upper extremities from Flex, which is what would be expected again by relating the findings to Newton's third law (Newton, 1846). For the HT condition for Ext, there was a change of force from baseline to peak of 27% through the front force plate, which recorded both hands, and a reduction of −14% through LK and −13% through RK. This is a similar pattern of force distribution and force change to that of the HA condition. The paired *t*-test again showed no significant difference between Trial HA1 and the HT test, demonstrating that for Ext, the quadruped position has an extremely consistent pattern, one that was not significantly different between trials ($p = 0.360$). The $ICC_{(3,1)}$ values of LK (0.94), RK (0.89), LH (0.95) and RH (0.96) demonstrate that they have good-to-excellent reliability of force exertion between the two HA trials for all four limbs, making this test position highly consistent in terms of the force exerted through the extremities during the test.

The LoA test and Bland–Altman plots in Ext (Figure 5.26 to Figure 5.30) showed a mean bias between the two knees of 3.44 N and LoA that were not statistically significant ($p = 0.450$). There was a mean bias between the two hands of −4.12 N, which was not statistically significant ($p = 0.586$). This demonstrates a highly consistent difference between the two rear and two front force plates at the time of peak Ext force. When the hands were placed together on a single force plate and compared to the two separate hands added together, the mean bias was −8.60 N, which again was not statistically significantly different ($p = 0.360$). The differences from left to right were also not statistically significant ($p = 0.936$), though front to back was statistically significantly different ($p < 0.001$). These results demonstrate that for Ext, the body position affords a reliable test position which does not vary test to test, regardless of whether the hands are placed together or a shoulder-width apart.

5.4.2.3 Force distribution at peak left side flexion

The two directions of movement that occur in the frontal plane (LSF and RSF) demonstrated lower reliability ICC values between participants than those calculated for the test directions in the sagittal plane (Flex and Ext).

The forces measured through the four extremities at the time of peak LSF demonstrate the same distribution in the two HA trials (Figure 5.8). The average change in forces shows that LK decreased from 28% to 8%, RK increased from 28.5% to 30%, LH decreased from 22% to 20% and RH increased from 22% to 42.5%. However, this pattern was not consistent between the two HA trials for the lower extremities, where the paired samples *t*-test results were significantly different for both RK ($p = 0.049$) and LK ($p = 0.013$). For the HT trial, there was a change in force from baseline to peak LSF: increasing from 45% to 56% for the two hands together, decreasing from 28% to 4% for LK, and increasing from 27% to 40% for RK. This is a similar pattern of force changes as seen in the HA test position, but the values were significantly different between the HT trial and the HA1 trial for both knees, LK ($p = 0.001$) and RK ($p = 0.001$).

The reliability between the two HA trials for each of the extremities was calculated using $ICC_{(3,1)}$ and demonstrated good reliability for LK (0.87), moderate for RK (0.68), good for LH (0.82) and excellent for RH (0.90).

The LoA tests and the Bland–Altman plots (Figure 5.31 to Figure 5.35) revealed a mean bias between the two knees of −134 N, which was statistically significant ($p < 0.001$). The mean bias of −121 N between the LH and RH was also statistically significant ($p < 0.001$). In addition, the mean bias left to right (LH+LK vs RH+RK) of −276 N was statistically significant ($p < 0.001$), and the mean bias front to back (LH+RH vs LK+RK) of −215 N was also statistically significant ($p < 0.001$). However, HT vs HA showed a mean bias between the two hands of −6.09 N, which was not statistically significant ($p = 0.456$).

The clear indication is that with LSF, participants predominantly exerted greater force through RH and RK and less through LH and LK. The biggest changes were seen in the reduction through LK and the increase through RH, with minimal changes occurring through RK and LH. The same pattern emerged whether the hands were together or apart. However, despite the good ICC values between trials, the wide LoA within these general patterns suggest that it is difficult to predict how the participant will use their body to generate the most force through the neck. This could suggest that if the neck force is being measured alongside a concomitant upper- or lower-body injury, it may impact the neck measurement in a way which cannot easily be seen. That said, these results do indicate that the force plates should be incorporated into LSF tests where a baseline comparison is being sought to enable the patterns of body movement during the test to be interpreted.

5.4.2.4 Force distribution at peak right side flexion

During the frontal plane direction of neck force MVIC of RSF, a similar variation in readings from the four force plates were recorded as during LSF. The force distribution between Trial HA1 and Trial HA3 were consistent between the two trials (Figure 5.8), and the pattern was a mirror image of the pattern seen for LSF. The opposite lower extremity to the test being performed (i.e. LK for RSF test) showed no change in force, and the lower extremity on the same side of the force being exerted at the neck (i.e. RK) demonstrated a large reduction in force. The opposite pattern was recorded for the upper extremities: the upper extremity on the same side as the neck force being exerted (i.e. RH) demonstrated no change in force, and the upper extremity on the opposite side to the force being exerted (i.e. LH) recorded a large increase in force. This indicates that during the neck SF effort, the participant was countering the neck force production by exerting force through the contralateral upper limb.

The average change in forces (Figure 5.14 to Figure 5.19) showed that LK increased very slightly overall from 29% to 29.5%, RK decreased in force from 28% to 8.5%, LH increased from 22.5% to 42.5%, and RH decreased – albeit a very small amount – from 20.5% to 19.5%. The paired *t*-tests for these results showed no significant difference for the upper extremities between HA1 and HA2 trials and only produced a statistically significant difference for RK ($p = 0.003$), but not LK. For the HT test, the two hands together demonstrated an increased force from 44% to 55%, which was almost the same as the average for the LSF test. LK increased from 30% to 41%, and RK decreased in force from 26% to 4%, again mirroring what happened to the opposite limbs in LSF. The *t*-test for the HT vs HA tests for RSF was the only test to show a statistically significant difference for the hands for the two tests ($p = 0.02$), along with RK ($p = 0.017$) and LK ($p < 0.001$), suggesting that the two start positions are not interchangeable for RSF.

As with LSF, the $ICC_{(3,1)}$ values were variable in this test condition. For LK, they were good (0.78); RK good (0.89); LH good (0.85); and RH good (0.87). The LoA tests and the Bland–Altman plots (Figure 5.36 to Figure 5.40) revealed a mean bias between LK and RK of 134 N, and the same bias between LH and RH, both statistically significant ($p < 0.001$); a statistically significantly different mean bias left to right ($p < 0.001$) at 268 N; and front-to-back bias was also statistically significantly different ($p < 0.001$) at −213 N. RSF was the only test to show a significant bias (−26.0 N) between HT and HA. The clear indication is that with RSF, the predominant participant movement on the force plates was to exert more force through LH and LK and reduced force through RH and RK. The biggest changes were seen in the reduction through RK and the increase through LH, with minimal changes occurring through LK or RH. The same pattern emerged with both HA and HT trials. In-keeping with the findings from LSF, greater LoA was recorded in RSF than in Flex or Ext (Table 5.3). Despite the good ICC values between trials (Table 5.2), this suggests that it is difficult to predict how a participant will use their body to generate the most force through the neck, and that there are forces exerted through the extremities which cannot be predicted. This could suggest – in a similar way to LSF – that if the neck force is being measured alongside a concomitant upper- or lower-body injury, it may impact upon the neck measurement in a way which cannot easily be accounted for. In this way, as with LSF, the results suggest that the force plates should be incorporated into RSF tests.

5.4.3 Interpreting the force plate findings alongside the peak cervical spine forces

The findings from the reliability study of the ForceFrame (Chapter 4) can be analysed alongside the findings from this chapter. The two neck strength tests performed on the ForceFrame that showed a statistically significant difference between the HT and HA tests were LSF, where trial HA1 (mean = 126; SD = 53) and Trial HT (mean = 109; SD = 42) were significantly different: $t(39) = 6.04$, $p = <0.001$, with a large effect size (Cohen's $d = 0.955$); and RSF, where trial HA1 (mean = 126; SD = 52) and Trial HT (mean = 105; SD = 42) were significantly different: $t(39) = 6.46$, $p < 0.001$, with a large effect size (Cohen's $d = 1.02$). These findings could now potentially be explained by the statistically significant differences in measurements between the four forces plates for those two frontal plane movements.

During Flex, there is a reduction in force through the upper extremities. Due to the results in these sagittal plane tests being reliable between the four force plates and between the two trials (HA1 and HA3), the sagittal plane neck strength tests can be accepted as reliable tests in such a way that, in future tests using similar populations and the same experimental approach, reliable neck strength testing could be conducted without parallel force plate measurements. That the forces recorded in LSF and RSF demonstrated greater variance between trials (HA1 and HA3) and between all four force plates during a test means that for practical solutions moving forward, force plate data should perhaps be considered as part of the testing protocol.

In summary, these findings suggest that participants reliably perform the neck strength test, showing little variation in their wider body forces. However, there are differences between participants – most notably in LSF and RSF – that require further investigation. This is because they could potentially lead to testing errors as a result of how strong the person is beyond the neck.

5.4.4 Limitations

Force plate measurements demonstrated some apparent anomalies, specifically with regard to knee readings for four participants who recorded a force of 0 N at peak Ext. This was assumed to be due to the participant pushing through their toes to exert as much force as possible through the neck by using leverage through the lower extremities. This was important, as it introduced an element of variability into the test. In future, further, clearer instructions need to be provided for the test, and researchers must carefully monitor participants throughout testing to ensure that they comply with the standardised procedure.

Alternatively, a third set of force plates could be placed under the toes of participants (in addition to the hands and knees) to account for any such leverage.

5.5 Conclusion

The results and subsequent analysis of the data gleaned from the force plates add vital, novel information to the process of measuring neck strength outlined in this thesis. This study has clearly demonstrated that the test of neck strength using the ForceFrame with the participant in a quadruped start position for the test delivers a reliable test position. In addition, it also highlighted that for the neck strength test into LSF and RSF, wider bodily forces are less predictable. This is especially the case for the lower extremities, where the findings of asymmetry through the force plates may have further practical implications.

The results may serve to aid practitioners' understanding of the absolute and relative reliability of the novel neck strength test. It has previously been impossible to regard any neck strength test as a gold standard – yet with the force plates in addition to the ForceFrame, this study has been able to demonstrate a method of quantifying neck strength while giving a confident prediction of what the wider body is doing during the test.

This will now enable researchers to explore their preferred method, which may have further practical implications. For example, if an HHD is the only affordable method for a practitioner, it could now be measured against the ForceFrame alongside the use of force plates to explore the LoA between the two methods, thereby enabling further exploration of the test's validity.

Chapter 6: Neck strength in professional rugby players

6.1 Context

6.1.1 Introduction

The previous three chapters have demonstrated the need for a consistent approach towards the task of quantifying neck strength in rugby players and provided a reliable method with which to complete this task. The aim of this chapter is to report the findings of a study that involved measuring the neck strength of professional rugby players in England using the VALD ForceFrame in conjunction with the protocol outlined in Chapter 4. Using the universal measurement technique proffered by this thesis to measure a cross-section of rugby players at different playing levels of professional rugby (English Premiership and Championship levels) and across all playing positions also serves to demonstrate the practical issues involved in administering the test outside of the research laboratory. In this way, this chapter will explore the transferability of the novel test procedure from research laboratory to rugby club settings by measuring the neck strength of professional rugby players. This is the vital next step in answering the question of whether a universally acceptable method of measuring neck strength can be achieved in professional rugby.

6.1.2 Rationale

As briefly explored at the very opening of the thesis, there is a pressing and ever-growing need to quantify the neck strength of rugby players due to its potential link to the significant increase in the reports of concussion in rugby players, which have been attributed to head injuries suffered both in training and during match-play (PRISP, 2022). Neck strength is considered to be one of the modifiable risk factors for the increase in concussion being recorded in rugby, despite the true extent of the relationship between neck strength and concussion having yet to be comprehensively explored (Farley et al., 2022; Maconi et al., 2016). It has been theorised that specific aspects of neck strength, particularly greater neck extension (Ext) strength, could lead to a decrease in concussion risk (Collins et al., 2014; Farley et al., 2022). However, there has not been a large enough body of neck strength data generated and mapped against high-quality injury audits to fully define what constitutes a "strong neck" (Chavarro-Nieto et al., 2021; Peek, 2022).

To determine whether this physical characteristic could be a factor in improving game safety and safeguarding the health of the player – both acutely (from match to match) and longer term (in the case of traumatic brain injury (TBI) and its neurodegenerative consequences) – the first step is to be able to quantify the strength of the neck with a reliable and user-friendly method. Without these measurements, the safe, effective prescription of exercises would be difficult to calculate; any progressions, regressions and associated benefits would be unquantifiable; and matching neck strength against injury frequency and severity would still prove elusive.

What is clear from the literature published on neck strength testing (Chavarro-Nieto et al., 2021) is that there is no single unified theory that has been applied in the research. This has resulted in many different protocols and pieces of equipment being adopted, meaning that the field remains confused in both research and practical terms. A major implication of this for players is that their own data cannot easily be used as a baseline measurement when they move from one club to another. In this way, because of the plurality of techniques and technologies available, neck strength measurement protocols are linked to practitioner knowledge as opposed to player history. In addition, more robust studies with higher sample sizes have been conducted within research laboratories rather than "out in the field" at rugby clubs. This has led to a reduction in face validity and, therefore, the overall transferability of the test from research into practice (Chavarro-Nieto et al., 2021). As a result, there remains a notable gap in the reporting of normative data for neck strength measurements for professional rugby players.

6.1.3 Rugby player neck strength

6.1.3.1 Analysing performance markers in rugby players

Across the whole spectrum of rugby playing levels and positions, factors such as upper and lower body strength, speed and agility are commonly analysed as part of performance monitoring and talent identification (Stoop et al., 2018). Traditionally, this is done using a combination of psychological, anthropometric and physiological factors, as well as technical and tactical skills (Dimundo et al., 2021; Zanrosso et al., 2022). The most commonly used physical markers are the anthropometric qualities of height (cm), mass (kg) and fat-free mass (kg) (Dimundo et al., 2021). The measurement of speed is also universally accepted as a marker of athletic ability and so is used as an objective marker in rugby players in numerous studies, via measurement of acceleration, maximal speed, speed endurance and agility (Dimundo et al., 2021). Such data is used to determine whether academy players are ready to move up to their senior rugby team, to chart specific progress after injury and to make decisions based on data around return to training (RTT) and return to play (RTP) following injury (Dimundo et al., 2021). These objective markers are also used as motivation for players, encouraging them to achieve specific targets relating to prehabilitation and rehabilitation goals.

For the measurement of strength, the most commonly cited attributes are one-repetition maximum bench press, chin up and squat (Stoop et al., 2018; Zanrosso et al., 2022). Neck strength is an underrepresented marker, potentially due to its inability to be measured with a reliable method which is universally accepted across not just different levels but between practitioners. This is important, because rugby is a collision sport in which the players contend with high-speed collisions that can cause injury, especially to the head, neck and spine (see also Section 2.2) (Prien et al., 2018). There is the potential in rugby for catastrophic injury to the head and neck, causing paralysis and/or permanent neurological damage (Prien et al., 2018). However, the majority of neck injuries in rugby are classified as not severe (PRISP, 2022), though many players are reported as suffering with neck pain (Daly et al., 2021). Previous studies of non-sporting populations have demonstrated that neck pain can reduce strength measurements (Oliveira & Silva, 2016), though such measurements have so far not been suitably quantified in the rugby population. That said, given the great extent of neck injury reporting, it could be assumed that professional rugby players may be particularly prone to suffering from reduced neck strength capacity, thus potentially putting them at further risk of injury (Salmon et al., 2018).

6.1.3.2 Performance markers by player position

The game of rugby involves 15 named positions (see Section 2.2.1, esp. Table 2.1 and Table 2.2), often divided into forwards and backs (Dimundo et al., 2021). However, on analysis of both the game and the anthropometric properties of rugby players (see Section 2.2.2), this seems to be a case of convenience grouping: there is not a sound evidence base to support this nominal division, whether based on the requirements of play and/or on players' body composition. On this account, the problem with such a simple grouping is that it fails to account for the highly varied roles and anthropometric qualities required to play each of the 15 positions in rugby. It would be beneficial to understand whether anthropometric and physiological measures can be used to group positions in different, more specific ways, with the potential benefit of enabling evidence-based exercise prescription for similar individual positions or groups of positions.

For example, one of the findings from this thesis's survey component (Chapter 3, esp. Section 3.3.3.1.2) was that the players who play in the front row of the scrum (front three: loosehead prop, tighthead prop and hooker) are prescribed different neck exercises, which are performed more regularly, to other players in the team. However, the survey data did not provide any explicit justification from the practitioners who devise such exercises. More research is therefore required to understand the rationale underpinning such prescription and, indeed, whether it can be empirically justified.

Although there have been 14 previous studies assessing the strength of the neck in rugby union players, only one of these (Hamilton & Gatherer, 2014) was assessed as methodologically strong in a systematic review conducted by Chavarro-Nieto et al. (2021). Only eight studies have been performed to test neck strength with professional rugby players (Davies et al., 2016; Farley et al., 2022; Geary et al., 2014; Gillies et al., 2022; Hamilton & Gatherer, 2014; Konrath & Appleby, 2013; Naish et al., 2013; Olivier & Du Toit, 2008). Of these eight, three were performed in the United Kingdom (Davies et al., 2016; Geary et al., 2013; Hamilton & Gatherer, 2014), with none of those in England. These three UK-based studies all employed “break” tests, in which the players had to resist an incremental load applied to their neck until they could not tolerate the load, using a custom-made load cell and head harness. Within these three studies, Davies et al. (2016) tested 21 players, Hamilton and Gatherer (2014) tested 27 players and Geary et al. (2014) tested 15 players. This greatly underrepresents the total number of players currently playing within the 31 professional teams in England.

Of the other studies which have measured the neck strength of professional players, two more involved break tests using a head harness and load cell (Gillies et al., 2022; Naish et al., 2013). Another used an isokinetic dynamometer in a seated position (Olivier & Du Toit, 2008), testing a total of 189 players in a laboratory setting as the equipment was not portable for use in clubs. A further two studies (Farley et al., 2022; Konrath & Appleby, 2013) employed a load cell to record a maximal voluntary isometric contraction (MVIC) with a “make” test, in which the participant pushes against the load cell. The most commonly described method used for this research with professional rugby players reported the peak of three repetitions of the strength test in each trial, with only one study which reported a single repetition maximum for each trial (Salmon et al., 2018). Alongside tests either being break or make tests, the study protocols themselves varied with regard to the rest period between muscle contractions, ranging from a 60-s rest (Farley et al., 2022; Geary et al., 2014; Konrath & Appleby, 2013), a 30-s rest between contractions (Hamilton & Gatherer, 2014; Naish et al., 2013), 15-s rest between repetitions (Davies et al., 2016) or a non-reported rest period between repetitions (Olivier & Du Toit, 2008). All trials measured Ext and flexion (Flex) along with right side flexion (RSF) and left side flexion (LSF), while Farley et al. (2022) also tested left and right rotation with a handheld dynamometer (HHD).

The majority of studies analysed data by dividing the participants into their nominal playing positions of forwards and backs. Due to the wide variation demonstrated between the testing protocols adopted and the lack of any two studies adopting the same protocol with the same equipment, data from these studies cannot be used in order to generate a larger database of information. Moreover, due to this lack of consistency of approach in the research of neck strength in professional rugby players, there is still a lack of definition of what constitutes a "strong" neck for any rugby player by position or playing level (i.e. national, Premiership, Championship).

6.1.3.3 The predictive potential of neck girth in rugby players for performance and injury

In addition to measuring neck strength, three studies also measured neck circumference (Hamilton & Gatherer, 2014; Konrath & Appleby, 2013; Salmon et al., 2018). Salmon et al. (2018) found that greater neck girth was correlated with greater strength in all test directions (r = 0.33–0.63, p = 0.01–0.02) in amateur rugby players. In elite players, Hamilton and Gatherer (2014) found neck girth to have a strong association only with neck Ext strength (r = 0.65). All three studies also reported that greater neck girth was found in rugby forwards than backs or control subjects.

Research has also been conducted to model cervical muscles, using three-dimensional reconstruction from magnetic resonance imaging (MRI) scans of cervical musculature to demonstrate that the greatest contributors to the neck volume are trapezius (34%), transversospinalis (12%) and sternocleidomastoid (11%) (Li et al., 2014). Based on this work, Caccese et al. (2017) measured the electromyographical (EMG) activity of upper trapezius and sternocleidomastoid in a study exploring the relationship between head and neck size, neck strength and head acceleration during head impacts. By testing shoulder elevation, neck Flex and side flexion (SF) to measure neck strength with an HHD alongside EMG activity, they demonstrated that sternocleidomastoid strength significantly predicted linear and rotational head acceleration and therefore provided a justification for strengthening this muscle as part of neck healthcare efforts. No other studies that have measured neck strength or girth have hypothesised exactly which muscles were under investigation as part of the research.

Another study, which specifically analysed the implications of neck girth in relation to neck strength, was conducted by Catenaccio et al. (2017). In the paper, greater neck girth was proposed to convey a protective factor against traumatic head injury by correlating it with an increase in strength into Ext and SF (but not Flex). This finding was proposed as a mechanism for increasing neck strength and girth, which could lead to improved head control when the body suffers a direct force. However, a systematic review conducted by Daly et al. (2021) concluded that there was no robust evidence, however plausible it may seem, to suggest that specific neck exercises or an increase in neck strength (or girth) can mitigate against injury by a reduction in head accelerations during impacts.

Concussions are the major injury of concern at present (PRISP, 2022), given their short-term acute impact on players and their serious long-term links to chronic traumatic encephalopathy (Stewart et al., 2016). Some studies that discuss the links between concussion and neck strength claim that having a strong neck can potentially mitigate some of the impacts suffered from the collisions which cause the concussion (Collins et al., 2014; Farley et al., 2022). However, these claims have not yet been robustly substantiated. The first task of moving towards achieving this goal is to develop a reliable, standardised, field-based test that clubs can use independently of each other, thereby negating the need for separate research facilities. The primary aim of the test would be to provide reliable neck strength results, but it would also be important to enable players to have easy access to their neck force data and, given the standardised and widely adopted status of the hypothetical protocol, to be (regularly) retested regardless of which club or country they represent.

6.1.3.4 Summary

In order to fully make use of anthropometric values and the markers of physical fitness and strength, it would be beneficial to identify these characteristics according to player position to explore whether a player's position can be classified by body composition. Were anthropometrics an accurate means of distinguishing between player positions or position groups, it would be useful then to combine attributes and to ascertain whether they can be used as predictive metrics for performance enhancement and susceptibility to injury.

In sum, current research into classification of rugby players neck strength by position has not been fully explored, both in the field or in the laboratory. While there are previous studies that have attempted to quantify neck strength, all existing data has been separated broadly into forwards and backs, leaving a dearth of normative data information on neck strength by position in rugby. By monitoring neck strength by specific player position, reliable data could then be analysed to understand whether neck strength testing should be more widely adopted in the healthcare screening of professional rugby players.

6.1.4 Aims, research questions and objectives

6.1.4.1 Aims

The aim of this chapter is to report the results of an empirical study exploring the differences between the anthropometric and neck strength data of professional rugby players using the novel neck strength testing protocol tested in Chapters 4 and 5, which involves the use of the ForceFrame fixed-frame dynamometer (FFD). Importantly, the study was conducted "in the field", i.e. beyond the research laboratory and in rugby clubs.

6.1.4.2 Research questions

RQ3 Can neck strength be measured in elite rugby players using the VALD ForceFrame?

RQ3a What are the normative values of player neck strength?

RQ3b What is the relationship between neck strength and player position?

6.1.4.3 Objectives

The objectives of this study were:

1) To measure the neck strength of rugby players in all playing positions at both English Premiership and Championship playing levels to create a normative database of neck strength by playing position and level;

2) To measure other anthropometric data (height, mass and neck girth) at both English Premiership and Championship playing levels to create a normative database of data by playing position and level; and
3) To determine differences in neck strength and anthropometrics between playing positions in professional rugby players using discriminant function analysis and, therefore, to better understand the usefulness of these measures in describing players by playing position or level.

6.2 Methods

6.2.1 Introduction

Neck strength was measured in a sample of 131 professional rugby players using the protocol and equipment developed and assessed in Chapters 4 and 5.

6.2.2 Ethical considerations

Ethical approval was sought from, and granted by, the Coventry University Human Research Ethics Committee (P93396). Consideration was given to the impact of the findings of this study, and assurances were given that the clubs would gain immediate access to their players' data. Clubs were also advised about the usefulness of holding data concerning neck strength as a tool for improving the planning and provision of exercise programmes for their players.

6.2.3 Sample

A gatekeeper letter (Appendix 5) was sent to the Head of Medical Services at England Rugby, as well as to every Premiership and Championship club who had responded positively to the final question in the questionnaire reported in Chapter 3, which had invited them to express an interest in further research into measuring the neck strength of rugby players. This gatekeeper letter resulted in positive responses from three Premiership clubs (out of five contacted) and one Championship club (out of two contacted).

As a result of travel restrictions and social distancing measures introduced in England during the COVID-19 pandemic, a more limited sample of players was recruited than initially anticipated. This sample (n = 131) consisted of players from one Championship club (n = 43, comprising n = 26 forwards and n = 17 backs) and two Premiership clubs (n = 73, comprising n = 45 forwards and n = 28 backs), as well as players from the England men's senior national squad (n = 15, comprising n = 11 forwards and n = 4 backs). All of the national-level players also played at Premiership level, for five further clubs (giving a total subsample of n = 88 Premiership players across seven clubs, comprising n = 56 forwards and n = 32 backs). This was not a truly random sample of the target population, as only clubs whose personnel had expressed interest in the study were invited to distribute the participant information sheet to their players in order that players could make an informed decision about participation in the study.

All of the invited players who conformed to the inclusion and exclusion criteria (Table 6.1) agreed to participate in testing. That said, a total of 13 players who presented for the study (eight at Premiership level and five at Championship level) were excluded as a result of injury at the time of testing, which precluded them from meeting the inclusion criteria for the study.

Although players could be classified into one or more of three levels (national, Premiership and Championship), the sample size for players in the national squad was small for both forwards (n = 11) and backs (n = 4). However, given that all of the national-level players also belonged to the Premiership-level group, this enabled them to be included within this group for statistical analysis, thus increasing the number of Premiership clubs represented by the players within the study.

Table 6.1 Inclusion and exclusion criteria for participation in the rugby player study

Inclusion Criteria	**Exclusion Criteria**
➢ Minimum age of 18 years ➢ Professional player of rugby at a club in England ➢ Able to safely perform neck exercises without pain ➢ Able to safely adopt the quadruped testing position without pain ➢ Able to read and understand the participant information sheet ➢ Read and signed the informed consent form	➢ Any cervical spine injury that resulted in an ongoing pain state ➢ Any upper or lower body neurological deficit ➢ Any other injury that rendered the player unfit for selection to play during the week in which the testing was conducted ➢ Diagnosis of any neuromuscular condition that might be exacerbated by testing ➢ Heavy physical activity on day of test ➢ Imbibed alcohol on day of test

6.2.4 Requirements for testing

Each club was requested to provide a suitable testing location for the setup of the ForceFrame, with essential and preferred criteria for this location (Table 6.2).

Table 6.2 Testing location criteria for the rugby player study

Essential	Preferred
➢ A minimum floor space of 2 m by 2 m for the testing equipment ➢ An area for participants to complete the warm-up activity ➢ Sufficiently quiet to maximise participants' concentration on the tests ➢ Ability to extend the platform and a rubber mat to ensure that hands and knees are on the same level	➢ An electricity supply (not essential, as the ForceFrame and laptop could run on battery power) ➢ Wi-Fi to enable data transfer from the laptop computer to the VALD hub (not essential, as data transfer can occur at a later point when Wi-Fi is next available)

6.2.5 Equipment

Neck force testing was conducted using the VALD ForceFrame (see Chapter 4, Section 4.2.5). A modified version of the frame with taller standing arms, supplied directly by VALD, was used for testing in all cases to cater for the fact that some participants were taller than 195 cm and therefore could not adopt the quadruped testing position and fit into the standard ForceFrame (as used in the study described in Chapters 4 and 5). The adapted ForceFrame was hard-wired to a private, portable computer with a sampling frequency of 400 Hz.

6.2.6 Testing protocol

The development of the testing procedure for the neck MVIC force is described in Chapter 4 (Section 4.2.6).

6.2.6.1 Pre-test protocol

The time of year at which players were tested at all three clubs, as well as in the national squad, was mid-season (January and February 2020). Access to the participants was requested to be at least 48 hours after a match to reduce the effect of post-match fatigue on the results, either on a rest day or before any upper-body gym work or on-field contact training session. All teams met this criterion.

Testing was arranged in a strict timetable, with 15 min allocated to each participant. This enabled the participants to plan their day and mitigate the inconvenience caused by the testing, which resulted in an on-the-day dropout rate of zero.

The ForceFrame was transported to the club training facilities. Either one or two researchers were in attendance at each testing venue. At the first Premiership club, all 38 participants were measured in a single day. At the second Premiership club, 35 participants were tested over three separate sessions. At the Championship club, 43 participants were tested over two sessions. Testing of players from the England men's national squad took place in one session.

On entering the test area, participants were instructed to read the participant information sheet, were checked against the inclusion and exclusion criteria and were invited to sign and date the informed consent form (Appendix 6).

Measurements were recorded of participants' height (to the nearest 0.5 cm; Leicester height stadiometer, SECA, UK, or similar as used at each club); body mass (to the nearest 0.5 kg; flat scales, SECA 877); and neck girth (to the nearest 0.5 cm; measuring tape, SECA 201), measured immediately cranial to the thyroid cartilage, with the participant instructed to look straight ahead (Table 6.3).

Each participant completed the previously described isometric warm-up (see Section 4.2.6.2), pushing their head against their own hand in each of the four test directions (Flex, Ext, LSF and RSF) with progressively increasing force from 50% to 75% of their self-perceived maximal effort, with a 10-s rest between each contraction. This was repeated a further four times in each test direction.

6.2.6.2 Testing position

Participants were instructed to adopt a quadruped starting position, with the head in proximity to the load cells of the ForceFrame (Figure 4.16). The load cell was in contact with the frontal bone just above the eyebrows for Flex, the occiput for Ext and the temporal bone just above the superior aspect of the helix of the ear for LSF and RSF. Participants placed their hands on the floor, a shoulder-width apart, perpendicularly below the shoulder and elbow joints. Elbows were fully extended, scapulae retracted (fully drawn together), and hips and knees set at 90°, with knees therefore directly below the hips. Before commencing the first test, participants became familiar with pushing against the load cell on the ForceFrame at an estimated 80% of their MVIC between one and three times in order to be able to record their maximum force from the first iteration of the test in the following testing procedure.

6.2.6.3 Testing procedure

For the test, participants were required to perform three repetitions of their neck MVIC for 3 s per repetition, with a minimum of 10 s between each repetition, into the test directions of Flex, Ext, LSF and RSF. These directions were presented in a randomised order, with 3 min between each. Randomisation was achieved by assigning the numbers 1–4 to each of the test directions and using a computer program to randomise the order.

After force recording commenced, participants were instructed to inhale and exhale, then, when ready, to push against the load cell as hard and as fast as they could (i.e. produce their MVIC) for 3 s (Salmon et al., 2015).

Force data from the ForceFrame was transferred at 400 Hz to a personal computer using custom-made software (ForceFrame, VALD Performance, Newstead, Queensland, Australia). It was subsequently uploaded to a private, institutional cloud account and exported into a customised Microsoft Excel 2008 spreadsheet for analysis.

6.2.7 Analysis

6.2.7.1 Data analysis

The maximum and average forces for each participant for Ext, Flex, LSF and RSF were determined automatically through the ForceFrame software and expressed as absolute force (N). Descriptive data of mass (kg), height (cm) and neck girth (cm) were analysed, along with peak neck force (N) of Ext, Flex, LSF and RSF.

Participants were grouped according to two different classification systems for data analysis. The first was the traditional grouping of forwards (n = 82) and backs (n = 49). Forwards comprised loosehead props (n = 11), hookers (n = 14), tighthead props (n = 14), second-row forwards (n = 18) and back-row forwards (n = 25); and backs comprised of scrum-halfs (n = 10), fly-halfs (n = 10), wingers (n = 9), centres (n = 11) and full-backs (n = 9).

The second system for grouping was adapted from Cahill et al. (2013). Groups were generally smaller and more specific than in the previous case, comprising front-row players (loosehead prop, hooker, tighthead prop), second-row players, back-row players (open-side flanker, blind-side flanker and number eight), half-backs (scrum-half and fly-half), centres (inside-centre and outside-centre) and back three (left-winger, right-winger and full-back). This allowed for more in-depth, position-specific analysis. Descriptive statistics (mean and SD) were calculated for all anthropometric variables (Table 6.3). Hypothesis tests by individual positions were not conducted.

6.2.7.2 Statistical analysis

Statistical analysis was performed using SPSS version 26 (IBM Corp, Armonk, New York, USA), and the criterion for statistical significance was set at $p \leq 0.05$ *a priori*. Descriptive statistics (mean ± SD) were calculated for peak neck force (N) in each of the four directions. The assumption of normality was assessed through Q-Q plot, and kurtosis and skewness values between −1 and 1 (Kline, 2016); all data sets met the assumption of normality.

6.2.7.2.1 Analysis of anthropometric data between forwards and backs

Independent samples *t*-tests were used to assess for statistical differences between player positions (forwards and backs) in the anthropometric measures of mass (kg), height (cm) and neck girth (cm).

6.2.7.2.2 Differences between player position, anthropometric variables and playing levels

A one-way analysis of variance (ANOVA) was conducted to determine the differences in the dependent anthropometric variables of mass, height and neck girth between the eight different groups of playing positions (loosehead prop, hooker, tighthead prop, second-rows, back-row forwards, half-backs, centres and back three) across both playing levels (Premiership and Championship). There were no outliers, as assessed by boxplot; data was normally distributed for each group, as assessed by Shapiro–Wilk test ($p > 0.05$); and there was homogeneity of variances, as assessed by Levene's test of homogeneity of variances.

6.2.7.2.3 Differences between player position, neck force and playing levels

One-way ANOVA was used to compare peak isometric neck strength for each of the four directions, with playing position (as defined in Section 2.2) as the fixed factor. Where differences were noted in ANOVA, pairwise comparisons (Bonferroni-adjusted) were made to identify where significant differences occurred. There were no outliers for Flex, Ext or LSF. There were two outliers for RSF in the back-three group, but these were not more than three box lengths from the median, as assessed by boxplot; data was normally distributed for each group, as assessed by Shapiro–Wilk test ($p > 0.05$); and there was homogeneity of variances, as assessed by Levene's test of homogeneity of variances.

6.2.7.2.4 Discriminant function analysis

Discriminant function analysis (DFA) was performed to determine whether playing positions or levels could be differentiated between (classified) by their anthropometric data or neck force data. This statistical test determined which of the participants' measures of neck strength or anthropometrics best discriminated the players, by position or level played, and the relative influence different measures had on discriminating between them.

6.3 Results

The results of the data analysis performed to address the aims of this study are presented by anthropometrics, neck force and player position.

6.3.1 Anthropometric data analysis

There was homogeneity of variance across anthropometric data as assessed by Levene's test for equality (mass $p = 0.526$, height $p = 0.264$ and neck girth $p = 0.236$). There was a statistically significant difference between forwards and backs for all anthropometric data with mass $t(129) = 14.2$, $p \leq 0.001$; height, $t(129) = 5.61$, $p \leq 0.001$; and neck girth $t(129) = 9.34$, $p \leq 0.001$ all significantly greater in forwards than in backs (Table 6.3).

Table 6.3 Anthropometric data for rugby player study participants (mean ± SD)

Playing position	***n* =**	**Mass (kg)**	**Height (cm)**	**Neck girth (cm)**
Loosehead prop	11	118 ± 5	184 ± 4	48.6 ± 1.5
Hooker	14	105 ± 8	183 ± 5	45.4 ± 2.8
Tighthead prop	14	121 ± 6	186 ± 5	49.3 ± 3.2
All front row	*39*	*115 ± 10*	*184 ± 5*	*47.7 ± 3.2*
Second row	18	118 ± 7	198 ± 3	45.3 ± 2.2
Back row	25	109 ± 5	190 ± 4	45.2 ± 2.2
All forwards	*82*	*114 ± 8**	*189 ± 7**	*46.4 ± 2.9**
Premiership forwards	*56*	*114 ± 9*	*189 ± 7*	*46.9 ± 2.9*
Championship forwards	*26*	*112 ± 8*	*189 ± 6*	*45.4 ± 2.8*
Half-backs	20	85.6 ± 7.0	181 ± 5	41.4 ± 1.8
Centres	11	99.8 ± 5.9	186 ± 4	43.1 ± 1.9
Back three	18	93.2 ± 8.0	182 ± 5	42.0 ± 2.0
All backs	*49*	*91.6 ± 9.0*	*182 ± 5*	*42.0 ± 2.0*
Premiership backs	*32*	*91.7 ± 8.3*	*182 ± 5*	*42.1 ± 1.9*
Championship backs	*17*	*91.3 ± 10.4*	*182 ± 5*	*41.7 ± 2.2*
Total	**131**	**105 ± 14**	**186 ± 7**	**44.7 ± 3.4**

* Significantly different from backs ($p < 0.001$)

6.3.1.1 Differences in anthropometric data by playing position

There were statistical differences in anthropometric data between player positions: ANOVA mass: $F(7, 123) = 65.9$, $p < 0.001$; height: $F(7, 123) = 30.3$, $p < 0.001$; and neck girth $F(7, 123) = 24.3$, $p < 0.001$. Bonferroni post-hoc comparisons between anthropometric values indicated significant differences between many player positions for height (Table 6.4), body mass (Table 6.5) and neck girth (Table 6.6).

Table 6.4 Mean difference and SD, significance (*p* value) and 95% confidence interval of playing position by height

Dependent variable	Positions	Mean difference (cm)	SD	Significance (*p* value)	95% CI	
					Lower bound	**Upper bound**
Height (cm)	Tighthead prop vs half-back	5.20	6.12	0.018	0.462	9.94
	Second row vs loosehead prop	14.1	6.21	0.001	8.86	19.3
	Second row vs hooker	15.1	6.07	0.001	10.3	20.0
	Second row vs tighthead prop	11.9	6.07	0.001	7.02	16.7
	Second row vs back row	7.99	6.10	0.001	3.79	12.2
	Second row vs half-back	17.1	6.03	0.001	12.6	21.5
	Second row vs centre	11.2	6.21	0.001	5.95	16.4
	Second row vs back three	15.5	6.02	0.001	11.0	20.0
	Back row vs loosehead prop	6.07	6.54	0.004	1.15	11.0
	Back row vs hooker	7.12	6.28	0.001	2.58	11.7
	Back row vs half-back	9.07	6.06	0.001	4.99	13.2
	Back row vs back three	7.51	6.10	0.001	3.31	11.7
	Centre vs half-back	5.90	6.54	0.009	0.800	11.0

95% CI = confidence interval

Table 6.5 Mean difference and SD, significance (*p* value), and 95% confidence interval of playing position by mass

Dependent variable	Position	Mean diff (kg)	SD	Significance (*p* value)	95% CI Lower bound	95% CI Upper bound
Body mass (kg)	Loosehead prop vs hooker	13.6	9.28	0.001	5.20	22.0
	Loosehead prop vs back row	9.14	10.0	0.005	1.62	16.7
	Loosehead prop vs half-back	32.9	9.62	0.001	25.1	40.7
	Loosehead prop vs centre	18.7	9.21	0.001	9.87	27.6
	Loosehead prop vs back three	25.3	9.49	0.001	17.4	33.3
	Hooker vs half-back	19.3	9.36	0.001	12.1	26.6
	Hooker vs back three	11.8	9.28	0.001	4.35	19.2
	Tighthead prop vs hooker	16.6	9.21	0.001	8.70	24.4
	Tighthead prop vs back row	12.1	9.60	0.001	5.18	19.1
	Tighthead prop vs half-back	35.9	9.36	0.001	28.7	43.2
	Tighthead prop vs centre	21.7	9.28	0.001	13.3	30.1
	Tighthead prop vs back three	28.3	9.28	0.001	20.9	35.7
	Second row vs hooker	12.9	9.28	0.001	5.47	20.3
	Second row vs back row	8.45	9.33	0.001	2.02	14.9
	Second row vs half-back	32.2	9.22	0.001	25.5	39.0
	Second row vs centre	18.0	9.49	0.001	10.1	26.0
	Second row vs back three	24.6	9.21	0.001	17.7	31.6
	Back row vs half-back	23.8	9.27	0.001	17.5	30.0
	Back row vs centre	9.59	10.0	0.002	2.07	17.1
	Back row vs back three	16.2	9.33	0.001	9.77	22.6
	Centre vs half-back	14.2	9.62	0.001	6.38	22.0
	Back three vs half-back	7.58	9.22	0.014	0.825	14.3

95% CI = confidence interval

Table 6.6 Mean difference and SD, significance (*p* value) and 95% confidence interval of playing position by neck girth

Dependent variable	Position	Mean diff (cm)	SD	Significance (*p* value)	95% CI	
					Lower bound	Upper bound
Neck girth (cm)	Loosehead prop vs hooker	3.12	3.21	0.023	0.218	6.02
	Loosehead prop vs second row	3.24	3.28	0.007	0.486	5.99
	Loosehead prop vs back row	3.39	3.46	0.002	0.782	5.99
	Loosehead prop vs half-back	7.17	3.33	0.001	4.47	9.87
	Loosehead prop vs centre	5.50	3.19	0.001	2.43	8.57
	Loosehead prop vs back three	6.55	3.28	0.001	3.79	9.30
	Hooker vs half-back	4.05	3.24	0.001	1.55	6.56
	Hooker vs back three	3.43	3.21	0.001	0.864	5.99
	Tighthead prop vs hooker	3.89	3.19	0.001	1.17	6.61
	Tighthead prop vs second row	4.02	3.21	0.001	1.45	6.58
	Tighthead prop vs back row	4.16	3.32	0.001	1.76	6.56
	Tighthead prop vs half-back	7.95	3.24	0.001	5.44	10.5
	Tighthead prop vs centre	6.28	3.21	0.001	3.38	9.18
	Tighthead prop vs back three	7.32	3.21	0.001	4.76	9.89
	Second row vs half-back	3.93	3.19	0.001	1.59	6.27
	Second row vs back three	3.31	3.19	0.001	0.907	5.70
	Back row vs half-back	3.79	3.21	0.001	1.63	5.94
	Back row vs back three	3.16	3.23	0.001	0.936	5.38

95% CI = confidence interval

The differences between all other playing positions in terms of mass, height and neck girth were not statistically significant ($p > 0.05$).

6.3.1.2 Anthropometric data and playing level: Premiership vs Championship

There was no statistically significant difference between playing level (Premiership vs Championship) for mass or height ($p > 0.05$) in any playing position. However, neck girth was significantly greater ($t(80) = 2.05$, $p = 0.022$) in Premiership forwards than Championship forwards (Table 6.3). There were no significant differences between playing level (Premiership vs Championship) for backs with regard to any anthropometric measures ($p > 0.05$).

6.3.1.3 Discriminant function analysis of anthropometric variables and playing position

DFA was performed to establish the percentage of players whose playing position could be predicted by either of the three anthropometric variables of mass (kg), height (cm) and neck girth (cm) (Table 6.7). DFA produced a model that predicted 71.5% (Eigenvalue = 3.78) of the variance in playing positions by mass (Wilks' lambda = 0.083, $df = 21$, $p < 0.001$); a further 28% (Eigenvalue = 1.48) by height (Wilks' lambda = 0.395, $df = 12$, $p < 0.001$) and the remaining 0.4% by neck girth (Wilks' lambda = 0.979, $df = 5$, $p = 0.750$).

Table 6.7 Discriminant function analysis of percentage classification of playing position by anthropometric variables of mass, height and neck girth

		Probability (%) of predicted playing position							
		Loose-head prop	Hooker	Tight-head prop	Second row	Back row	Half-back	Centre	Back three
Playing position	Loosehead prop	0.00	9.10	90.9	0.00	0.00	0.00	0.00	0.00
	Hooker	0.00	42.9	7.10	0.00	35.7	7.10	0.00	7.10
	Tighthead prop	0.00	0.00	85.7	0.00	14.3	0.00	0.00	0.00
	Second row	0.00	0.00	0.00	88.9	11.1	0.00	0.00	0.00
	Back row	0.00	0.00	4.00	8.00	76.0	0.00	12.0	0.00
	Half-back	0.00	5.00	0.00	0.00	0.00	75.0	20.0	20.0
	Centre	0.00	9.10	0.00	9.10	9.10	0.00	27.3	45.5
	Back three	0.00	5.60	0.00	0.00	16.7	33.3	5.60	38.9

The data demonstrates 89% of second-row players were classified correctly in that position by anthropometric data, 91% of props (where tighthead and loosehead were classified as the same position), 76% of back-row players, and 75% of half-backs (Table 6.7). However, centres and back-three players could be classified as any back playing position when DFA is used to analyse anthropometric data.

6.3.2 Differences in peak neck force between test directions

Peak neck force generated in the four neck strength test directions (Flex, Ext, LSF and RSF) by player position and level is presented in Table 6.8. There was homogeneity of variance, as assessed by Levene's test for equality: Flex $p = 0.139$, Ext $p = 0.736$, LSF $p = 0.334$ and RSF *p* = 0.092. There was a statistically significant difference between forwards and backs for all test directions: Flex $t(129) = 4.71$, $p \leq 0.001$; Ext $t(129) = 8.21$, $p \leq 0.001$; LSF $t(129) = 6.56$, $p \leq 0.001$; RSF $t(129) = 7.57$, $p \leq 0.001$. The difference was significantly greater in forwards than in backs (Table 6.8).

Table 6.8 Mean ± SD of neck force (N) in four test directions (flexion, extension, left side flexion, right side flexion) for all rugby playing positions

Playing position	***n* =**	**Flex peak force (N)**	**Ext peak force (N)**	**LSF peak force (N)**	**RSF peak force (N)**
Loosehead prop	11	337 ± 56.2	460 ± 67.3	336 ± 51.2	338 ± 35.3
Hooker	14	332 ± 53.2	437 ± 70.9	297 ± 67.1	300 ± 64.2
Tighthead prop	14	371 ± 83.0	524 ± 70.2	355 ± 97.2	358 ± 78.4
All front row	*39*	347 ± 66.9	475 ± 77.9	329 ± 78.1	332 ± 67.1
Second row	18	314 ± 89.6	406 ± 65.6	290 ± 67.8	301 ± 59.6
Back row	25	342 ± 64.0	421 ± 63.7	279 ± 52.8	281 ± 69.6
All forwards	*82*	338 ± 71.9*	443 ± 76.9*	305 ± 72.1*	309 ± 69.2*
Premiership forwards	*56*	343 ± 77.1	458 ± 71.0	307 ± 76.6	307 ± 69.8
Championship forwards	*26*	328 ± 59.4	413 ± 81.1	301 ± 62.3	315 ± 69.1
Half-backs	20	272 ± 44.4	309 ± 45.8	220 ± 48.1	225 ± 42.2
Centres	11	303 ± 44.2	367 ± 53.5	240 ± 50.4	227 ± 41.6
Back three	18	286 ± 46.9	345 ± 82.0	232 ± 50.5	229 ± 42.7
All backs	*49*	284 ± 45.9	335 ± 66.1	229 ± 49.2	227 ± 41.4
Premiership backs	*32*	285 ± 46.9	337 ± 59.0	226 ± 46.6	221 ± 40.4
Championship backs	*17*	283 ± 45.6	331 ± 79.5	235 ± 54.6	238 ± 42.4
Total	**131**				

Flex = flexion; Ext = extension; LSF = left side flexion; RSF = right side flexion

* Significantly different from backs ($p < 0.001$)

Neck strength normalised to body mass was calculated by dividing the absolute neck force (N) by the players body mass (kg) (Table 6.9).

Table 6.9 Mean ± SD of neck force (normalised to body weight) in four test directions (flexion, extension, left side flexion, right side flexion) for all rugby playing positions

Playing position	*n* =	Flex force normalised to body mass	Ext force normalised to body mass	LSF force normalised to body mass	RSF force normalised to body mass
Loosehead prop	11	2.85 ± 0.46	3.89 ± 0.56	2.84 ± 0.40	2.86 ± 0.27
Hooker	14	3.16 ± 0.39	4.16 ± 0.53	2.83 ± 0.57	2.85 ± 0.54
Tighthead prop	14	3.05 ± 0.61	4.31 ± 0.47	2.92 ± 0.75	2.95 ± 0.61
All front row	*39*	3.02 ± 0.49	4.12 ± 0.52	2.86 ± 0.57	2.89 ± 0.48
Second row	18	2.67 ± 0.72	3.45 ± 0.50	2.46 ± 0.55	2.56 ± 0.51
Back row	25	3.12 ± 0.53	3.85 ± 0.51	2.55 ± 0.50	2.57 ± 0.62
All forwards	*82*	2.98 ± 0.60	3.90 ± 0.59	2.68 ± 0.59	2.72 ± 0.57
Half-backs	20	3.19 ± 0.49	3.60 ± 0.38	2.55 ± 0.43	2.62 ± 0.40
Centres	11	3.04 ± 0.37	3.69 ± 0.58	2.41 ± 0.48	2.27 ± 0.36
Back three	18	3.08 ± 0.47	3.70 ± 0.79	2.50 ± 0.51	2.46 ± 0.42
All backs	*49*	3.11 ± 0.46	3.66 ± 0.60	2.50 ± 0.48	2.49 ± 0.42
Total	**131**				

Flex = flexion; Ext = extension; LSF = left side flexion; RSF = right side flexion

No significant difference was found between forwards and backs (p>0.05) or between playing positions (P>0.05) when neck strength was normalised by body weight.

6.3.2.1 Variation in neck force by playing position

There were significant differences in peak neck force between player positions: Flex: F(7, 123) = 4.42, $p < 0.001$; Ext: $F(7,123) = 17.3$, $p < 0.001$; LSF: $F(7,123) = 9.46$, $p < 0.001$; RSF: $F(7,123) = 11.9$, $p < 0.001$ were all statistically significantly different for the eight different grouped positions of play. Bonferroni post-hoc comparisons for peak force indicated significant differences between the following groups of players in the direction of testing indicated (Table 6.10 and Table 6.11).

Table 6.10 Mean difference and SD of playing position by neck force (N) for flexion and extension

Dependent variable (direction of test)	**Position**	**Mean diff (N)**	**SD**	**Significance (*p* value)**	**95% CI**	
					Lower bound	**Upper bound**
Flex	Tighthead prop vs half-back	98.5	90.4	0.001	28.5	169
	Tighthead prop vs back three	84.6	89.7	0.007	13.0	156
	Back row vs half-back	69.5	89.6	0.010	9.22	130
Ext	Loosehead prop vs half-back	152	96.8	0.001	73.1	230
	Loosehead prop vs centre	93.3	92.6	0.031	4.07	182
	Loosehead prop vs back three	115	95.5	0.001	35.4	196
	Hooker vs half-back	129	94.1	0.001	55.7	202
	Hooker vs back three	92.4	93.4	0.004	17.9	167
	Tighthead prop vs hooker	86.9	92.6	0.018	7.80	166
	Tighthead prop vs second row	118	93.4	0.001	43.8	193
	Tighthead prop vs back row	103	96.6	0.001	33.4	173
	Tighthead prop vs half-back	216	94.1	0.001	143	288
	Tighthead prop vs centre	157	93.3	0.001	72.9	241
	Tighthead prop vs back three	179	93.4	0.001	105	254
	Second row vs half-back	97.1	92.8	0.001	29.2	165

Flex = flexion; Ext = extension

Table 6.11 Mean difference and SD of playing position by neck force (N) for left side flexion and right side flexion

Dependent variable (direction of test)	Position	Mean diff (N)	SD	Significance (*p* value)	95% CI	
					Lower bound	Upper bound
LSF	Loosehead prop vs half-back	117	90.9	0.001	42.9	190
	Loosehead prop vs centre	96.0	87.0	0.010	12.3	180
	Loosehead prop vs back three	104	89.6	0.001	29.1	179
	Hooker vs half-back	77.8	88.4	0.012	9.34	146
	Tighthead prop vs back row	76.5	90.7	0.008	10.9	142
	Tighthead prop vs half-back	136	88.4	0.001	67.2	204
	Tighthead prop vs centre	115	87.6	0.001	35.9	194
	Tighthead prop vs back three	123	87.7	0.001	53.3	193
	Second row vs half-back	70.5	87.1	0.016	6.71	134
	Back row vs half-back	59.1	87.5	0.048	0.223	118
RSF	Loosehead prop vs half-back	114	84.8	0.001	44.7	182
	Loosehead prop vs centre	112	81.1	0.001	33.4	190
	Loosehead prop vs back three	109	83.6	0.001	39.2	179
	Hooker vs half-back	74.6	82.4	0.008	10.8	138
	Hooker vs back three	70.4	81.8	0.022	5.10	136
	Tighthead prop vs back row	77.2	84.6	0.003	16.1	138
	Tighthead prop vs half-back	133	82.4	0.001	69.6	197
	Tighthead prop vs centre	131	81.7	0.001	57.7	205
	Tighthead prop vs back three	129	81.8	0.001	63.9	195
	Second row vs half-back	75.8	81.2	0.002	16.3	135
	Second row vs centre	73.9	83.6	0.029	3.76	144
	Second row vs back three	71.6	81.1	0.008	10.5	133
	Back row vs half-back	56.2	81.6	0.040	1.25	111

LSF = left side flexion; RSF = right side flexion

All other player combinations were not statistically significant at the $p < 0.05$ level.

6.3.2.2 Correlation of neck strength with body mass by playing position

6.3.2.2.1 Flexion

Body mass (kg) was plotted against peak neck force (N) in flexion by playing position in order to assess the relationship between these two variables. For the test direction of flexion, correlation was low (R^2=0.23) but player groupings were clearly demonstrated (figure 6.1).

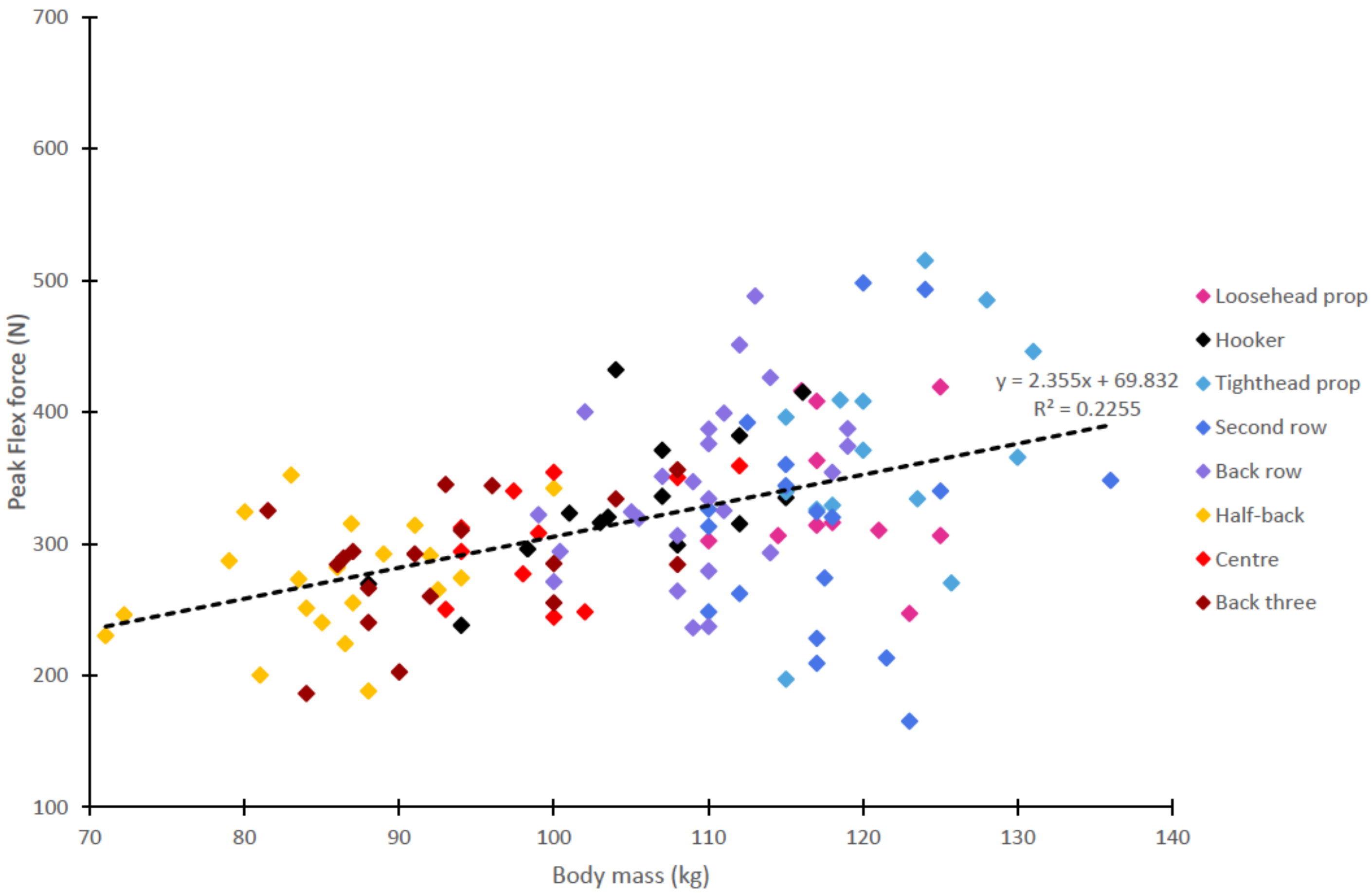


Figure 6.1 Body mass (kg) against peak Flex force (N) plotted by playing position (each point represents one player)

6.3.2.2.2 Extension

For the test direction of extension, correlation was R^2=0.49 and player groupings were clearly demonstrated (figure 6.2).

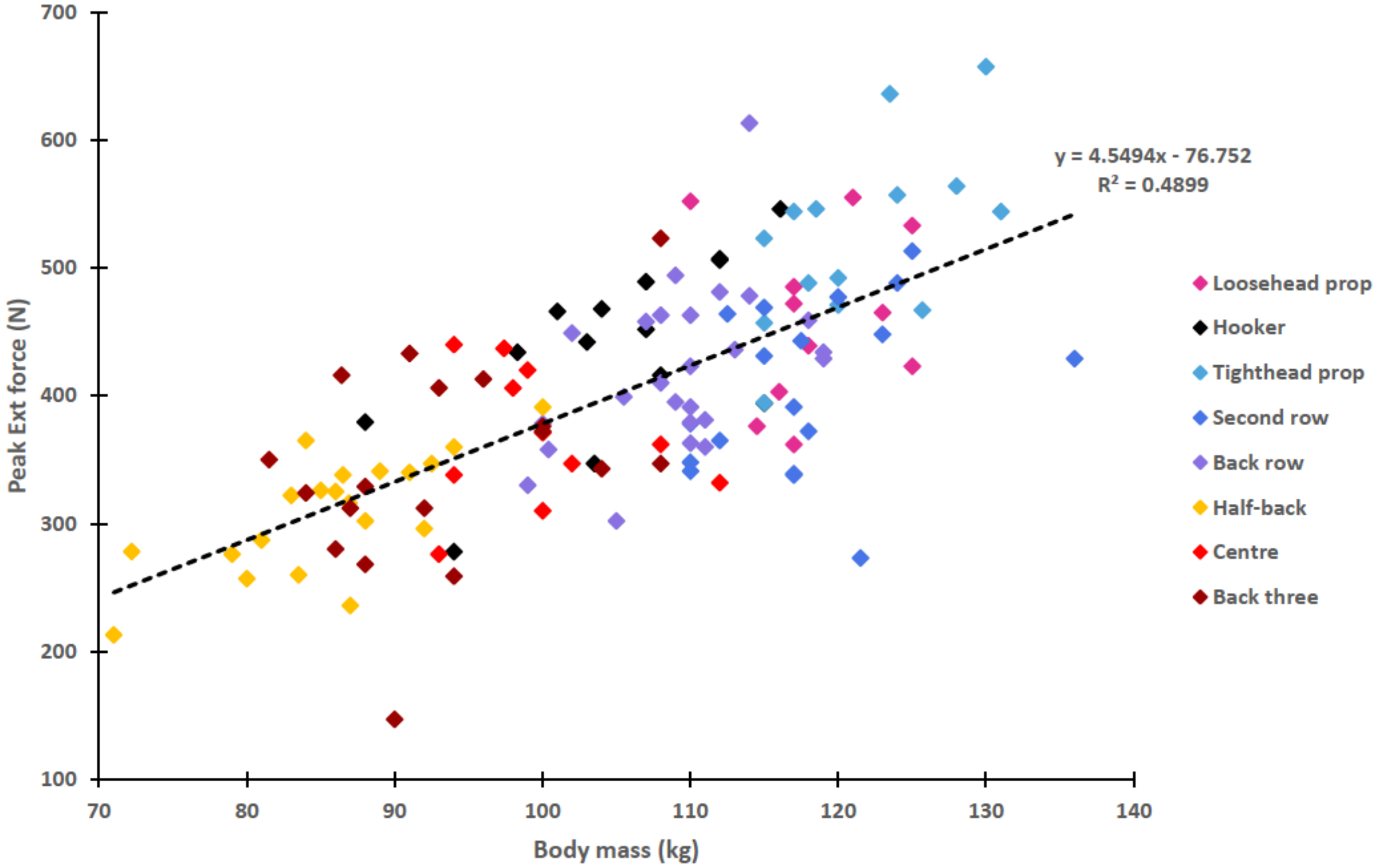


Figure 6.2 Body mass (kg) against peak Ext force (N) plotted by playing position (each point represents one player)

6.3.2.2.3 Left side flexion

For the test direction of left side flexion, correlation was R^2=0.33) and player groupings were clearly demonstrated (figure 6.3).

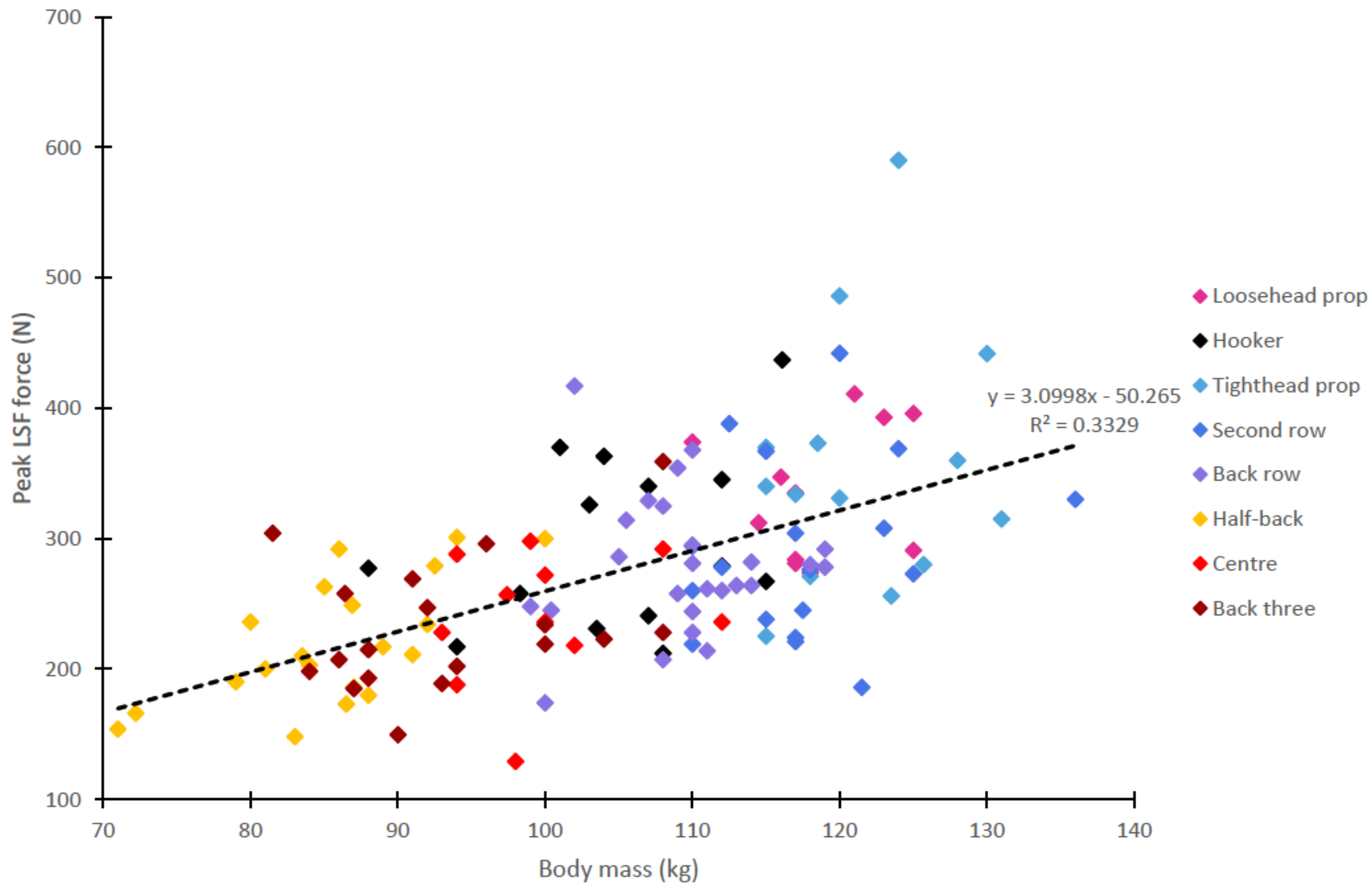


Figure 6.3 Body mass against peak LSF force plotted by playing position (each point represents one player)

6.3.2.2.4 Right side flexion

For the test direction of right side flexion, correlation was R^2=0.38 and player groupings were clearly demonstrated (figure 6.4).

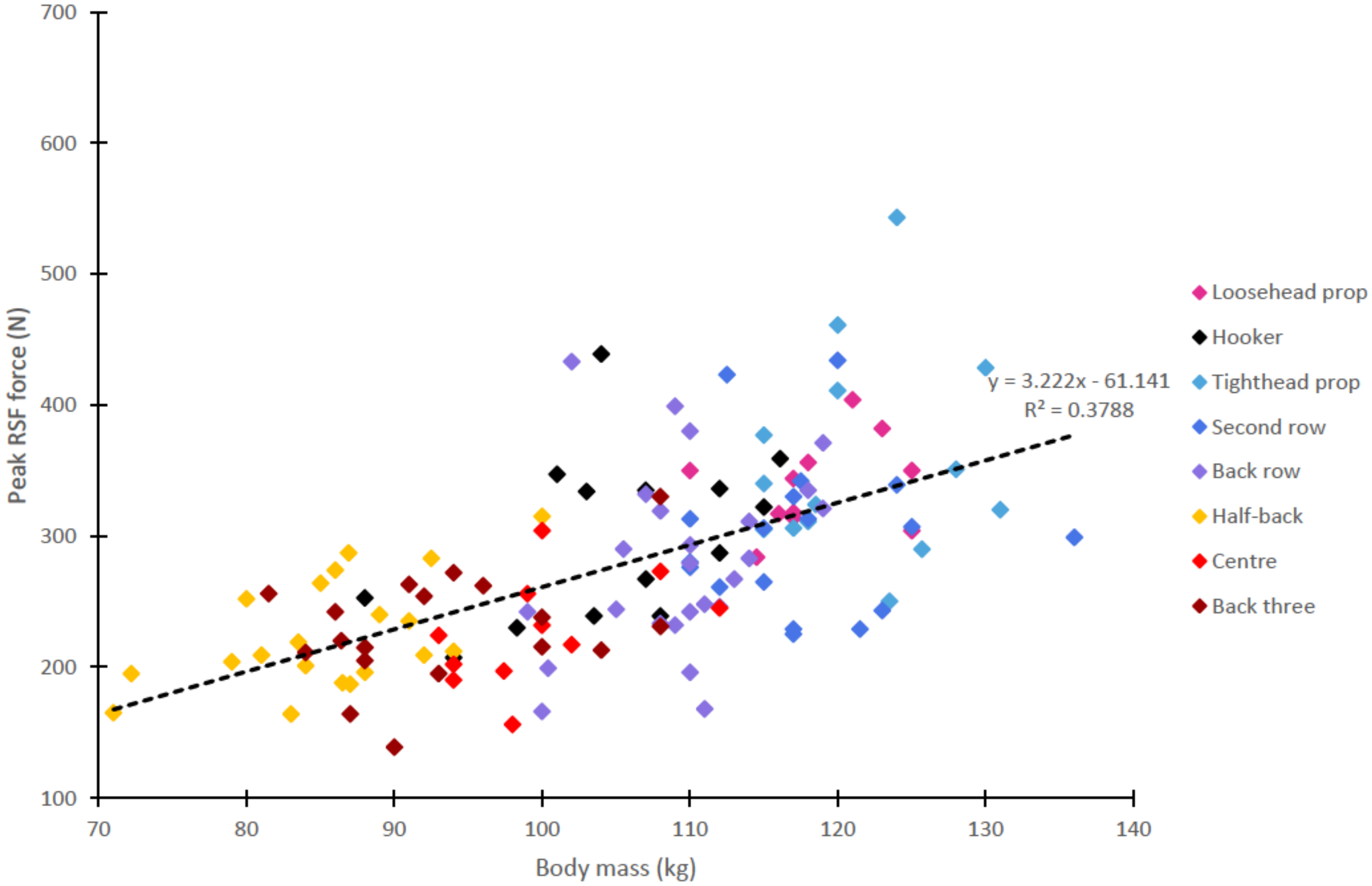


Figure 6.4 Body mass against peak RSF force plotted by playing position (each point represents one player)

6.3.2.3 Differences in neck strength between player levels

6.3.2.3.1 All players

When overall neck strength was compared by playing level for all players (n = 131), there was no significant difference reported for peak neck force (N) between Premiership and Championship level players.

6.3.2.3.2 Forwards

Only the neck strength test direction of Ext demonstrated a significant difference when measured by playing level. Premiership forwards (mean = 458, SD = 71.0) were significantly stronger (11%) than Championship forwards (mean = 413, SD = 81.1): $F(2, 79) = 3.43$, $p = 0.037$.

6.3.2.3.3 Backs

No statistically significant differences were observed between the playing levels in any neck strength test directions for the backs.

6.3.2.4 Discriminant function analysis for neck strength testing

DFA was performed to establish the percentage of players that could be correctly classified into playing position by the four test directions of neck force (Table 6.11). DFA produced a model that predicted 89.4% (Eigenvalue = 1.17) of the variance between playing positions by Ext force (Wilks' lambda = 0.488, df = 18, $p < 0.001$). No further predictions could be made by individual test directions, which all returned non-significant values ($p > 0.116$ in all cases).

Table 6.12 Discriminant function analysis of percentage classification of playing position by total neck force in all test directions

		Probability (%) of predicted playing position							
		Loose-head prop	Hooker	Tight-head prop	Second row	Back row	Half-back	Centre	Back three
Playing position	Loosehead prop	9.10	0.00	27.3	18.2	45.5	0.00	0.00	0.00
	Hooker	7.10	0.00	21.4	21.4	28.6	7.10	0.00	14.3
	Tighthead prop	14.3	0.00	57.1	14.3	14.3	0.00	0.00	0.00
	Second row	5.60	0.00	11.1	38.9	27.8	11.1	0.00	5.60
	Back row	8.00	0.00	8.00	12.0	44.0	8.00	4.00	16.0
	Half-back	0.00	0.00	0.00	5.00	5.00	70.0	0.00	20.0
	Centre	0.00	0.00	0.00	0.00	45.5	27.3	9.10	18.2
	Back three	0.00	0.00	5.60	0.00	22.2	38.9	0.00	33.3

The data demonstrates that 57% of tighthead props and 70% of half-backs can be correctly classified into their playing position by their neck strength. Combined loosehead and tighthead props are correctly classified as props by neck strength in 84% of cases. However, hookers demonstrate an ability to be classified in multiple playing positions, including as back-row players (29%) and as props (28%).

6.3.2.5 Discriminant function analysis of peak extension force and anthropometrics

The two highest predictive factors of anthropometric data, body mass (Figure 6.5) and height (Figure 6.6), were plotted against the highest predictive neck strength test (Ext force) to determine how well these factors could describe playing positions at all playing levels (*n* = 131). As the DFA for body mass increased, so did the DFA for peak Ext force, with props demonstrating both greater body mass and peak Ext force, followed by back row, second row, centres, back three and half-backs (Figure 6.5).

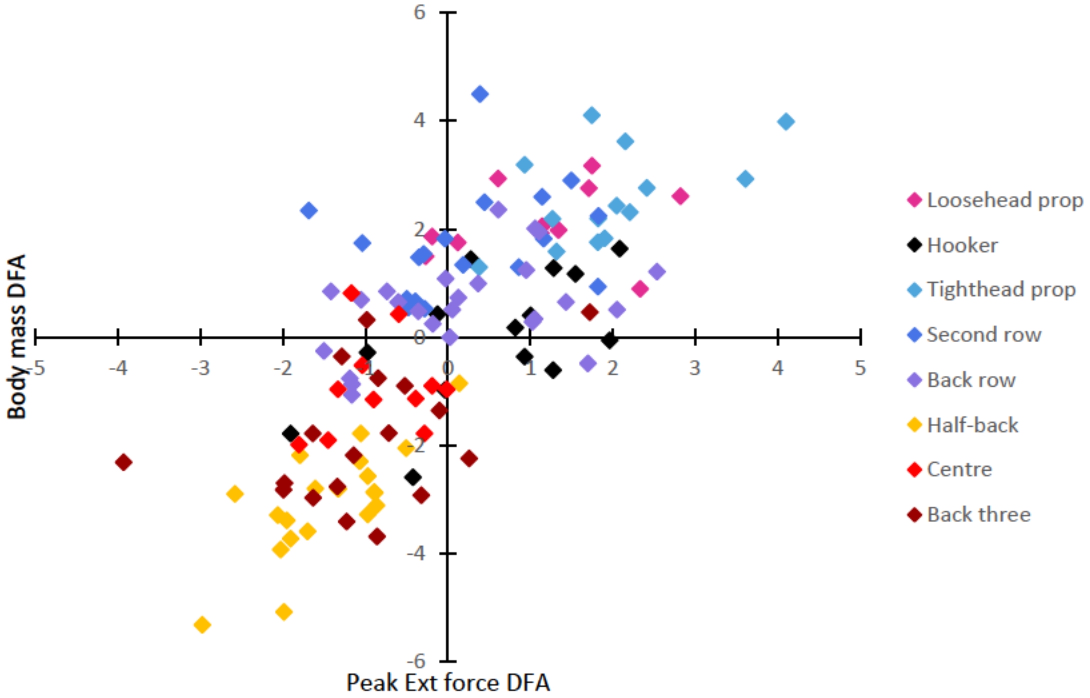


Figure 6.5 Discriminant function analysis (DFA) of extension (Ext) force against body mass plotted by playing position (each point represents one player)

The plot of DFA for height and DFA for peak Ext force showed far more scatter than when body mass was plotted against DFA for peak Ext (Figure 6.6).

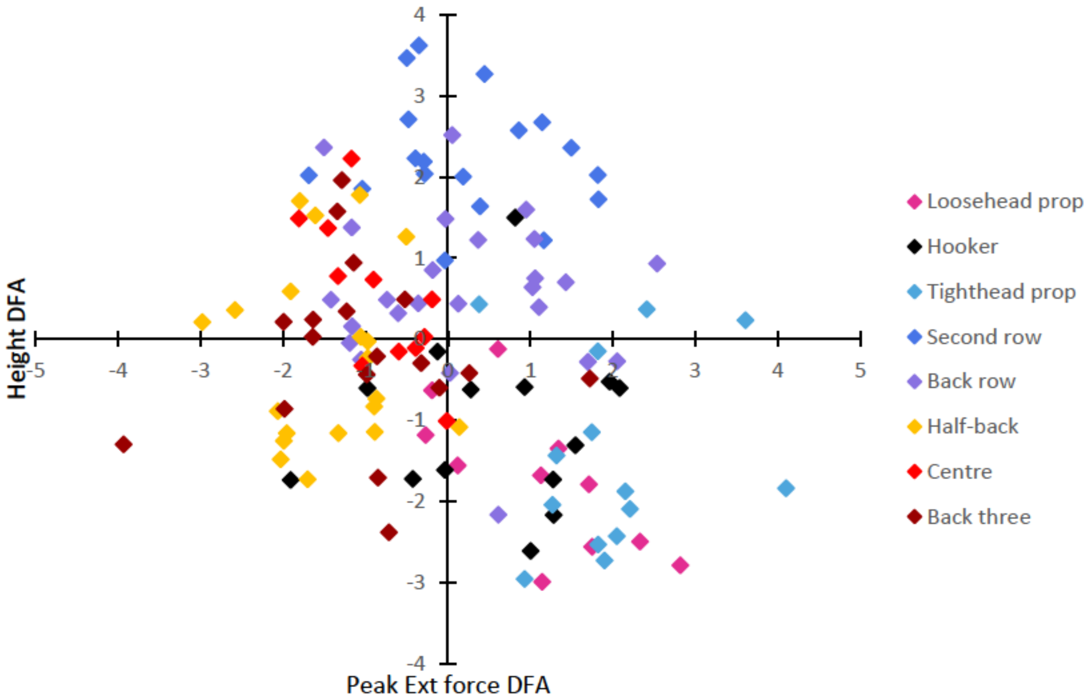


Figure 6.6 Discriminant function analysis (DFA) of extension (Ext) force against height plotted by playing position (each point represents one player)

The two highest predictive factors of anthropometric data, body mass (Figure 6.7) and height (Figure 6.8), were plotted against the highest predictive test position, Ext force, by playing level (English Premiership and Championship). As the DFA for body mass increased, so did the DFA for peak Ext force, with forwards demonstrating both greater body mass and peak Ext force than backs (Figure 6.7).

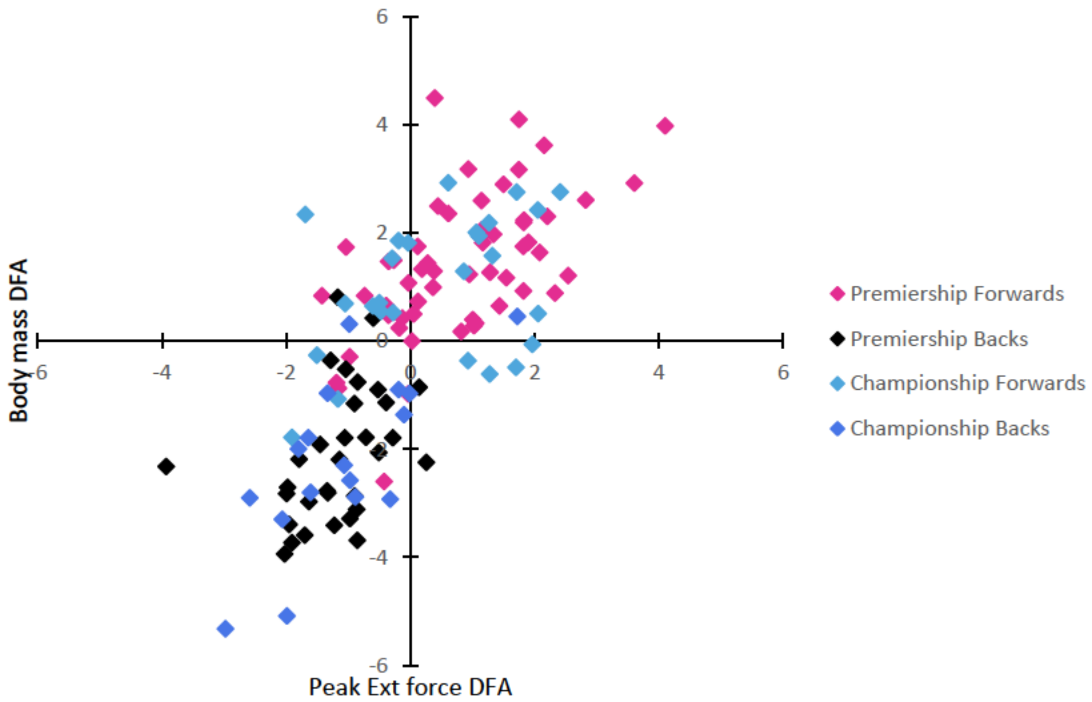


Figure 6.7 Discriminant function analysis (DFA) of extension (Ext) force against DFA of body mass plotted by playing level and playing position (forwards/backs) (each point represents one player)

The plot of DFA for height and DFA for peak Ext force showed far more scatter than when body mass was plotted against DFA for peak Ext (Figure 6.8).

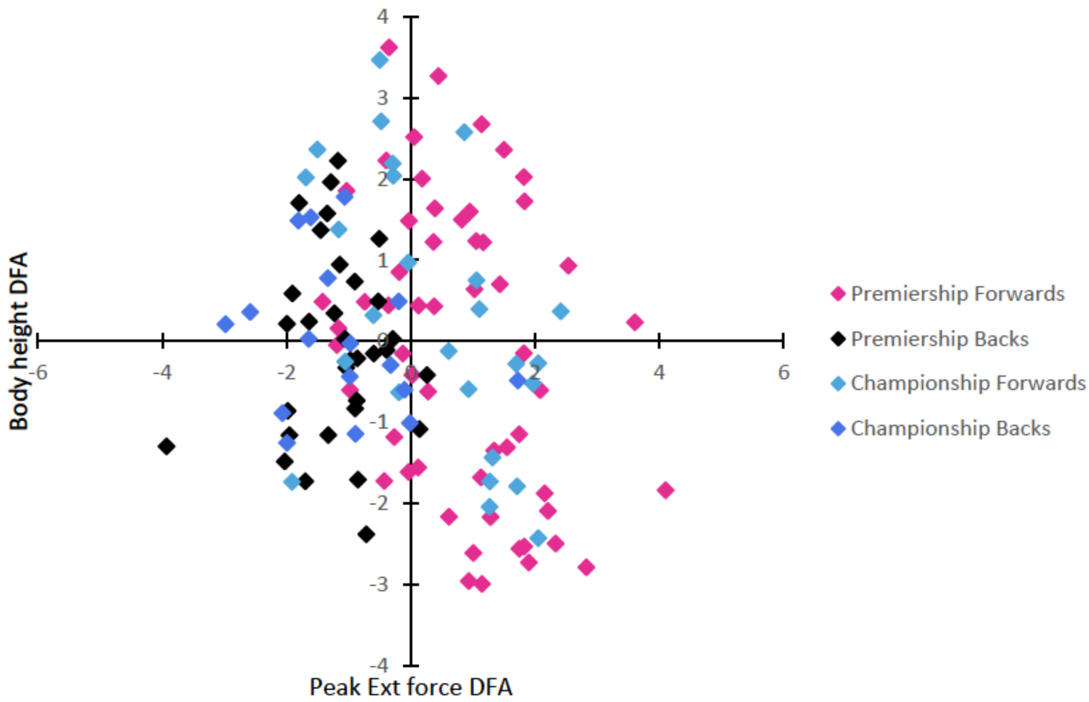


Figure 6.8 Discriminant fuction analysis (DFA) of extension (Ext) force against height plotted by playing level and playing position (forwards/backs) (each point represents one player)

6.4 Discussion

6.4.1 Introduction

The aim of this study was to measure and analyse anthropometric and neck strength data collected from professional male rugby players at Premiership (n = 88) and Championship (n = 43) levels. This has led to the generation of a database of normative measures for this specific cohort of professional rugby players, presented according to two different classification systems. The first was the traditional grouping of forwards (loosehead prop, hooker, tighthead prop, second-rows, back row) and backs (scrum-half, fly-half, wingers, centres and full-back); and the second involved smaller groupings, adapted from Cahill et al. (2013), of front-row players (loosehead prop, hooker, tighthead prop), second-row players, back-row players (open-side flanker, blind-side flanker and number eight), half-backs (scrum-half and fly-half), centres (inside-centre and outside-centre) and back three (left-winger, right-winger and full-back). This allowed for more in-depth, position-specific analysis.

Most research published on rugby players' anthropometric and strength data has grouped players into forwards and backs (Chavarro-Nieto et al., 2021; Stoop et al., 2018). This is because a very large cohort of players would be required to generate sufficient data for analysis by the 15 different playing positions, and most such research has been undertaken at a single club. Moreover, there have been studies exploring neck strength values at different levels of rugby, such as in community (Maconi et al., 2016; Salmon et al., 2018), professional (Farley et al., 2022; Naish et al., 2013) and semi-professional (Snodgrass et al., 2018) settings. However, strength data has yet to be compared between playing levels, as no two studies have used the same testing equipment or protocols to enable this comparison to occur – and, as discussed at length earlier in the thesis (see, e.g., Sections 4.4 and 5.4), there are significant challenges in comparing studies that employ different equipment.

6.4.2 Rugby players' anthropometric qualities

6.4.2.1 Height and body mass

The findings of the present study were that, playing level notwithstanding, the forwards were consistently taller ($p < 0.001$) and heavier ($p < 0.001$) than the backs (Table 6.3). This aligns with recent studies of professional rugby players, as measured since the advent of professionalism in 1995 (Bevan et al., 2022; Hill et al., 2018; Stoop et al., 2018). However, there were no such significant differences in anthropometric values between Premiership and Championship playing levels ($p > 0.05$). Moreover, unlike other metrics such as mass and neck girth, training has no influence on height, meaning that height is a predictor through natural selection of those playing at the top level of rugby. This aligns with previous findings that sub-elite players were significantly shorter than elite players (Quarrie et al., 1995; Sedeaud et al., 2012). It has also been noted that the height of both forwards and backs has increased in northern-hemisphere rugby teams competing at the highest levels, and that having taller players confers a statistically greater ability to win matches (Hill et al., 2018; Sedeaud et al., 2013). The average height of an elite back player increased by 5.4 cm over the 20 years between 1988 and 2008, and elite forwards by 2.9 cm (Sedeaud et al., 2012).

In addition, results from the present study showed that height was statistically significantly different between a number of positions (Table 6.4). Notably, the second-rows were significantly taller than every other playing position, with an average height of 198 ± 3 cm ($p < 0.001$). This finding is also consistent with the reported height of 200 cm recorded from ten professional second-row players measured in 2015 by Hill et al. (2018).

The significant difference recorded between the heights of the second-row and front-row players ($p = 0.001$) (Table 6.4) brings into question the curious decision made by Bevan et al. (2022) to perform their analysis based on grouping the forwards into front five and back row. As the results of the present study suggest, this grouping appears artificial, as player anthropometrics are not homogeneous within these groups. Bevan et al.'s study analysed the anthropometric properties of 291 professional rugby players over 20 seasons. Given such a large data set, the authors could have chosen to display their results by individual playing position rather than choosing these groupings. That said, the back-five backs were also treated as one group by Bevan et al., and results from this thesis supports that grouping. This is because the only group of backs who were shown to be statistically significantly different from the others were the half-backs, who were both shorter ($p = 0.009$) and lighter ($p < 0.014$) than the back five. What the results of the present study contribute to knowledge, then, relates to the appropriateness of certain player groupings over others based on robust anthropometric data.

Thinking more broadly, as stated in the literature review, it has been noted that rugby players' mass generally increased significantly from 1991 to 2011 but then plateaued (Tucker et al., 2021). However, there is little data to support this claim with regard to individual playing positions, as such research has never been previously undertaken. The results from the present study demonstrated that across all participants, loosehead and tighthead props, together with second-rows, were the heaviest positions on the pitch (Table 6.3), with statistically significantly ($p < 0.005$) greater body mass than hookers, back-row players and all the backs (Table 6.5). Back-row players were all statistically significantly heavier than all the backs ($p < 0.002$). Within the backs, centres ($p < 0.001$) and the back three ($p < 0.014$) were both statistically significantly heavier than the half-backs. These results reveal that classifying players as forwards and backs does not go far enough towards monitoring variations in mass and height, as these groups are by no means homogeneous. If researchers were to continue collecting anthropometric data about individual playing positions to the level of granularity proposed in the present study, longitudinal reporting of height and body mass changes by position would be made possible over future decades.

Thinking in terms of the practical applications of these findings, analysing anthropometric data by individual playing position together with the knowledge that mass represents an important component in the calculation of both momentum and force in collision-based injuries (Fuller et al., 2007; Murray et al., 2014; Tucker, Raftery, Kemp et al.,

2017) can lead to greater understanding of the relationship between anthropometric changes and injury incidence and severity.

Moreover, consideration should be given to the anthropometric profiles of individual playing positions with specific regard to the potential interchangeability of players on the pitch. By contrasting such profiles between individual positions, detailed comparison of similarities between player characteristics could enable more robust, evidence-based decision-making in this area, with implications for both performance enhancement and injury prevention.

6.4.2.2 Neck girth

In a sporting population, a larger neck girth is hypothesised as being the result of the hypertrophy of cervical muscles (see also Section 2.3.3) (Hrysomallis, 2016; Krzysztofik et al., 2019; Schoenfeld, 2010). In addition, it has previously been suggested, both for soccer players (Caccese et al., 2017) and amateur rugby players (Salmon et al., 2018), that this measurement correlates with neck strength and may in turn function as a potential predictor for it.

Given the large number of participants involved in the present study (n = 131), it was possible to analyse the measurement of neck girth by playing position, as well as by player groups. Forwards had significantly larger neck girth than backs at both Premiership (forwards 46.9 ± 2.9 cm; backs 42.1 ± 1.9 cm) and Championship (forwards 45.4 ± 2.8 cm; backs 41.7 ± 2.2 cm) levels ($p \leq 0.05$), suggesting that neck girth could also be used as a predictor of playing level (Table 6.3). The absolute measurements of neck girth were similar to those from studies by Salmon et al. (2018), which involved participants from the highest level of amateur leagues in New Zealand (forwards 43.5 ± 2.5 cm; backs 40.0 ± 2.2 cm), and Konrath and

Appleby (2013), who measured the neck girth of elite players in Australia (forwards 43.8 ± 2.2 cm; backs 40.1 ± 1.75 cm). However, more research is required to state with any confidence that neck girth can function as a predictor for neck strength.

In the present study, the neck girth measurements by position (Table 6.6) revealed the following significant differences: tighthead props (49.3 ± 3.2 cm) and loosehead props (48.6 ± 1.5 cm) were significantly larger than all other playing positions ($p < 0.001$), with the exception of each other ($p > 0.05$). Hookers, second-rows and back-rows were significantly different from half-backs ($p < 0.001$) and back-three players ($p < 0.001$), but not from the centres ($p > 0.277$ in all cases). This is a novel finding, as previous reports have simply stated that forwards have greater neck girth than backs (Konrath & Appleby, 2013; Salmon et al., 2018). In studies where neck strength has been described in greater detail by player position (Davies et al., 2016; Farley et al., 2022), the front row have consistently been treated as a homogeneous group of players. However, as with mass (see Section 6.4.2.1), the hookers in the present study demonstrated significant differences in neck girth from loosehead props ($p = 0.023$) and tighthead props ($p < 0.001$). This is a particular key finding, as hookers are generally grouped together with props as front-row forwards, yet the anthropometric data reported here shows the shortcomings of such an approach.

Moreover, the backs showed no statistically significant difference between playing positions with regard to neck girth ($p > 0.05$). However, the centres were the only backs playing position that showed no significant difference from either hooker, second-row or back-row players ($p > 0.05$). The clinical implications of these findings relating to neck girth suggest that centres, who demonstrate a similar neck girth to all forwards except props, could potentially train in the gym with the forwards if neck girth is shown to have a protective feature for injury, as suggested by Hamilton et al. (2014).

Despite these suggestions, according to DFA, mass and height are much greater predictors of playing position than neck girth. This suggests that neck girth may have limited value as an anthropometric variable in the classification of players.

6.4.3 Neck force by playing level, direction and playing position

Neck Ext force was significantly greater in Premiership than Championship forwards (11%; $p = 0.037$). This is important, as according to Farley et al. (2022), Ext strength is the only directional predictor for concussion, with greater Ext strength being correlated with lower incidence of concussive injury in elite rugby players. All other neck strength directions between playing levels were not significantly different. It could be hypothesised that for forwards, playing rugby at a higher level both results in and requires greater neck strength due to the increased forces being exerted through the neck by players in the opposition during scrums (Martin & Beckham, 2020). Moreover, there was a difference in neck girth between playing levels, which suggests greater muscle mass in Premiership forwards than Championship forwards.

Neck force data for all of the four test directions (Flex, Ext, LSF and RSF) demonstrated significantly different findings between player positions regardless of level played. Again, this is an important and novel finding in the reporting of neck strength of rugby players in that it could facilitate talent identification by position, decision-making regarding when academy players have the necessary neck strength to advance to senior rugby and the identification of which playing positions could train together in the gym based on similar neck strength profiles.

When neck force (N) was calculated as a normalised value using body mass, the positional differences were not statistically significant (table 6.9). The protocol tested within this thesis, with the test position being quadruped, reduces the probability that the neck force is influenced directly by body mass. Therefore, if using the test for a squad of players to measure relative strength of players in relation to each other then it might be suggested that normalised data would be a useful measurement. If however, the data is required as an absolute value for that athlete such as for post injury monitoring, or return play objective markers, then absolute values would be the most useful.

6.4.3.1 Tighthead props

The tighthead prop plays the most important role in stabilising the scrum, whereby they are expected to push up into Ext against the opposition loosehead prop and hooker. In the present study's findings, tightheads showed the greatest Ext strength values (524 N), significantly stronger than all the backs players ($p < 0.001$), the hookers ($p = 0.018$), second-row and back-row players ($p < 0.001$). The only position that did not demonstrate a significantly weaker neck into Ext than the tighthead was the loosehead prop (Table 6.9). Tighthead props were also stronger than the back-row forwards into LSF ($p = 0.008$) and RSF ($p = 0.003$), and stronger than all the backs players ($p < 0.001$). However, into Flex, they were only significantly stronger than the half-backs ($p < 0.001$) and the back-three players ($p = 0.007$). In this way, while there may be a potential weakness in relation to the other strength values recorded into Flex, LSF and RSF, tighthead props have greatest need for Ext strength given the fundamental role they play in scrummaging.

6.4.3.2 Loosehead props

The loosehead props were not significantly different from the tightheads in any of the strength measurements. The most notable observation was the lack of significant strength differences seen in Ext from all other forwards. This is perhaps surprising given looseheads' role in the scrum, as well as the fact that their neck girth was significantly greater than hookers (p = 0.023), second row (p = 0.007) and back row (p = 0.002). However, the two props perform different roles in the scrum: for example, the tighthead prop stabilises the scrum, and their head is held between the opposition hooker's and loosehead prop's heads. This means that tightheads must regularly push up into Ext with their neck, which thereby confers a training effect upon them every time they perform a scrum. However, the law change that came into effect in 2013 necessitated that a prebind was necessary for the scrum, meaning that looseheads – unlike tightheads – were no longer able to push up into Ext and instead were required to push horizontally. In this way, a loosehead's left shoulder (the loosehead prop is always on the left side of the scrum) is where their force is directed to stabilise them, hence there being little difference between LSF and RSF. This is because as the loosehead's neck pushes right, the left shoulder has to counter this force, meaning that an equal force is observed as being produced for LSF and RSF in both props.

6.4.3.3 Hookers

The only statistically significantly different findings for the strength for the hooker position was that they were stronger than the half-backs (p = 0.001) and back three (p = 0.004) into Ext, than the half-backs (p = 0.012) into LSF, and than the half-backs (p = 0.008) and back three (p = 0.022) into RSF. Again, it is novel to note that the hooker is not significantly stronger than the centres into Ext, or any other position into Flex. Given their larger neck girth, this lack of significant force production suggests that an increased fat mass, rather than muscle tissue, could account for their overall greater mass (Bevan et al., 2022). A hooker's job in the scrum, as their name implies, is to hook the ball, and to do this they rely on their props holding them up. Therefore, while they need to be able to hold their head against the opposition hooker's and tighthead props' heads in a scrum, they are always looking down to see the ball, meaning that they do not apply as much Ext strength as props.

Overall, the job of the front row is to engage with the opposition front row and allow the five players behind them to push them forwards with as much force as possible. These anthropometric and neck strength properties, reported in the present study, are therefore in-keeping with the defined roles of each player position. In turn, these measurements could be used to predict the position that these players adopt. In total, the average force applied by a full pack of eight male professional rugby players has been measured as being between 4,000 and 8,000 N (Martin & Beckham, 2020). Although measuring these forces has not been achieved in live scrums with any success, the forces measured on scrum machines at least give an insight into why the muscles controlling the head and neck need to be strong to withstand high forces.

6.4.3.4 Second row

Second-row players are notably significantly taller than any other playing position ($p < 0.001$, except the back row ($p = 0.008$). However, they are also significantly stronger than the half-backs in Ext ($p = 0.001$) and LSF ($p = 0.016$), and stronger than all the backs in RSF ($p < 0.04$ in all cases). This difference between LSF and RSF strength findings could be explained by right-hand dominance. However, more data is required to confirm whether this finding is replicable.

6.4.3.5 Back row

Back-row players only displayed a significant difference in strength to the half-backs ($p = 0.010$ for Flex, $p = 0.048$ for LSF, and $p = 0.040$ for RSF). This data conforms to role-specific predictions of back-row players, namely to push directly forwards in a horizontal position in the scrum, and to tackle hard and low from the base of the scrum (Table 2.1).

These differences noted between the individual playing positions within the forwards justify the separation of them into smaller units for research. This calls into question the convention, both in research and among practitioners, of considering all forwards as a single, homogeneous group.

6.4.3.6 Half-backs, centres and back three

No statistically significant differences in neck force were found between the three groups of playing positions into which the backs were categorised. Overall trends showed that the centres were the strongest in every test direction of neck movement, while the half-backs were the weakest. Moreover, as established above (Section 6.4.3.3), while hookers were not significantly stronger than centres into Ext, they were significantly stronger than all other backs.

6.4.4 Overall insights from discriminant function analyses

In relation to the anthropometric data, DFA produced a model that predicted 71.5% of the variance in playing positions by mass, with height and neck girth being non-significant by comparison.

Of the DFAs conducted regarding neck strength data, most interesting were the insights that 70% of half-backs and 84% of props could be correctly classified into their playing position by their neck strength alone. However, hookers were classified in multiple playing positions according to their neck strength measurements, including as back-row players (29%) or props (28%). Most importantly, the DFA model predicted 89.4% of the variance between playing position by Ext force, whereas all other neck test direction forces returned non-significant values ($p > 0.116$). In this way, Ext force represents the most robust measure with which to predict player position based solely on neck strength measurement. This is especially notable in light of Farley et al.'s (2022) finding that only Ext force can be adequately used as a predictor of concussion.

6.4.5 Limitations

In terms of the present study's limitations, the COVID-19 pandemic had an impact on the extent to which a range of clubs could be involved in data collection. While this could have been rectified by continuing data collection post-lockdown, due to changes in training and playing during the COVID period (Sarto et al., 2020), data collected after the pandemic period may not have been comparable to that collected in the initial phase. As a result, return visits were not made to clubs visited pre-COVID.

Relatedly, certain playing positions were underrepresented in the sample, and there were more Premiership (*n* = 88) than Championship (*n* = 43) players involved in the study. Future instantiations of the study would benefit from greater numbers across playing levels and player positions. No power calculation could be performed to determine how robust these calculations are due to the lack of similar data in published literature, meaning that these results should potentially be verified by further work with larger sample sizes.

6.5 Conclusion

Results show that the ForceFrame successfully met both criteria of being robust enough to measure every rugby player within this population and to generate baseline results at a given moment in the season for rugby players. It enabled the players to be classified by both position and level at which they play, meaning that any measurements that flag up a potential neck weakness can be reliably used as a predictor of the player requiring further assessment or rehabilitation exercises to address the weakness. Furthermore, the test was easy and quick to administer, and the results indicate that its efficacy is robust outside of the laboratory. This ecological validity significantly increases the chances of real-world take-up, thereby overcoming many of the barriers to successfully and consistently measuring neck strength (see Chapter 3).

The findings suggest that traditional groupings (say, into forwards and backs) may not be ideal in terms of anthropometric homogeneity. Instead, attending more closely to the detail of variations between individual playing positions and smaller groupings may have positive implications. For example, expectations of athletic performance regarding the maintenance of a fully match-fit strength profile may be improved through more tailored regimes, in turn serving to maximise performance and potentially protect against injury, as well as to encourage buy-in from both players and clubs.

This novel outcome ultimately enables a player to be measured if they have access to an FFD wherever they are situated rather than the measurement being specific to a research facility.

Chapter 7: Discussion

7.1 Introduction

Discussion in this chapter is broadly split into two parts that draw holistic meaning from the four empirical chapters. Following a brief overview, the first half considers the implications of findings from Chapters 3, 4, 5 and 6, both in terms of addressing specific research questions and also in terms of their mutual interaction, to give a picture of the overall contribution of the ideas, issues and solutions generated. The second half of the chapter augments consideration of the four empirical chapters with discussion of wider contribution, taking care to regard practitioners, players and the sport of rugby as interconnected. Through this lens, real-world significance is established.

7.2 Overview of findings

The overall aim of this thesis was to establish, measure and implement best practice for neck strength screening in professional rugby. To meet this aim, current practice in neck strength testing and exercise provision in professional rugby players was determined (Chapter 3). Protocol development was underpinned by the objective to devise and test a credible method that delivers a simple, practical and highly effective approach which inspires confidence in both practitioners and athletes and can be widely used. This objective was met in a series of cumulative steps, reported in Chapters 3, 4, 5 and 6. Ultimately, this thesis presents the development of a reliable protocol for testing neck strength, not just in the research lab, but also in the field, and specifically for the sport of rugby.

After surveying the current literature landscape (Chapter 2), a notable issue identified in previous research was failure to engage with the stakeholders who ultimately utilise, and so must believe in, the neck strength tests developed. Key stakeholders in the field of professional rugby, with regard to neck health, include medical and sports science support staff, strength-and-conditioning (S&C) coaches, and athletic trainers, all of whom hold relevant roles in the sport of rugby. The experience-based opinions of this group, who all work within Premiership and Championship clubs, were therefore surveyed (Chapter 3) in order to gain full insight into what is currently happening at professional rugby clubs with regards to player neck health. Specific practice-based insight gained from this survey included how neck strength is measured, how that data is used, where the sources of knowledge came from and how that knowledge was then implemented across the spectrum of clubs from professional teams in England. Survey findings include expression of the significant lack of understanding, and strong desire for, reliable neck strength measurement practices from key stakeholders. These early empirical findings mark a novel contribution to existing knowledge by confirming what the landscape of current practice in professional rugby union in England consists of in terms of neck screening protocols, specifically regarding widespread inconsistencies and knowledge gaps. Chapter 3's findings were also augmented by some empirical evidence from the review of literature in Chapter 2 where only three studies were identified which addressed neck exercise provision for rugby players, and none which revealed the impact of neck strengthening on cervical spine injuries (Daly et al., 2021). Moreover, there were several studies which explored methods to measure neck strength (Chavarro-Nieto et al., 2021; Peek, 2022; Selistre et al., 2021), but none which were then reported or used as a gold standard, which confirm the real-world and widespread user need for a universally accepted and robustly tested method of measuring neck strength.

Results from Chapter 3 instigated the development of a reliable, universally available neck strength test, which was reported in Chapters 4, 5 and 6. Chapter 4 and Chapter 5 respectively chart the development and testing of a rugby-specific method for quantifying neck strength through re-purposing the ForceFrame equipment. The ultimate demonstration of widespread and reliable usage of the ForceFrame, which is applicable from field-based to gym contexts, offers the sport of rugby a new way of addressing a longstanding issue. The novel contribution of the proposed approach lies in the reliability of the method developed and also its ease of deployment in real-world settings.

In the final step of the cumulative research design of this thesis, the new work undertaken to establish a general neck strength measurement method successfully established in Chapters 4 and 5 was applied to elite level rugby in Chapter 6. This targeted application fostered new insight into differences associated with players' assigned field position. The overall contribution to new knowledge of findings from the three empirical chapters is attested to by the potential of the proposed method to become a universal gold standard, and its ultimate implications for the progression of player performance and welfare.

In what follows, each research question is addressed individually, and evidence is collated from the thesis as a whole to provide answers.

7.3 Surveying the state of the field and establishing need for best practices (RQ1)

Chapter 3 directly addressed RQ1: *What, if any, neck management practices (screening and strengthening provision) are used in elite-level rugby union in England?* The lack of knowledge around this question was highlighted through the literature review (Chapter 2), which established that there is a dearth of published data explaining the nature of current practice in professional rugby union specific to neck management. While a significant amount of data was identified on the subject of neck injury sustained in the sport of rugby (Brooks & Kemp, 2011; McIntosh & McCrory, 2005; Murray et al., 2014; Snodgrass et al., 2018; Swain et al., 2011; Viviers et al., 2018), alongside the emergence of new links between neck strength and rugby-related injury (Cooney et al., 2022; Eckner et al., 2018; Eckner et al., 2014; Farley et al., 2022; Schmidt et al., 2014), the authors of these studies used highly variable methods to measure and report the neck force data. This lack of consensus indicated a pressing need for robust neck screening and measurement practices in rugby. Analysis of the survey responses provided an overview of the contemporary state of clinical practitioners' knowledge and practices.

The survey was distributed to 40 professional and semi-professional rugby clubs. It allowed for snowball sampling and, as a consequence, 42 responses were received. Findings revealed a heterogeneity in approaches to neck care across clubs and playing levels, as well as a diversity of approaches to neck measurement. While the sample size was by definition small, due to the eligibility criteria, analysis led to the identification of gaps in current knowledge and practice within the targeted Premiership, Championship, National League 1 and professional senior academy squads. The open nature of the responses, particularly the honesty of the practitioners regarding their lack of knowledge but desire to learn more, was noteworthy.

A key finding from the survey results was that there was little or no consensus regarding the equipment used to measure neck strength in professional English rugby clubs. Methods used ranged from a low-cost yet low-objectivity procedure of measuring strength by having the participant push their head against the practitioner's hand to using expensive and sophisticated (but as yet untested for reliability) systems such as the GSA Analyser™. The types of measurements taken were also inconsistent across the board, comprising a range of strength tests including maximum voluntary isometric contraction (both make and break tests), endurance, and "time to fatigue". A relevant by-product of this finding is that if a player moves to another club with different practices, as is common, then their data is not universal, which renders the tracking of progress over time impossible.

The survey also revealed significant (self-professed) lack of knowledge among practitioners regarding the subject of neck strength measuring, and widespread lack of engagement with published research to inform practice. This finding is at odds with professional expectations both in healthcare and in sport: physiotherapists, who comprised the majority of participants, are required to conform to the specific codes of conduct that stipulate a need for evidence-based practice. For example, the Chartered Society of Physiotherapy's (2019) *Code of Members' Professional Values and Behaviour* requires members to be able to account for how their professional judgement and decisions are informed by the profession's evolving evidence base (2019, Section 1.3.2, p. 3) as well as to use available information and evidence to assess risk and make decisions (2019, Section 1.3.3, p. 3). The lack of a strong body of evidence on best practice to underpin this key aspect of

S&C training perhaps explains why the practitioners do not engage with the heterogeneous literature that does exist. Ultimately, findings in this chapter demonstrate that current neck strength screening practices do not serve players or the game of rugby adequately.

Despite the issues identified with current practice, the responses received from the survey demonstrated that clubs do wish to measure neck strength in their professional rugby players. The evidence showed that attempts were being made to do this at all clubs who responded. An obvious potential confounding issue may be that the small numbers of responses from Championship clubs (Figure 3.4) was perhaps because the non-responders were not attempting to measure this key objective marker at all. However, a high response rate from the Premiership clubs (Figure 3.4) clearly demonstrated the relevance of the survey to them and legitimised the relevance of the topic. These responses, as well as the potential interpretation of the non-responders, highlighted the lack of knowledge regarding neck strength, therefore underlining the possibility for the promotion of education around this key aspect of player welfare.

An incidental finding from the survey is that, because of the heterogeneity of literature, there was a lack of understanding of what clubs should be doing. In other words, there was *no* universally accepted or promoted reliable and valid method that relevant personnel could adopt. Pieced together, responses gave a picture of a lack of commercially available equipment, stringent reliability testing or gold standard of measurement for validation purposes. Further, laboratory-based research findings were not transferrable to the general practitioner in a rugby club setting. Respondents asked for advice on how to test neck strength and, in response to questions about what they did and where they got their information from, published research was cited as a source, but they were then unable to name authors of this research.

Garnering the opinions of practitioners in rugby from this questionnaire enabled the voices of a range of current practitioners to be heard and listened to in the context of a rigorous, empirical study for the first time. It is important to acknowledge that respondents have a stake in the inception of developing a trusted way of measuring neck strength and a vested interest in adopting it in order to progress this important aspect of player welfare. These voices were unified in conveying that there was no single technique that they trusted or used to measure neck strength. Furthermore, there was a lack of knowledge of practices adopted between clubs. This absence of collaboration can be understood as stifling the development of this important aspect of neck strength and player welfare.

The resounding conclusion drawn from Chapter 3 findings was a call from stakeholders for the establishment of a reliable *universal* method for measuring neck strength. The survey responses gave unique insight into the practices (or, rather, the lack of consistent reliable practices) taking place at professional level rugby for measuring neck strength and prescribing tailored exercises. Although the literature identifies this as an extremely important aspect for both injury prevention and athletic performance (Peek, 2022), both of which were stated by the respondents as being the reason why they would screen the neck for health, no practitioner claimed to have an in-depth evidence-based knowledge or understanding of how to translate any published research into their current practice.

Chapter 3 findings therefore guided and legitimised the research trajectory of the rest of this thesis by enabling a clear picture to emerge surrounding the current practice of neck strength screening. The in-depth responses from practitioners clearly demonstrated an interest in, yet gap around, the transfer of current knowledge from research into the real world of practice.

Ultimately, questionnaire responses strongly concluded that a consistent, evidence-based measurement protocol for neck strength which could be accepted by professional rugby should be sought and tested. Practitioners reported that neck strength research and information was not being implemented or supported by the Rugby Football Union (RFU), the professional sport's national governing body, or rolled out as part of an educational package. The relevance of this finding (which resulted from a survey administered in 2018) is arguably amplified by the rapidly changing levels of attention paid to the consequences of head collisions in rugby (West et al., 2021), occurring in the context of an increase in media interest in concussion and subsequent neurodegenerative disease.

Conclusions from Chapter 3 guided the direction of the next experimental study in Chapter 4. Prior to applying any proposed method for measuring neck strength to the rugby setting, it was imperative that the method was tested for reliability within the carefully controlled setting of a research lab, and that both the equipment being proposed and the protocol being detailed were analysed. Chapter 3 findings showed that practitioners will not accept a protocol that is not applicable in multiple settings. Any method developed must, therefore, be sport-specific and utilisable in the field. In response to the genuine emergent need revealed by the survey in Chapter 3, the next two experimental chapters, Chapters 4 and 5, document the development and reliability testing of a novel method for quantifying neck strength that is rugby-specific and can be utilised in different field-based settings, such as within a gym, a changing room or designated area at a rugby club.

7.4 Establishment of reliability of a novel neck strength test (RQ2)

The key findings from the questionnaire, reported in Chapter 3, indicated the lack of a well-established neck strength test for rugby players that was understood and available to practitioners in the field. Therefore, it was imperative to explore a test to measure neck strength which could be performed on rugby players with confidence by practitioners. Exploration of the equipment and test protocol reliability and applicability for end users was required to ensure ready transfer from the closely monitored environment of the research laboratory into the field of sport. The data output from the test needed to be easy to interpret and to be clearly understood by all stakeholders, namely the athletes, physiotherapists and S&C coaches. These requirements were addressed in Chapters 4 and 5, which answer RQ2: *Can neck strength be reliably tested using existing equipment?* These chapters demonstrate the reliability of a novel neck strength test that re-purposes existing, commercially available equipment, in the form a modified fixed-frame dynamometer (FFD), the ForceFrame.

One of the key findings from Chapter 2 was that existing neck measurement protocols, as proposed in the academic literature, are generally inconsistent and lack detail regarding the start position adopted by participants. The literature illustrates the diversity of test positions, including seated (Geary et al., 2013; Hamilton & Gatherer, 2014), a comparison of seated and standing (McDaniel et al., 2021), forward lean onto a laboratory constructed bench (Salmon et al., 2015) and standing unsupported (Farley et al., 2022; Versteegh et al., 2015). This lack of consensus regarding how to standardise the start position of the test renders the results from these studies difficult to compare. Moreover, this issue of inconsistency was also reflected in the results of Chapter 3, as clinical practitioners reported that they employed a wide variety of techniques, and an analysis of these responses showed a distinct lack of consensus throughout. As a result, there has been little progress – both in the academic literature and in clinical settings – in accounting for the influence of wider body stability on neck strength measurements (Peek, 2022).

Chapter 4 therefore paid particular attention to issues of reliability, with emphasis on the issue of bodily stability during neck strength testing. The test position was fully described and justified, and every decision regarding the novel protocol was carefully chosen to ensure clarity of detail for reproducibility and stability of the body to allow the neck to have a stable base from which to work.

The optimal position for participants to adopt when using the ForceFrame rig for testing neck strength was established. The size and structure of the rig only accommodates two possible positions, quadruped and lying. If lying, the participant would have to move between prone and supine positions to measure in the sagittal plane (flexion [Flex] and extension [Ext]), which was deemed to be far less practical and to invite unnecessary variables into the protocol. As a result, the quadruped position was chosen as the optimal test position.

To ensure consistency in the quadruped position adopted by participants, verbal instructions were given requiring full retraction of the scapulae during testing. This in turn ensured that the spine could not be flexed during the test, further reinforcing the overall consistency of the protocol.

Having reduced the potential for extraneous variables within the procedure, testing then involved a comparison of two different quadruped positions: the first requiring participants to keep their hands a shoulder-width apart, the second to put their hands together to create a single pillar of support at the front of the body. In general, the "hands apart" (HA) test condition enabled participants to generate greater neck force in all directions than with “hands together” (HT). Neck strength in the HA condition was significantly greater for both left and right side flexion (LSF/RSF) ($t(39) > 6.46$, $p < 0.001$ in both cases) than HT. This finding corresponds with evidence drawn from existing studies, which suggests that a stable base of support for the body enables muscles to generate greater maximal voluntary isometric contraction than when acting with a less stable base of support (Behm & Anderson, 2006). However, Flex ($t(39) = 1.46$, $p = 0.48$) and Ext ($t(39) = 0.72$, $p = 0.15$) were not significantly different between HA and HT test conditions. Nonetheless, the overall analysis showed that the quadruped HA test position demonstrated the greatest potential efficacy as a test position and therefore represented the most promising procedural basis.

The findings from the ForceFrame results were then considered alongside data collected regarding force distribution throughout the body during testing (Chapter 5). This data was collected through the use of force plates positioned at the participant’s points of contact with the floor, which measured the ground force distribution as conveyed through the extremities. These results showed that the force distribution of the body recorded only moderate-to-good reliability ($ICC_{3,1}$) for the LSF/RSF tests, but good-to-excellent reliability for the Flex/Ext tests. These results strengthen the argument to use the HA test position rather than the less stable position of HT, especially for the LSF/RSF tests. These novel findings regarding the stability and repeatability of the test position ensure that, uniquely, this protocol can describe and account for the influence of the body position at the commencement of the test, unlike any other published results.

The results of the reliability study documented in Chapter 4 constitute a major novel contribution to research on neck strength testing by 1) comparing two suggested start positions to justify the chosen testing protocol; and 2) using a widely available, multi-purpose

FFD that does not suffer from the challenges of the handheld dynamometer (Farley et al., 2022; Versteegh et al., 2015) nor the reduced applicability of bespoke, laboratory-made equipment (Salmon et al., 2015), thereby giving confidence for its adoption in the field, relevant for both healthcare and sporting contexts.

To the author's knowledge, no previous research has explored the start position of the test with regard to the distribution of the body forces in relation to the measurement of neck strength, as is described in Chapter 5. Importantly, results from Chapters 4 and 5 strongly highlighted that the quadruped test position is a credible posture for measuring neck strength, while simultaneously being able to explore the distribution of force through the extremities. The findings clearly demonstrated that a standard quadruped position (hands apart) gave excellent reliability between trials as measured by $ICC_{3,1}$ and CV for both neck strength tests of Flex and Ext and for distribution of force from the body during neck strength testing. As a proposed novel examination tool and protocol for measuring neck strength, these findings add clarity to the process with sufficient robust evidence supporting its adoption in the field for the stakeholders.

The tests performed in the sagittal plane, Flex and Ext, showed good-to-excellent reliability both with regard to the neck force measured by the ForceFrame ($ICC_{(3,1)}$ 0.87–0.92) and the distribution of force demonstrated through the force plates during the test ($ICC_{(3,1)}$ 0.77–0.96). Lateral tests into LSF and RSF demonstrated good reliability with regard to the neck force measured by the ForceFrame ($ICC_{(3,1)}$ 0.83–0.94) and the distribution of force demonstrated through the force plates during the test ($ICC_{(3,1)}$ 0.68–0.90) (Chapter 4 and 5). The benefit of knowing that neck strength tests in the sagittal plane show no asymmetry through force distribution at the extremities at baseline or during the test, but that there is greater variability in the shift of force distribution to the left and right during the neck strength test for side flexion, adds gravitas and a greater depth of understanding of the potential limitations to testing using this equipment and protocol.

Since testing was undertaken, both the software and hardware of the ForceFrame have been improved. The sampling frequency for force measurement has increased from 50 Hz, when this study was undertaken (2018), to 400 Hz (when hard-wired) at the time of writing (2023). However, 50 Hz has been found to be a sufficient rate for isometric peak force measurement (Ryan et al., 2019). This issue suggests that the protocol developed in Chapter 4 has relevance in the field, as it addresses the limitations inherent to all previous studies into neck strength whereby test positions demonstrated variability due to a lack of standardisation or lack of ability to measure force distribution during the test. All tests demonstrated excellent test–retest start position reliability, and – given that no extra equipment is required, such as a chair – consistent set-up of the ForceFrame. Alongside the verbal instructions described to ensure the optimal test position adopted, users of the test can be assured of consistency. Findings reported in Chapters 4 and 5 therefore help to further understanding of, and justification for, using the quadruped position as the test position.

Findings relating to the usefulness of testing in the quadruped position are directly relevant to rugby, but also more broadly for research into all neck strength, as in this position it was possible to quantify force distribution through the body at the commencement of the test and at the time of peak neck force production. This broader application potential allows for a richer understanding of the forces involved during the test from not only the neck but also from the body during the time of peak force recorded at the neck. This new knowledge contributes to the face and ecological validity of the test. By demonstrating that both the start position and the neck strength test itself are reliable, this thesis goes a long way towards addressing the inherent mistrust of previous tests proposed in the literature.

With the development of this complete protocol, practitioners can now be confident that they can correctly interpret neck strength results gained through testing using an FFD, in the traditional quadruped position with HA and scapulae retracted to give thoracic spine stability. This insight into the impact of body force distribution marks a crucial finding from the current research. In summary, this reliability study of both the FFD (Chapter 4) and exploration of the start position for the test (Chapter 5) demonstrated a test for neck strength that showed high levels of reliability, as well as one that has the potential for high face validity and clear practical applicability in its administration and production of results. It addressed many of the limitations in previous research into neck strength, and consequently it led to the final research question of the thesis.

7.5 Field testing of neck strength to determine potential differences between player positions and levels (RQ3)

Following the establishment of a reliable method, as reported in Chapters 4 and 5, Chapter 6 led to further investigation of the utility of the developed neck strength test to rugby players. In this way, it responded to RQ3: *Can neck strength be measured in elite rugby players using the VALD ForceFrame?* The additional question of whether this robust test of neck strength could be taken out of the research laboratory and into the field with confidence was also indirectly answered in the process.

Chapter 6 reported the testing of 131 professional rugby players across two levels of play: English Championship and Premiership. The developed neck strength testing protocol was successfully transferred from the laboratory to a rugby club-based setting and implemented for field-based testing. Findings established that the protocol was transferrable to club settings, making it accessible to relevant key stakeholders, including medical/S&C practitioners and rugby players.

Findings from Chapter 4 indicated that players need to receive clear verbal instructions for the adoption of the start position. This finding pertained specifically to ensuring that the scapulae remain in the retracted position throughout the test. Following the standardised warm-up, which took 5 min, the test took no longer than 8 min per player to administer. This short duration has the potential to garner credibility within the field, as it would be possible to complete testing on a squad of 33 players within a day.

The integrity of the normative neck strength data of the 131 professional rugby players in this thesis cannot be undervalued, despite the readings representing a single snapshot in time. The ability to break down the analysis of the data into individual playing positions, or at least into small playing groups, adds depth and richness to the data that is missing from many other small-sample research studies involving professional rugby players (Table 2.3). The implications of the present study's finding that players could be classified through discriminant function analysis specifically through the measurement neck Ext strength is unique within the field. Where previous work has analysed rugby players as a collective group, it should be now noted that player data is not a homogeneous set, neither anthropometrically nor in terms of neck strength. Thinking in terms of practical implications, the groupings of players who follow similar gym programmes in preparation for the matches should perhaps be analysed in greater depth with regard to which positions are most similar in terms of anthropometric and strength-related characteristics.

7.6 Methodological coherence

The literature review for this thesis highlighted the pressing need for a number of different issues to be addressed in order to answer the research questions. The results have demonstrated that the individual empirical studies were able to answer the research questions in a sequential manner, but when considered together, they also address the overarching aims and objectives of the study as a whole.

The overall aim of this thesis has been necessarily ambitious. It has required attention to a wide range of issues, including recognising contemporaneous practice with regard to neck health within the sport of professional rugby, addressing the need for a ubiquitously acceptable piece of equipment and protocol that can address the lack of translation of research into practice, and subsequent testing of that approach back in the field. Given its unprecedented nature, there has been no simple methodological model to follow when designing the research and undertaking analysis. That said, every effort has been made throughout the research process to ensure that the research questions are answered to a high degree of rigour using the most appropriate methods.

The structure that was proposed and subsequently accomplished was rooted in the requirement for a practical approach to the identified need. As a consequence of this, the original question (RQ1) was based around garnering the voices of the practitioners to whom this research would ultimately serve. Following the needs that were identified through this approach, it was essential for the research to move into the laboratory in order to control for the numerous variables which were required to test the reliability and practicality of the proposed equipment and protocol. Having asserted its inter- and intra-rater reliability in the laboratory setting, both with male and female participants, the logical next study was to use the established novel technique back in the field with professional rugby players. This sequential approach to the research design was logical, not only in terms of its overall trajectory but also its focus on practical applications. These individual but methodologically coherent studies coalesce in order to answer the research questions.

A number of features of the research are important for their methodological and analytical originality. The range of data-analytical and statistical techniques used within this study – namely, intra-class correlation coefficient (ICC), coefficient of variance (CV), minimal detectable change (MDC), limits of agreement (LoA) and discriminant function analysis (DFA) – was broad, robust and unique. By reporting both ICC and CV in Chapter 4 (Section 4.3.5), the description of both relative and absolute reliability was enhanced, strengthening the robustness of the research (Atkinson & Nevill, 1998). Within the scholarly field, many reported studies only use a limited range of statistical tests as part of their analysis (Ashall et al., 2021; Chiu & Sing, 2002; McDaniel et al., 2021; Peolsson et al., 2001; Salmon et al., 2018; Tudini et al., 2019), which has led to the lack of transferability of these tests into the field for universal adoption.

The key finding from Chapter 5 was that the chosen test position of a quadruped stance, required by the physical attributes of the ForceFrame, represented a reliable start position in the measurement of neck strength. The force involved in any given start position is entirely unknown in every other proposed method for measuring neck strength. Using the LoA test also highlighted the variability in the body forces during neck strength tests into LSF and RSF, which was also previously untested in any research to date. It was necessary to conduct this test using force plates in a carefully controlled laboratory setting to confirm the robustness of the proposed protocol. Having analysed the findings and learnt how to best conduct the test, it was possible to take the next step (Chapter 6) and conduct this trusted test in the field with professional rugby players.

The majority of previous research into neck strength either completed reliability testing (Chavarro-Nieto et al., 2022; Fuller et al., 2022; Hall et al., 2017; McDaniel et al., 2021; Peolsson et al., 2001; Peolsson et al., 2007; Strimpakos et al., 2004; Tudini et al., 2019) but never took the research out of the laboratory, or the opposite, being conducted in the field without the requisite reliability testing (Hamilton & Gatherer, 2014; Hamilton et al., 2012; Hamilton et al., 2014). What this thesis has achieved is that, having identified this gap, it has sequentially and rigorously tested relevant equipment and developed a practically oriented protocol, then applied the research knowledge into practice. In sum, then, the thesis represents a cohesive project in that it has held both the laboratory (rigorous) testing at the same level of importance as the on-field (practical) testing.

Considered as a whole, the procedures proposed as part of the studies reported here, as well as the analytical protocols related to them, can be understood as an exemplar for reporting neck strength. These methods can be replicated to collect similar data in future to further understanding of player positions and player levels in terms of anthropometrics and strength.

Chapter 8: Conclusion

8.1 Contributions to scholarly knowledge

The overall focus of this thesis has been to address a key problem in contemporary sports science – namely, the lack of a reliable, widely practicable method for measuring neck strength – and to provide a novel, evidence-based solution that contributes substantially to contemporary knowledge. By surveying both existing academic research (Chapter 2) and current clinical practices (Chapter 3), a clear depiction of the state of the field was achieved, one that is unprecedented in both scholarly and professional circles. The literature review found that there was little consensus regarding both technology and technique in relation to neck strength measurement practices, and that there was a pressing need for direction and reform (RQ1). Based on this clear research need, a novel protocol was deemed essential, one that made use of reliable, existing equipment and could be effectively and confidently adopted by clinical professionals. The VALD ForceFrame rig was identified as an optimal tool for neck strength measurement and was tested in a laboratory setting for its reliability (Chapter 4). Attention was also paid to the importance of the position adopted by participants during the protocol, with a similar reliability study being conducted to account for this (Chapter 5). Both the equipment and the test position were rigorously assessed, with multiple variables addressed within a controlled environment (RQ2). These reliability tests far exceeded the depth and detail currently available in the published academic literature. Following the laboratory studies, the protocol was tested "in the field" with elite-level rugby players to examine the method's applicability and feasibility in clinical settings (Chapter 6). The protocol was shown to be a gold standard for neck strength measurement beyond the laboratory (RQ3). In turn, the research conducted with professional players has led to the establishment of a normative database of neck strength measurements, forming the foundations of an original – and vital – initiative for the monitoring of specific anthropometric data at the highest levels of sporting prowess. The result of the research, then, is a standardised, well-tested protocol for neck strength measurement using a reliable and widely available piece of specialist equipment. This novel approach, which has already been positively adopted in some professional and semi-professional spheres of rugby and other sports, has great potential to impact both academic research and clinical practice in a significant, meaningful way.

8.2 Limitations of the thesis

Certain aspects of the research limited the wider generalisability of the results. In this section, the aim is to outline overarching limitations of the research as opposed to specific facets of individual studies, as these were identified at the end of each of the empirical chapters.

As with any study, an increased sample size may have edified the generalisability of the findings. Part of the issue with the target populations for many of the studies was their discreteness: there is necessarily a limited number of professional (and semi-professional) rugby teams active in England. Broadening the eligibility criteria was generally deemed inappropriate in these studies: for example, including amateur clubs would have lessened the impact of the central focus on professional-level rugby; and the likelihood of achieving responses to, say, the survey component of the study (Chapter 3) from international clubs was markedly low, as there is a great deal of competition between teams at the international level.

Moreover, while both men and women were invited to participate in the reliability study (Chapter 4), only male clubs were included in the survey (Chapter 3) and professional player (Chapter 6) study. This is because women's rugby was not professionalised until 2019, a year after the survey was first distributed (England Rugby, 2019). In light of these welcome changes to the professional sphere, it is vital that future research into rugby players' neck strength addresses this gender imbalance to account for women's professional rugby.

The recent professionalisation of the women's game is emblematic of the ever-changing state of rugby. Over recent years since the present study began, rugby's laws have evolved in light of an increased interest in the epidemiology of rugby-related injury. This burgeoning of the research area has, in part, been bolstered by a surge in new technological breakthroughs that afford greater monitoring of in-game actions: tools such as video analysis, instrumented mouthguards, and wearable Global Positioning System (GPS) technologies have enabled researchers to observe the impact of collisions and other actions to determine their effects on players' bodies. Clearly, recent changes to the laws of the game, and in turn to the demands of match play, have not been addressed within the present study, which may in turn result in such changes affecting the design of future studies. In addition, further changes are imminent, including to the tackle height law. What is required of future research, then, is a more longitudinal, continual approach to player monitoring and data collection. For example, the scoping review survey (Chapter 3) would ideally be distributed again to clubs to see how practices have shifted over intervening years. The present study should therefore be regarded as a "snapshot" of a particular moment in rugby, and future studies should aim to build upon and update its insights in due course. Insights from recent technology-mediated sports research – for instance, research involving instrumented mouthguards – might also be usefully compared with the results of neck strength measurements and injury audits to nuance epidemiological accounts.

The issue of rapid and diverse technological proliferation is also important in the context of the present study. While a fixed-frame dynamometer was deemed the most effective equipment to use for neck strength measurement, the VALD ForceFrame rig is one of at least two common tools on the contemporary market, the other being KangaTech's KT360. In this case, given the scope of the project, VALD's ForceFrame was chosen as the focus, as it was – and, at time of writing, remains – the most widely used piece of equipment by physiotherapists working at professional rugby clubs in the UK. Moreover, KangaTech's KT360 was more limited in its usability, not least because having participants adopt the quadruped position would have been impossible due to the equipment's physical constraints. That said, ideally, future research would test the reliability (and validity) of the proposed protocol on all similar technologies on the market. In addition, attempts could be made to test the protocol on a range of different technologies beyond merely fixed-frame dynamometers – for example, using handheld dynamometers – to compare efficacy and affirm the validity of the method. Fixed-frame dynamometry has already been proposed as the gold standard method for measuring maximal isometric contraction strength (Ryan et al., 2019), as it allows for the comparative assessment of other techniques or pieces of equipment in order to confer validity against this reliable test.

Specific limitations with regards to the reported data in both chapter 4 (reliability study) and chapter 6 (rugby player study) pertain to the fact that neck length was not measured – which although is a characteristic that cannot be changed, will by its very nature affect torque and therefore the production of neck force. Equally there were parameters that could have been reported, such as rate of force development (RFD), comparison of RFD between neck test directions, which were not calculated due to the sampling frequency (50Hz) being not deemed sufficiently high to make these calculations robust. This thesis also did not ask questions of strength endurance which may have relevance within the sporting setting in terms of both injury prevention and performance enhancement, and which could be explored as a future development using this proposed protocol but using a longer length of contraction time.

Finally, as with a great deal of research conducted during the pandemic period, COVID restrictions hampered some aspects of the empirical work. Perhaps most notably, it was not possible to retest the professional rugby players involved in the final component of the study (Chapter 6). This meant that the protocol's reliability could not be evidenced in relation to the professional players and relied solely on the reliability implied by laboratory testing that used non-athletes (Chapters 4 and 5). That said, despite the lack of retesting, the data collected from the 131 professional rugby players is considerable, not least because it has afforded a level of granularity in the analysis otherwise unavailable in the published literature – namely, the comparison of neck strength across various player positions at the elite level.

8.3 Recommendations for future research and applications

There are many potential avenues for future research derived from the thesis's insights. In the short term, an important aspect of the development of the protocol would be to engage with clinical practitioners to workshop the procedure and action any practical improvements in light of feedback. This would involve post-hoc analysis of stakeholder satisfaction with the method, further improving the protocol. Regular evaluation and review are vital for the wider adoption and continued efficacy of such a standardised protocol.

In terms of the potential expansion and application of the research, the testing of 131 professional players was foundational to the establishment of a corpus of data pertaining specifically to the neck strength of contemporary athletes involved in rugby. When looking towards the future potential of the novel protocol posited here, expanding this dataset should be a core objective. An aim for future research, then, is the creation of an open-access database, one that is ever-evolving, is updated by clinical practitioners globally and forms the basis of longitudinal studies of athletes' anthropometrics. Such a resource would also be fundamental to future epidemiological research exploring the relationship between neck strength, injury incidence and injury severity, as well as to strength-and-conditioning (S&C) research exploring the impact of timely events (matches, seasons, etc.) on neck strength. Moreover, as shown in the study of professional players' neck strength (Chapter 6), the database would provide substantial evidence of anthropometric differences between individual playing positions in rugby – something otherwise absent from contemporary research but which is crucial to understanding the specific needs and susceptibilities to injury of the different roles in a rugby team. None of this will be plausible without a rigorous, practicable method that is universally accepted and highly regarded worldwide. It is hoped that the research underpinning this thesis will have provided such a candidate.

In the first instance, future expansions of the method, both nationally and internationally, would benefit from industry partnerships with equipment suppliers to ensure that the requisite tools are as widely accessible as possible, as well as from widespread training opportunities for clinical practitioners. This will not only encourage clinicians from around the world to contribute to the ongoing database but will also provide an important platform for the research and encourage greater knowledge exchange between the academic and clinical communities.

The applications of such an internationally updated database could be vast. Thinking first from an academic perspective, encouraging uniformity of empirical protocol would enable researchers to perform meta-analyses of the available data – something that has, until this point, been impossible due to the plurality of methods adopted, with no two studies using the same technology. Moreover, the data could readily be harnessed by researchers working in other fields, including those who work on the epidemiology of head- and neck-related injuries such as concussion and other traumatic brain injury, as well as neurodegenerative conditions. For example, data from the neck strength database could be compared with data pertaining to athletes' susceptibility to injury, their diagnostic track record, and other measures to ascertain whether neck strength has a causal relationship with such parameters.

In addition, drawing from the comparative work uniting neck strength measurement with epidemiological concerns, a future application of the research could be in harnessing data pertaining to neck strength to produce predictive measures that could indicate susceptibility to injury based on anthropometrics. For example, debates are initiating within the academic literature regarding the possibility of using neck strength as a predictor for concussive events in rugby (Farley et al., 2022; Liston et al., 2023). Given these differences in findings, particularly when considered in light of the lack of consistency between the studies' methodologies, future research is vital to enable greater comparison between individual empirical studies and to ascertain the potential role of neck strength in injury incidence and severity based on a more substantial body of evidence.

Regardless of whether a clearer indication emerges of any potential links between neck strength and injury, a future goal of research should be to establish an evidence-based neck-strengthening programme. Given the efficacy of the neck measurement protocol posited here, the actual impact of neck-strengthening techniques and regimens can now be adequately monitored. Strengthening programmes are fundamental to the continued improvement of S&C practices and have the potential to provide protection from injury for athletes. However, it is essential for practitioners to measure necks regularly to ensure that the training exercises are having the desired impact. For example, a Delphi study could be conducted to generate consensus from expert practitioners regarding a player position-specific programme that includes regular neck strength measurements.

Finally, a further expansion of the database project would be afforded by the adaptation of the protocol to include other sports. The cumulative design of the testing protocol established in this thesis provides a replicable model through which to explore other sports in a similar way, provided sport-specific adjustments are made to ensure optimal data collection. In order to expand the neck strength measurement database beyond a central focus on rugby players, future empirical testing should therefore incorporate different test positions as appropriate to specific sports. For example, in the context of motorsports, neck strength testing could be conducted through the use of a modified car seat ("racing simulator") to emulate the specific postures required of the sport. Moreover, the protocol could be adapted for use by athletes involved in sledding sports, such as skeleton and luge, through the use of a lying test position.

8.4 Ongoing and future impacts on clinical practice

Opportunities for expansion into different sporting spheres are already being pursued by the researcher through industry partnerships. For example, a knowledge exchange training session was conducted in 2021 for Alpine, the Formula One motorsports team, and involved the collection of neck strength data from two of its associated elite-level drivers. The protocol has also been tested in collaboration with the British Racing Drivers' Club as part of the Aston Martin Autosport Young Driver of the Year Award in 2021 and 2022. In the sphere of football (soccer), in 2022 a focus group was conducted with the Premier League to generate their consensus statement on neck strength testing and the impacts of heading the ball. In addition, in 2022, a training session was also undertaken with St Kilda Football Club, a professional Australian Football League team based in Melbourne. Further collaborations are underway with AC Milan's under-17s football (soccer) team, the organisers of Formula One's Powerboat Championship, and Leicester City Football Club.

Moreover, in the world of rugby, knowledge exchange training sessions have recently been conducted with the Scottish Rugby Football Union team, five (of the twelve) England Premiership rugby clubs, and the "Red Roses" England women's national rugby team. Consultation is ongoing with a number of other clubs, including the All Blacks, the national rugby team of New Zealand.

In terms of the ongoing impact of the research through publication, dissemination has been achieved through the publication of a peer-reviewed journal article (McBride et al., 2022) and a number of conference presentations with peer-reviewed abstracts (e.g. McBride, 2019), invited talks (e.g. McBride, 2022) and industry events (e.g. McBride, 2023 on behalf of VALD). VALD, the company who produces the ForceFrame, also makes use of the journal article in their marketing literature, interpolating data from the reliability study into their sales copy. In addition, through engagement with these publications, and due to the ease with which practitioners may adopt the novel protocol, physiotherapists will be able to incorporate current best, research-informed practice into their working approaches to improve the overall effectiveness of treatment (Chartered Society of Physiotherapy, 2019).

8.5 Implications for the future of rugby

The rugby player position-specific information reported in Chapter 6 is unique in its depth of analysis of neck strength in relation to common anthropometric measures. Due to the large numbers of players measured, for a study on professional players, it enabled data to be analysed mostly by individual positions, rather than solely by the generic grouping of forwards and backs previously utilised in most research into rugby players' physical attributes. Analysis of results therefore enabled a richer understanding of the qualities of players in different positions and how these impact on performance within the game of rugby. It is well established that clubs with the least injuries win more matches (Sedeaud et al., 2012), so this level of detail in the data may help towards progressing talent identification and understanding player robustness.

Records of strength data and the level at which a player performs offer insight that may contribute towards understanding a player's readiness to move from academy to senior level. Further, the capacity for individual clubs to maintain an ongoing database of player neck strength, as conferred by the development of the reported test, assists in the audit of injury profiles. Moreover, this can support targeted preventative rehabilitation in the gym, because return-to-training criteria following an upper quadrant injury and return-to-play criteria can be more robustly defined and measured. Player welfare is a central concern for medics and sports scientists associated not only with professional teams but with all levels of play (Bolling et al., 2020). Confirming the reliability and validity of a test that can be adopted universally across professional rugby teams means that player data can move with them wherever they play, rather than belonging solely to the practitioner or club who measures them, in turn ensuring that a complete strength history is recorded and available. A significant contribution of this research is ultimately to facilitate player progression, and, perhaps most importantly, to better support player welfare.

References

Abu-Rajab, R. B., Marsh, A., Young, D., & Rymaszewski, L. A. (2010). Visual estimation of joint angles at the elbow. *European Journal of Orthopaedic Surgery and Traumatology, 20*(6), 463-467. https://doi.org/10.1007/s00590-010-0586-8

Adams, M. A. (2016). Functional anatomy of the musculoskeletal system. In S. Standring (Ed.), *Gray's Anatomy* (41st ed., pp. 81-122). Elsevier. https://doi.org/10.1016/B978-0-7020-5230-9.00005-4

Almosnino, S., Pelland, L., & Stevenson, J. M. (2010). Retest reliability of force-time variables of neck muscles under isometric conditions. *Journal of Athletic Training, 45*(5), 453-458. https://doi.org/10.4085/1062-6050-45.5.453

Amonoo-Kuofi, H. S. (1983). The density of muscle spindles in the medial, intermediate and lateral columns of human intrinsic postvertebral muscles. *Journal of Anatomy, 136*(Pt 3), 509-519. https://www.ncbi.nlm.nih.gov/pubmed/6224767

Andrade, C. (2018). Internal, external, and ecological validity in research design, conduct, and evaluation. *Indian Journal of Psychological Medicine, 40*(5), 498-499. https://doi.org/10.4103/IJPSYM.IJPSYM_334_18

Armstrong, B., McNair, P., & Taylor, D. (2008). Head and neck position sense. *Sports Medicine, 38*(2), 101-117. https://doi.org/10.2165/00007256-200838020-00002

Artz, N. J., Adams, M. A., & Dolan, P. (2015). Sensorimotor function of the cervical spine in healthy volunteers. *Clinical Biomechanics, 30*(3), 260-268. https://doi.org/10.1016/j.clinbiomech.2015.01.005

Ashall, A., Dobbin, N., & Thorpe, C. (2021). The concurrent validity and intrarater reliability of a hand-held dynamometer for the assessment of neck strength in semi-professional rugby union players. *Physical Therapy in Sport, 49*(1), 229-235. https://doi.org/10.1016/j.ptsp.2021.03.007

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine, 26*(4), 217-238. https://doi.org/10.2165/00007256-199826040-00002

Attwood, M. J., Roberts, S. P., Trewartha, G., England, M. E., & Stokes, K. A. (2018). Efficacy of a movement control injury prevention programme in adult men’s community rugby union: A cluster randomised controlled trial. *British Journal of Sports Medicine, 52*(6), 368-374. https://doi.org/10.1136/bjsports-2017-098005

Badenhorst, M., Verhagen, E. A. L. M., van Mechelen, W., Lambert, M. I., Viljoen, W., Readhead, C., Baerecke, G., & Brown, J. C. (2017). A comparison of catastrophic injury incidence rates by Provincial Rugby Union in South Africa. *Journal of Science and Medicine in Sport, 20*(7), 643-647. https://doi.org/10.1016/j.jsams.2017.01.232

Baker, M., Quesnele, J., Baldisera, T., Kenrick-Rochon, S., Laurence, M., & Grenier, S. (2019). Exploring the role of cervical spine endurance as a predictor of concussion risk and recovery following sports related concussion. *Musculoskeletal Science and Practice, 42*(1), 193-197. https://doi.org/10.1016/j.msksp.2019.04.002

Barrett, M. D., McLoughlin, T. F., Gallagher, K. R., Gatherer, D., Parratt, M. T., Perera, J. R., & Briggs, T. W. (2015). Effectiveness of a tailored neck training program on neck strength, movement, and fatigue in under-19 male rugby players: A randomized controlled pilot study. *Open Access Journal of Sports Medicine, 6*(1), 137-147. https://doi.org/10.2147/OAJSM.S74622

Beckerman, H., Roebroeck, M. E., Lankhorst, G. J., Becher, J. G., Bezemer, P. D., & Verbeek, A. L. M. (2001). Smallest real difference: A link between reproducibility and responsiveness. *Quality of Life Research, 10*(7), 571-578. https://doi.org/10.1023/A:1013138911638

Beckham, G., Mizuguchi, S., Carter, C., Sato, K., Ramsey, M., Lamont, H., Hornsby, G., Haff, G., & Stone, M. (2013). Relationships of isometric mid-thigh pull variables to weightlifting performance. *The Journal of Sports Medicine and Physical Fitness, 53*(5), 573-581. https://pubmed.ncbi.nlm.nih.gov/23903539

Behm, D. G., & Anderson, K. G. (2006). The role of instability with resistance training. *Journal of Strength and Conditioning Research, 20*(3), 716-722. https://doi.org/10.1519/R-18475.1

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvořák, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *British Journal of Sports Medicine, 47*(5), 321-326. https://doi.org/10.1136/bjsports-2013-092216

Berge, J., Marque, B., Vital, J., Sénégas, J., & Caillé, J. (1999). Age-related changes in the cervical spines of front-line rugby players. *The American Journal of Sports Medicine, 27*(4), 422-429. https://doi.org/10.1177/03635465990270040401

Bevan, T., Chew, S., Godsland, I., Oliver, N. S., & Hill, N. E. (2022). A game for all shapes and sizes? Changes in anthropometric and performance measures of elite professional rugby union players 1999–2018. *BMJ Open Sport and Exercise Medicine, 8*(1), e001235. https://doi.org/10.1136/bmjsem-2021-001235

Bishop, C., Lake, J., Loturco, I., Papadopoulos, K., Turner, A., & Read, P. (2021). Interlimb asymmetries: The need for an individual approach to data analysis. *Journal of Strength and Conditioning Research, 35*(3), 695-701. https://doi.org/10.1519/JSC.0000000000002729

Bishop, C., Turner, A., Jarvis, P., Chavda, S., & Read, P. (2017). Considerations for selecting field-based strength and power fitness tests to measure asymmetries. *Journal of Strength and Conditioning Research, 31*(9), 2635-2644. https://doi.org/10.1519/JSC.0000000000002023

Blair, J., Czaja, R. F., & Blair, E. A. (2013). *Designing surveys: a guide to decisions and procedures* (3rd ed.). Sage.

Bland, J. M., & Altman, D. G. (1999). Measuring agreement in method comparison studies. *Statistical Methods in Medical Research, 8*(2), 135-160. https://doi.org/10.1177/096228029900800204

Bleakley, C., Tully, M., & O'Connor, S. (2011). Epidemiology of adolescent rugby injuries: A systematic review. *Journal of Athletic Training, 46*(5), 555-565. https://doi.org/10.4085/1062-6050-46.5.555

Bohu, Y., Julia, M., Bagate, C., Peyrin, J., Colonna, J., Thoreux, P., & Pascal-Moussellard, H. (2009). Declining incidence of catastrophic cervical spine injuries in French rugby: 1996-2006. *The American Journal of Sports Medicine, 37*(2), 319-323. https://doi.org/10.1177/0363546508325926

Bolling, C., Delfino Barboza, S., van Mechelen, W., & Pasman, H. R. (2020). Letting the cat out of the bag: Athletes, coaches and physiotherapists share their perspectives on injury prevention in elite sports. *British Journal of Sports Medicine, 54*(14), 871-877. https://doi.org/10.1136/bjsports-2019-100773

Bolling, C., van Mechelen, W., Pasman, H. R. W., & Verhagen, E. (2018). Context matters: Revisiting the first step of the "sequence of prevention" of sports injuries. *Sports Medicine, 48*(10), 2227-2234. https://doi.org/10.1007/s40279-018-0953-x

Boyd-Clark, L. C., Briggs, C. A., & Galea, M. P. (2001). Comparative histochemical composition of muscle fibres in a pre- and a postvertebral muscle of the cervical spine. *Journal of Anatomy, 199*(6), 709-716. https://10.1046/j.1469-7580.2001.19960709.x

Brady, C. J., Harrison, A. J., & Comyns, T. M. (2020). A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data. *Journal of Biomechanics, 19*(1), 1-25. https://doi.org/10.1080/14763141.2018.1452968

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T., & Reddin, D. B. (2005). Epidemiology of injuries in English professional rugby union: Part 1. Match injuries. *British Journal of Sports Medicine, 39*(10), 757-766. https://doi.org/10.1136/bjsm.2005.018135

Brooks, J. H. M., & Kemp, S. P. T. (2011). Injury-prevention priorities according to playing position in professional rugby union players. *British Journal of Sports Medicine, 45*(10), 765-775. https://doi.org/10.1136/bjsm.2009.066985

Brown, J. C., Lambert, M. I., Verhagen, E., Readhead, C., van Mechelen, W., & Viljoen, W. (2013). The incidence of rugby-related catastrophic injuries (including cardiac events) in South Africa from 2008 to 2011: A cohort study. *BMJ Open, 3*(2), e002475. https://doi.org/10.1136/bmjopen-2012-002475

Buchholtz, K., Lambert, M., & Burgess, T. L. (2022). A masterclass on developing clinical tools in sport and exercise medicine using principles of clinimetrics. *Physical Therapy in Sport, 55*(1), 155-159. https://doi.org/10.1016/j.ptsp.2022.04.003

Buckner, S. L., Jessee, M. B., Mattocks, K. T., Mouser, J. G., Counts, B. R., Dankel, S. J., & Loenneke, J. P. (2016). Determining strength: A case for multiple methods of measurement. *Sports Medicine, 47*(2), 193-195. https://doi.org/10.1007/s40279-016-0580-3

Caccese, J. B., Buckley, T. A., Tierney, R. T., Rose, W. C., Arbogast, K. B., Glutting, J. J., & Kaminski, T. W. (2017). Head and neck size and neck strength minimise the head acceleration during repeated head impacts. *British Journal of Sports Medicine, 51*(11), A66. https://doi.org/10.1136/bjsports-2016-097270.171

Cahill, N., Lamb, K., Worsfold, P., Headey, R., & Murray, S. (2013). The movement characteristics of English Premiership rugby union players. *Journal of Sports Sciences, 31*(3), 229-237. https://doi.org/10.1080/02640414.2012.727456

Campbell, P. G., Peake, J. M., & Minett, G. M. (2018). The specificity of rugby union training sessions in preparation for match demands. *International Journal of Sports Physiology and Performance, 13*(4), 496-503. https://doi.org/10.1123/ijspp.2017-0082

Castinel, B. H., Adam, P., Milburn, P. D., Castinel, A., Quarrie, K. L., Peyrin, J. C., & Yeo, J. D. (2010). Epidemiology of cervical spine abnormalities in asymptomatic adult professional rugby union players using static and dynamic MRI protocols: 2002 to 2006. *British Journal of Sports Medicine, 44*(3), 194-199. https://doi.org/10.1136/bjsm.2007.045815

Catenaccio, E., Mu, W., Kaplan, A., Fleysher, R., Kim, N., Bachrach, T., Zughaft Sears, M., Jaspan, O., Caccese, J., Kim, M., Wagshul, M., Stewart, W. F., Lipton, R. B., & Lipton, M. L. (2017). Characterization of neck strength in healthy young adults. *Physical Medicine and Rehabilitation, 9*(9), 884-891. https://doi.org/10.1016/j.pmrj.2017.01.005

Cazzola, D., Holsgrove, T. P., Preatoni, E., Gill, H. S., & Trewartha, G. (2017). Cervical spine injuries: A whole-body musculoskeletal model for the analysis of spinal loading. *PLoS ONE, 12*(1), e0169329. https://doi.org/10.1371/journal.pone.0169329

Cazzola, D., Preatoni, E., Stokes, K. A., England, M. E., & Trewartha, G. (2015). A modified prebind engagement process reduces biomechanical loading on front row players during scrummaging: A cross-sectional study of 11 elite teams. *British Journal of Sports Medicine, 49*(8), 541-546. https://doi.org/10.1136/bjsports-2013-092904

Cazzola, D., Stone, B., Holsgrove, T. P., Trewartha, G., & Preatoni, E. (2016). Spinal muscle activity in simulated rugby union scrummaging is affected by different engagement conditions. *Scandinavian Journal of Medicine and Science in Sports, 26*(4), 432-440. https://doi.org/10.1111/sms.12446

Chambers, R. M., Gabbett, T. J., & Cole, M. H. (2019). Validity of a microsensor-based algorithm for detecting scrum events in rugby union. *International Journal of Sports Physiology and Performance, 14*(2), 176-182. https://doi.org/10.1123/ijspp.2018-0222

Chartered Society of Physiotherapy. (2019). *Code of Members' Professional Values and Behaviour.* https://www.csp.org.uk/system/files/publication_files/000529_Code%20of%20Members%20Professional%20Values%20and%20Behaviours%202019.pdf

Chavarro-Nieto, C., Beaven, M., Gill, N., & Hébert-Losier, K. (2021). Neck strength in rugby union players: A systematic review of the literature. *The Physician and Sportsmedicine, 49*(4), 392-409. https://doi.org/10.1080/00913847.2021.1886574

Chavarro-Nieto, C., Beaven, M., Gill, N., & Hébert-Losier, K. (2022). Reliability of repeated isometric neck strength in rugby union players using a load cell device. *Sensors, 22*(8), 2872. https://doi.org/10.3390/s22082872

Chavarro-Nieto, C., Beaven, M., Gill, N., & Hébert-Losier, K. (2023a). Hamstrings injury incidence, risk factors, and prevention in rugby union players: A systematic review. *The Physician and Sportsmedicine, 51*(1), 1-19. https://doi.org/10.1080/00913847.2021.1992601

Chavarro-Nieto, C., Beaven, M., Gill, N., & Hébert-Losier, K. (2023b). To make or to break in isometric neck strength testing? *Science & Sports, online first*https://doi.org/10.1016/j.scispo.2022.10.002

Chen, B., Liu, P., Xiao, F., Liu, Z., & Wang, Y. (2021). Review of the upright balance assessment based on the force plate. *International Journal of Environmental Research and Public Health, 18*(5), 2696. https://doi.org/10.3390/ijerph18052696

Chéradame, J., Piscione, J., Carling, C., Guinoiseau, J., Dufour, B., Jacqmin-Gadda, H., & Decq, P. (2021). Incidence and risk factors in concussion events: A 5-season study in the French Top 14 rugby union championship. *The American Journal of Sports Medicine, 49*(7), 3635465211006480. https://doi.org/10.1177/03635465211006480

Chiu, T. T., & Sing, K. L. (2002). Evaluation of cervical range of motion and isometric neck muscle strength: Reliability and validity. *Clinical Rehabilitation, 16*(8), 851-858. https://doi.org/10.1191/0269215502cr550oa

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014). Neck strength: A protective factor reducing risk for concussion in high school sports. *Journal of Primary Prevention, 35*(5), 309-319. https://doi.org/10.1007/s10935-014-0355-2

Cooke, R., Strang, M., Lowe, R., & Jain, N. (2022). The epidemiology of head injuries at 2019 Rugby Union World Cup. *The Physician and Sportsmedicine, 51*(4), 336-342. https://doi.org/10.1080/00913847.2022.2083458

Cools, A. M., Maenhout, A. G., Vanderstukken, F., Declève, P., Johansson, F. R., & Borms, D. (2021). The challenge of the sporting shoulder: From injury prevention through sport-specific rehabilitation toward return to play. *Annals of Physical and Rehabilitation Medicine, 64*(4), 101384. https://doi.org/10.1016/j.rehab.2020.03.009

Cooney, N. J., Sowman, P., Schilaty, N., Bates, N., Hewett, T. E., & Doyle, T. L. A. (2022). Head and neck characteristics as risk factors for and protective factors against mild traumatic brain injury in military and sporting populations: A systematic review. *Sports Medicine, 52*(9), 2221-2245. https://doi.org/10.1007/s40279-022-01683-2

Cosgrave, C., Fuller, C., Franklyn-Miller, A., Falvey, E., Beirne, C., Ryan, J., & McCrory, P. (2018). Concussion in adolescent rugby union players: Comprehensive acute assessment protocol and development of the SSC concussion passport to monitor long-term health. *BMJ Open Sport and Exercise Medicine, 4*(1), e000455. https://doi.org/10.1136/bmjsem-2018-000455

Cross, M. J., Tucker, R., Raftery, M., Hester, B., Williams, S., Stokes, K. A., Ranson, C., Mathema, P., & Kemp, S. (2019). Tackling concussion in professional rugby union: A case–control study of tackle-based risk factors and recommendations for primary prevention. *British Journal of Sports Medicine, 53*(16), 1021-1025. https://doi.org/10.1136/bjsports-2017-097912

CrossFit. (2019a). *Cervical muscles: Part 1.* CrossFit. Retrieved November 28, 2022, from https://www.crossfit.com/essentials/lon-cervical-muscles-part-1

CrossFit. (2019b). *The cervical vertebrae.* CrossFit. Retrieved November 28, 2022, from https://www.crossfit.com/essentials/cervical-vertebrae

Cunningham, D. J., Shearer, D. A., Drawer, S., Pollard, B., Cook, C. J., Bennett, M., Russell, M., & Kilduff, L. P. (2018). Relationships between physical qualities and key performance indicators during match-play in senior international rugby union players. *PLoS ONE, 13*(9), e0202811. https://doi.org/10.1371/journal.pone.0202811

Daly, E., Pearce, A. J., & Ryan, L. (2021). A systematic review of strength and conditioning protocols for improving neck strength and reducing concussion incidence and impact injury risk in collision sports: Is there evidence? *Journal of Functional Morphology and Kinesiology, 6*(1), 8. https://doi.org/10.3390/jfmk6010008

Davies, M., Moore, I. S., Moran, P., Mathema, P., & Ranson, C. A. (2016). Cervical range of motion, cervical and shoulder strength in senior versus age-grade rugby union international front-row forwards. *Physical Therapy in Sport, 19*(1), 36-42. https://doi.org/10.1016/j.ptsp.2015.10.001

de Koning, C. H., van den Heuvel, S. P., Staal, J. B., Smits-Engelsman, B. C., & Hendriks, E. J. (2008). Clinimetric evaluation of methods to measure muscle functioning in patients with non-specific neck pain: A systematic review. *BMC Musculoskeletal Disorders, 9*(1), 142. https://doi.org/10.1186/1471-2474-9-142

Dillman, D. A., & Smyth, J. D. (2007). Design effects in the transition to web-based surveys. *American Journal of Preventive Medicine, 32*(5), S90-S96. https://doi.org/10.1016/j.amepre.2007.03.008

Dimundo, F., Cole, M., Blagrove, R. C., Till, K., McAuley, A. B. T., Hall, M., Gale, C., & Kelly, A. L. (2021). Talent identification and development in male rugby union: A systematic review. *Journal of Expertise, 4*(1), 33-55. https://journalofexpertise.org/articles/volume4_issue1/JoE_4_1_Dimundo_etal.html

Downes, P., & Collins, D. (2021). Examining the roles and consequent decision-making processes of high-level strength and conditioning coaches. *Societies, 11*(3), 76. https://doi.org/10.3390/soc11030076

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine, 42*(3), 566-576. https://doi.org/10.1177/0363546513517869

Eckner, J. T., Goshtasbi, A., Curtis, K., Kapshai, A., Myyra, E., Franco, L. M., Favre, M., Jacobson, J. A., & Ashton-Miller, J. A. (2018). Feasibility and effect of cervical resistance training on head kinematics in youth athletes: A pilot study. *American Journal of Physical Medicine and Rehabilitation, 97*(4), 292-297. https://doi.org/10.1097/PHM.0000000000000843

Ekstrand, J. (2013). Keeping your top players on the pitch: The key to football medicine at a professional level. *British Journal of Sports Medicine, 47*(12), 723-724. https://doi.org/10.1136/bjsports-2013-092771

England Rugby. (2019, September 30). Red Roses contracts for the 2019/20 season announced. *England Rugby,* https://www.englandrugby.com/news/article/red-roses-contracts-for-the-201920-season-announced

England Rugby. (2021). *HEADCASE: Extended guidelines.* https://keepyourbootson.co.uk/wp-content/uploads/2022/12/HEADCASE-EXTENDED-Nov-22.pdf

Eysenbach, G. (2004). Improving the quality of web surveys: The Checklist for Reporting Results of Internet E-Surveys (CHERRIES). *Journal of Medical Internet Research, 6*(3), e34. https://doi.org/10.2196/jmir.6.3.e34

Farley, T., Barry, E., Bester, K., Barbero, A., Thoroughgood, J., de Medici, A., Sylvester, R., & Wilson, M. G. (2022). Poor cervical proprioception as a risk factor for concussion in professional male rugby union players. *Physical Therapy in Sport, 55*(1), 211-217. https://doi.org/10.1016/j.ptsp.2022.03.010

Farley, T., Barry, E., Sylvester, R., Medici, A. D., & Wilson, M. G. (2022). Poor isometric neck extension strength as a risk factor for concussion in male professional Rugby Union players. *British Journal of Sports Medicine, 56*(11), 616-621. https://doi.org/10.1136/bjsports-2021-104414

Ferguson, C. J. (2009). An effect size primer: A guide for clinicians and researchers. *Professional Psychology: Research and Practice, 40*(5), 532-538. https://doi.org/10.1037/a0015808

Finch, C. (2006). A new framework for research leading to sports injury prevention. *Journal of Science and Medicine in Sport, 9*(1), 3-9. https://doi.org/10.1016/j.jsams.2006.02.009

Fraas, M. R., Coughlan, G. F., Hart, E. C., & McCarthy, C. (2014). Concussion history and reporting rates in elite Irish rugby union players. *Physical Therapy in Sport, 15*(3), 136-142. https://doi.org/10.1016/j.ptsp.2013.08.002

Franco, J. L., & Herzog, W. (1987). A comparative assessment of neck muscle strength and vertebral stability. *Journal of Orthopaedic and Sports Physical Therapy, 8*(7), 351-356. https://doi.org/10.2519/jospt.1987.8.7.351

Franko, O. I., & Tirrell, T. F. (2012). Smartphone app use among medical providers in ACGME training programs. *Journal of Medical Systems, 36*(5), 3135-3139. https://doi.org/10.1007/s10916-011-9798-7

Fuller, C. W., Brooks, J. H. M., Cancea, R. J., Hall, J., & Kemp, S. P. T. (2007). Contact events in rugby union and their propensity to cause injury. *British Journal of Sports Medicine, 41*(12), 862-867. https://doi.org/10.1136/bjsm.2007.037499

Fuller, C., Falvey, É, & Schneider, K. (2022). Reliability of a neck strength test in schoolboy rugby players. *Musculoskeletal Science and Practice, 60*(1), 102566. https://doi.org/10.1016/j.msksp.2022.102566

Gabbett, T. J. (2016). Influence of fatigue on tackling ability in rugby league players: Role of muscular strength, endurance, and aerobic qualities. *PLoS ONE, 11*(10), e0163161. https://doi.org/10.1371/journal.pone.0163161

Garces, G. L., Medina, D., Milutinovic, L., Garavote, P., & Guerado, E. (2002). Normative database of isometric cervical strength in a healthy population. *Medicine and Science in Sports and Exercise, 34*(3), 464-470. https://doi.org/10.1097/00005768-200203000-00013

Gardner, A. J., Iverson, G. L., Williams, W. H., Baker, S., & Stanwell, P. (2014). A systematic review and meta-analysis of concussion in rugby union. *Sports Medicine, 44*(12), 1717-1731. https://doi.org/10.1007/s40279-014-0233-3

Garraway, W. M., Lee, A. J., Hutton, S. J., Russell, E. B. A. W., & Macleod, D. A. D. (2000). Impact of professionalism on injuries in rugby union. *British Journal of Sports Medicine, 34*(5), 348-351. https://doi.org/10.1136/bjsm.34.5.348

Geary, K., Green, B. S., & Delahunt, E. (2014). Effects of neck strength training on isometric neck strength in rugby union players. *Clinical Journal of Sport Medicine, 24*(6), 502-508. https://doi.org/10.1097/JSM.0000000000000071

Geary, K., Green, B. S., & Delahunt, E. (2013). Intrarater reliability of neck strength measurement of rugby union players using a handheld dynamometer. *Journal of Manipulative and Physiological Therapeutics, 36*(7), 444-449. https://doi.org/10.1016/j.jmpt.2013.05.026

Giavarina, D. (2015). Understanding Bland Altman analysis. *Biochemia Medica, 25*(2), 141-151. https://doi.org/10.11613/BM.2015.015

Gillies, L., McKay, M., Kertanegara, S., Huertas, N., Nutt, S., & Peek, K. (2022). The implementation of a neck strengthening exercise program in elite rugby union: A team case study over one season. *Physical Therapy in Sport, 55*(1), 248-255. https://doi.org/10.1016/j.ptsp.2022.05.003

Gold, R., Reichman, M., Greenberg, E., Ivanidze, J., Elias, E., Tsiouris, A. J., Comunale, J. P., Johnson, C. E., & Sanelli, P. C. (2010). Developing a new reference standard: Is validation necessary? *Academic Radiology, 17*(9), 1079-1082. https://doi.org/10.1016/j.acra.2010.05.021

Gosselin, G., & Fagan, M. J. (2014). The effects of cervical muscle fatigue on balance: A study with elite amateur rugby league players. *Journal of Sports Science and Medicine, 13*(2), 329-337. https://www.jssm.org/jssm-13-329.xml%3EFulltext

Green, A., Coopoo, Y., Jason Cameron Tee, & Warrick McKinon. (2019). A review of the biomechanical determinants of rugby scrummaging performance. *South African Journal of Sports Medicine, 31*(1), v31i1a7521. https://doi.org/10.17159/2078-516X/2019/v31i1a7521

Haff, G. G., Carlock, J. M., Hartman, M. J., Kilgore, J. L., Kawamori, N., Jackson, J. R., Morris, R. T., Sands, W. A., & Stone, M. H. (2005). Force–time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. *Journal of Strength and Conditioning Research, 19*(4), 741-748. https://journals.lww.com/nsca-jscr/Abstract/2005/11000/FORCE___TIME_CURVE_CHARACTERISTICS_OF_DYNAMIC_AND.4.aspx

Haff, G. G., Ruben, R. P., Lider, J., Twine, C., & Cormie, P. (2015). A comparison of methods for determining the rate of force development during isometric midthigh clean pulls. *Journal of Strength and Conditioning Research, 29*(2), 386-395. https://doi.org/10.1519/JSC.0000000000000705

Hägglund, M., Waldén, M., Magnusson, H., Kristenson, K., Bengtsson, H., & Ekstrand, J. (2013). Injuries affect team performance negatively in professional football: An 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine, 47*(12), 738-742. https://doi.org/10.1136/bjsports-2013-092215

Hall, S. J. (2015). *Basic biomechanics* (7th ed.). McGraw-Hill Education.

Hall, T., Morissette, M. P., Cordingley, D., & Leiter, J. (2017). Reliability of a novel technique for the measurement of neck strength. *International Journal of Athletic Therapy and Training, 22*(4), 43-50. https://doi.org/10.1123/ijatt.2016-0070

Hamilton, D. F., Gatherer, D., Jenkins, P. J., Maclean, J. G. B., Hutchison, J. D., Nutton, R. W., & Simpson, A. H. R. W. (2012). Age-related differences in the neck strength of adolescent rugby players: A cross-sectional cohort study of Scottish schoolchildren. *Bone and Joint Research, 1*(7), 152-157. https://doi.org/10.1302/2046-3758.17.2000079

Hamilton, D. F., Gatherer, D., Robson, J., Graham, N., Rennie, N., Maclean, J. G. B., & Simpson, A. H. R. W. (2014). Comparative cervical profiles of adult and under-18 front-row rugby players: Implications for playing policy. *BMJ Open, 4*(5), e004975. https://doi.org/10.1136/bmjopen-2014-004975

Hamilton, D. F., & Gatherer, D. (2014). Cervical isometric strength and range of motion of elite rugby union players: A cohort study. *BMC Sports Science, Medicine and Rehabilitation, 6*(1), 32. https://doi.org/10.1186/2052-1847-6-32

Hamilton, D. F., Simpson, H. R., & Gatherer, D. (2010, May 27). Repeatability and inter-tester reliability of a new tool to assess isometric neck strength in adolescents. Paper presented at the *29th Scientific Meeting of the Physiotherapy Research Society,* Teesside University.

Haseler, C. M., Carmont, M. R., & England, M. (2010). The epidemiology of injuries in English youth community rugby union. *British Journal of Sports Medicine, 44*(15), 1093-1099. https://doi.org/10.1136/bjsm.2010.074021

Heale, R., & Twycross, A. (2015). Validity and reliability in quantitative studies. *Evidence-Based Nursing, 18*(3), 66-67. https://doi.org/10.1136/eb-2015-102129

Hendricks, S., Lambert, M. I., Brown, J. C., Readhead, C., & Viljoen, W. (2014). An evidence-driven approach to scrum law modifications in amateur rugby played in South Africa. *British Journal of Sports Medicine, 48*(14), 1115-1119. https://doi.org/10.1136/bjsports-2013-092877

Hildenbrand, K. J., & Vasavada, A. N. (2013). Collegiate and high school athlete neck strength in neutral and rotated postures. *Journal of Strength and Conditioning Research, 27*(11), 3173-3182. https://doi.org/10.1519/JSC.0b013e31828a1fe2

Hill, N. E., Rilstone, S., Stacey, M. J., Amiras, D., Chew, S., Flatman, D., & Oliver, N. S. (2018). Changes in northern hemisphere male international rugby union players' body mass and height between 1955 and 2015. *BMJ Open Sport and Exercise Medicine, 4*(1), e000459. https://doi.org/10.1136/bmjsem-2018-000459

Hogan, B. A., Hogan, N. A., Vos, P. M., Eustace, S. J., & Kenny, P. J. (2010). The cervical spine of professional front-row rugby players: Correlation between degenerative changes and symptoms. *Irish Journal of Medical Science, 179*(2), 259-263. https://doi.org/10.1007/s11845-009-0432-3

Holsgrove, T. P., Cazzola, D., Preatoni, E., Trewartha, G., Miles, A. W., Gill, H. S., & Gheduzzi, S. (2015). An investigation into axial impacts of the cervical spine using digital image correlation. *The Spine Journal, 15*(8), 1856-1863. https://doi.org/10.1016/j.spinee.2015.04.005

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15. https://doi.org/10.2165/00007256-200030010-00001

Hrysomallis, C. (2016). Neck muscular strength, training, performance and sport injury risk: A review. *Sports Medicine, 46*(8), 1111-1124. https://doi.org/10.1007/s40279-016-0490-4

Kirkwood, G., Parekh, N., Ofori-Asenso, R., & Pollock, A. M. (2015). Concussion in youth rugby union and rugby league: A systematic review. *British Journal of Sports Medicine, 49*(8), 506-510. https://doi.org/10.1136/bjsports-2014-093774

Kline, R. B. (2016). *Principles and practice of structural equation modeling* (4th ed.). Guilford Press.

Koch, J., Riemann, B. L., & Davies, G. J. (2012). Ground reaction force patterns in plyometric push-ups. *Journal of Strength and Conditioning Research, 26*(8), 2220-2227. https://doi.org/10.1519/JSC.0b013e318239f867

Konrath, J., & Appleby, B. (2013). An investigation of cervical strength and anthropometry in professional rugby union players. *Journal of Australian Strength and Conditioning, 21*(2), 12-18. https://www.strengthandconditioning.org/jasc-21-2/1157-peer-review-an-investigation-of-cervical-strength-and-anthropometry-in-professional-rugby-union-players

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155-163. https://doi.org/10.1016/j.jcm.2016.02.012

Krause, D. A., Hansen, K. A., Hastreiter, M. J., Kuhn, T. N., Peichel, M. L., & Hollman, J. H. (2019). A comparison of various cervical muscle strength testing methods using a handheld dynamometer. *Sports Health, 11*(1), 59-63. https://doi.org/10.1177/1941738118812767

Krzysztofik, M., Wilk, M., Wojdała, G., & Gołaś, A. (2019). Maximizing muscle hypertrophy: A systematic review of advanced resistance training techniques and methods. *International Journal of Environmental Research and Public Health, 16*(24), 4897. https://doi.org/10.3390/ijerph16244897

Kuster, D., Gibson, A., Abboud, R., & Drew, T. (2012). Mechanisms of cervical spine injury in rugby union: A systematic review of the literature. *British Journal of Sports Medicine, 46*(8), 550-554. https://doi.org/10.1136/bjsports-2011-090360

Lake, J., Mundy, P., Comfort, P., McMahon, J. J., Suchomel, T. J., & Carden, P. (2018). Concurrent validity of a portable force plate using vertical jump force-time characteristics. *Journal of Applied Biomechanics, 34*(5), 410-413. https://doi.org/10.1123/jab.2017-0371

Lacome, M., Peeters, A., Mathieu, B., Bruno, M., Christopher, C., & Piscione, J. (2019). Can we use GPS for assessing sprinting performance in rugby sevens? A concurrent validity and between-device reliability study. *Biology of Sport, 36*(1), 25-29. https://doi.org/10.5114/biolsport.2018.78903

Lallemand B., Clanet C., Blanchard S., Noriega P., Piscione J., Chaplain O., Retière D., Cohen C. (2020). Peak Compression Force Physics in Rugby Union Scrum. *Proceedings*.; 49(1):151. https://doi.org/10.3390/proceedings2020049151

Lark, S. D., & McCarthy, P. W. (2007). Cervical range of motion and proprioception in rugby players versus non-rugby players. *Journal of Sports Sciences, 25*(8), 887-894. https://doi.org/10.1080/02640410600944543

Lemeunier, N., Suri-Chilana, M., Welsh, P., Shearer, H. M., Nordin, M., Wong, J. J., Torres, P., Oolup-da Silva, S., D'Silva, C., Jeoun, E. B., Stern, P., Yu, H., Murnaghan, K., Sutton, D., & Côté, P. (2020). Reliability and validity of clinical tests to assess the function of the cervical spine in adults with neck pain and its associated disorders: Part 5. A systematic review from the Cervical Assessment and Diagnosis Research Evaluation (CADRE) collaboration. *European Journal of Physiotherapy, 22*(6), 332-363. https://doi.org/10.1080/21679169.2019.1626906

Leys, C., Delacre, M., Mora, Y. L., Lakens, D., & Ley, C. (2019). How to classify, detect, and manage univariate and multivariate outliers, with emphasis on pre-registration. *International Review of Social Psychology, 32*(1), 5. https://doi.org/10.5334/irsp.289

Leys, C., Klein, O., Dominicy, Y., & Ley, C. (2018). Detecting multivariate outliers: Use a robust variant of the Mahalanobis distance. *Journal of Experimental Social Psychology, 74*(1), 150-156. https://doi.org/10.1016/j.jesp.2017.09.011

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *Journal of Experimental Social Psychology, 49*(4), 764-766. https://doi.org/10.1016/j.jesp.2013.03.013

Li, F., Laville, A., Bonneau, D., Laporte, S., & Skalli, W. (2014). Study on cervical muscle volume by means of three-dimensional reconstruction. *Journal of Magnetic Resonance Imaging, 39*(6), 1411-1416. https://doi.org/10.1002/jmri.24326

Lisman, P. J. (2009). *Slow isoinertial cervical strength training does not alter dynamic stabilization of the head and neck during a standard football tackle* (PhD dissertation, University of Miami). https://scholarship.miami.edu/esploro/outputs/991031447461102976

Liston, M., Leckey, C., Whale, A., & van Dyk, N. (2023). Neck strength assessment offers no clinical value in predicting concussion in male professional rugby players: A prospective cohort study. *Journal of Orthopaedic and Sports Physical Therapy, 53*(5), 317-323. https://doi.org/10.2519/jospt.2023.11723

Lourenço, A. S., Lameiras, C., & Silva, A. G. (2016). Neck flexor and extensor muscle endurance in subclinical neck pain: Intrarater reliability, standard error of measurement, minimal detectable change, and comparison with asymptomatic participants in a university student population. *Journal of Manipulative and Physiological Therapeutics, 39*(6), 427-433. https://doi.org/10.1016/j.jmpt.2016.05.005

Lundon, K., & Bolton, K. (2001). Structure and function of the lumbar intervertebral disk in health, aging, and pathologic conditions. *Journal of Orthopaedic and Sports Physical Therapy, 31*(6), 291-306. https://doi.org/10.2519/jospt.2001.31.6.291

Maconi, F., Venturelli, M., Limonta, E., Rampichini, S., Bisconti, A. V., Monti, E., Longo, S., Esposito, F., & Cè, E. (2016). Effects of a 12-week neck muscles training on muscle function and perceived level of muscle soreness in amateur rugby players. *Sport Sciences for Health, 12*(3), 443-452. https://doi.org/10.1007/s11332-016-0314-9

MacQueen, A. E., & Dexter, W. W. (2010). Injury trends and prevention in rugby union football. *Current Sports Medicine Reports, 9*(3), 139-143. https://doi.org/10.1249/JSR.0b013e3181df124c

Malliaras, P., Hogan, A., Nawrocki, A., Crossley, K., & Schache, A. (2009). Hip flexibility and strength measures: reliability and association with athletic groin pain. *British Journal of Sports Medicine, 43*(10), 739-744. https://doi.org/10.1136/bjsm.2008.055749

Martin, E., & Beckham, G. (2020). Force production during the sustained phase of rugby scrums: A systematic literature review. *BMC Sports Science, Medicine and Rehabilitation, 12*(1), 33. https://doi.org/10.1186/s13102-020-00174-z

Mattucci, S. F. E., Moulton, J. A., Chandrashekar, N., & Cronin, D. S. (2012). Strain rate dependent properties of younger human cervical spine ligaments. *Journal of the Mechanical Behavior of Biomedical Materials, 10*(1), 216-226. https://doi.org/10.1016/j.jmbbm.2012.02.004

McBride, L. (2019, 12 May). Preventing cervical spine injury in elite rugby players: Current practice for screening and exercise provision [Conference presentation]. *WCPT Congress 2019, Geneva*

McBride, L. (2022, 1 October). ForceFrame: A reliable tool to measure neck strength [Conference presentation]. *2022 UKSCA Annual Conference, University of Nottingham*

McBride, L. (2023, 23 March). A novel technique to measure rugby players' neck strength: The reliability of the ForceFrame [Conference presentation]. *Symposium in Sports Science and Performance, University of Suffolk* https://www.youtube.com/watch?v=ssHCyy2cOrM&list=PLKZGlEezgKvffLE9hm5Gm4gXmhQrxzPiY&index=1

McBride, L., James, R. S., Alsop, S., & Oxford, S. W. (2022). Intra and inter-rater reliability of a novel isometric test of neck strength. *Sports, 11*(1), 2. https://doi.org/10.3390/sports11010002

McCall, A., Davison, M., Andersen, T. E., Beasley, I., Bizzini, M., Dupont, G., Duffield, R., Carling, C., & Dvorak, J. (2015). Injury prevention strategies at the FIFA 2014 World Cup: Perceptions and practices of the physicians from the 32 participating national teams. *British Journal of Sports Medicine, 49*(9), 603-608. https://doi.org/10.1136/bjsports-2015-094747

McDaniel, A. T., Schroeder, L. H., Freedman, J. A., Wang, Y., & Heijnen, M. J. H. (2021). Evaluating the intra-rater and inter-rater reliability of fixed tension scale instrumentation for determining isometric neck strength. *International Journal of Exercise Science, 14*(3), 563-577. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8136575

McGinnis, P. M. (2005). *Biomechanics of sport and exercise* (2nd ed.). Human Kinetics.

McGuigan, M. (2019). *Testing and evaluation of strength and power*. Routledge. https://doi.org/10.4324/9780429028182

McGuigan, M., Cormack, S. J., & Gill, N. D. (2013). Strength and power profiling of athletes. *Strength and Conditioning Journal, 35*(6), 7-14. https://doi.org/10.1519/SSC.0000000000000011

McIntosh, A. S., & McCrory, P. (2005). Preventing head and neck injury. *British Journal of Sports Medicine, 39*(6), 314-318. https://doi.org/10.1136/bjsm.2005.018200

Meagher, G. (2022, June 21). Concussion rates in elite rugby hit highest levels since records began. *The Guardian* https://www.theguardian.com/sport/2022/jun/21/concussion-rates-in-elite-rugby-hit-highest-levels-since-records-began

Mellalieu, S., Trewartha, G., & Stokes, K. (2008). Science and rugby union. *Journal of Sports Sciences, 26*(8), 791-794. https://doi.org/10.1080/02640410701819099

Miller, C. A., Hwang, S. J., Cotter, M. M., & Vorperian, H. K. (2021). Developmental morphology of the cervical vertebrae and the emergence of sexual dimorphism in size and shape: A computed tomography study. *The Anatomical Record, 304*(8), 1692-1708. https://doi.org/10.1002/ar.24559

Moya-Angeler, J., Vaquero, J., & Forriol, F. (2017). Evaluation of lower limb kinetics during gait, sprint and hop tests before and after anterior cruciate ligament reconstruction. *Journal of Orthopaedics and Traumatology, 18*(2), 177-184. https://doi.org/10.1007/s10195-017-0456-9

Murray, A. D., Murray, I. R., & Robson, J. (2014). Rugby union: Faster, higher, stronger: Keeping an evolving sport safe. *British Journal of Sports Medicine, 48*(2), 73-74. https://doi.org/10.1136/bjsports-2012-091844

Naish, R., Burnett, A., Burrows, S., Andrews, W., & Appleby, B. (2013). Can a specific neck strengthening program decrease cervical spine injuries in a men's professional rugby union team? A retrospective analysis. *Journal of Sports Science and Medicine, 12*(3), 542-550. https://www.jssm.org/jssm-12-542.xml%3EFulltext

Newton, I. (1846). *Newton's Principia: the mathematical principles of natural philosophy* (A. Motte Trans.). (American ed.). Daniel Adee.

Nightingale, R. W., McElhaney, J. H., Richardson, W. J., & Myers, B. S. (1996). Dynamic responses of the head and cervical spine to axial impact loading. *Journal of Biomechanics, 29*(3), 307-318. https://doi.org/10.1016/0021-9290(95)00056-9

O'Brien, J., & Finch, C. F. (2014). The implementation of musculoskeletal injury-prevention exercise programmes in team ball sports: A systematic review employing the RE-AIM framework. *Sports Medicine, 44*(9), 1305-1318. https://doi.org/10.1007/s40279-014-0208-4

Oliveira, A. C., & Silva, A. G. (2016). Neck muscle endurance and head posture: A comparison between adolescents with and without neck pain. *Manual Therapy, 22*(1), 62-67. https://doi.org/10.1016/j.math.2015.10.002

Olivier, P. E., & Du Toit, D.,E. (2008). Isokinetic neck strength profile of senior elite rugby union players. *Journal of Science and Medicine in Sport, 11*(2), 96-105. https://doi.org/10.1016/j.jsams.2007.01.009

Orchard, J., Rae, K., Brooks, J., Hägglund, M., Til, L., Wales, D., & Wood, T. (2010). Revision, uptake and coding issues related to the open access Orchard Sports Injury Classification System (OSICS) versions 8, 9 and 10.1. *Open Access Journal of Sports Medicine, 1*(1), 207-214. https://doi.org/10.2147/OAJSM.S7715

Owoeye, O. B. A., Rauvola, R. S., & Brownson, R. C. (2020). Dissemination and implementation research in sports and exercise medicine and sports physical therapy: Translating evidence to practice and policy. *BMJ Open Sport and Exercise Medicine, 6*(1), e000974. https://doi.org/10.1136/bmjsem-2020-000974

Oxland, T. R. (2015). Fundamental biomechanics of the spine: What we have learned in the past 25 years and future directions. *Journal of Biomechanics, 49*(6), 817-832. https://doi.org/10.1016/j.jbiomech.2015.10.035

PA Media. (2023, March 20). World Cup winner Steve Thompson reveals he was put on suicide watch amid dementia battle. *The Independent* https://www.independent.co.uk/sport/rugby/rugby-union/england-australia-rugby-world-rugby-rugby-football-union-b2063851.html

Palmer-Green, D. S., Stokes, K. A., Fuller, C. W., England, M., Kemp, S. P. T., & Trewartha, G. (2015). Training activities and injuries in English youth academy and schools rugby union. *The American Journal of Sports Medicine, 43*(2), 475-481. https://doi.org/10.1177/0363546514560337

Panjabi, M. M. (1992). The stabilizing system of the spine: Part I. Function, dysfunction, adaptation, and enhancement. *Journal of Spinal Disorders, 5*(4), 383-389. https://doi.org/10.1097/00002517-199212000-00001

Paredes, P. E., Hamdan, N. A., Clark, D., Cai, C., Ju, W., & Landay, J. A. (2017). Evaluating in-car movements in the design of mindful commute interventions: Exploratory study. *Journal of Medical Internet Research, 19*(12), e372. https://doi.org/10.2196/jmir.6983

Paul, L., Naughton, M., Jones, B., Davidow, D., Patel, A., Lambert, M., & Hendricks, S. (2022). Quantifying collision frequency and intensity in rugby union and rugby sevens: A systematic review. *Sports Medicine: Open, 8*(1), 12. https://doi.org/10.1186/s40798-021-00398-4

Peek, K. (2022). The measurement of neck strength: A guide for sports medicine clinicians. *Physical Therapy in Sport, 55*(1), 282-288. https://doi.org/10.1016/j.ptsp.2022.05.006

Peolsson, A., Hamp, C., Albinsson, A., Engdahl, S., & Kvist, J. (2007). Test position and reliability in measurements of dorsal neck muscle endurance. *Advances in Physiotherapy, 9*(4), 181-189. https://doi.org/10.1080/14038190701702058

Peolsson, A., Oberg, B., & Hedlund, R. (2001). Intra- and inter-tester reliability and reference values for isometric neck strength. *Physiotherapy Research International, 6*(1), 15-26. https://doi.org/10.1002/pri.210

Physiquipe. (n.d.). *Multi-Cervical Unit.* Physiquipe. Retrieved 2023-08-19, from https://www.physiquipe.com/products/multi-cervical-unit/

Pinsault, N., Fleury, A., Virone, G., Bouvier, B., Vaillant, J., & Vuillerme, N. (2008). Test-retest reliability of cervicocephalic relocation test to neutral head position. *Physiotherapy Theory and Practice, 24*(5), 380-391. https://doi.org/10.1080/09593980701884824

Pitchbooking. (n.d.). *How big? Rugby pitch sizes, dimensions and markings.* Pitchbooking. Retrieved April 13, 2023, from https://pitchbooking.com/blog/rugby-union-pitch-size-dimension-meters-feet

Prien, A., Grafe, A., Rössler, R., Junge, A., & Verhagen, E. (2018). Epidemiology of head injuries focusing on concussions in team contact sports: A systematic review. *Sports Medicine, 48*(4), 953-969. https://doi.org/10.1007/s40279-017-0854-4

PRISP. (2019). *England Professional Rugby Injury Surveillance Project: 2017–18 Season Report.* https://www.englandrugby.com/dxdam/96/960006d9-269d-4250-a15f-d9e62f8bfe70/PRISP_1718.pdf

PRISP. (2022). *England Professional Rugby Injury Surveillance Project: 2020–21 Season Report.* https://www.englandrugby.com/dxdam/93/935f2247-f8df-4a56-93b3-19bee4bcf923/PRISP%202020-21.pdf

Prushansky, T., & Dvir, Z. (2008). Cervical motion testing: Methodology and clinical implications. *Journal of Manipulative and Physiological Therapeutics, 31*(7), 503-508. https://doi.org/10.1016/j.jmpt.2008.08.004

Quarrie, K. L., Handcock, P., Waller, A. E., Chalmers, D. J., Toomey, M. J., & Wilson, B. D. (1995). The New Zealand rugby injury and performance project: III. Anthropometric and physical performance characteristics of players. *British Journal of Sports Medicine, 29*(4), 263-270. https://doi.org/10.1136/bjsm.29.4.263

Quarrie, K. L., Raftery, M., Blackie, J., Cook, C. J., Fuller, C. W., Gabbett, T. J., Gray, A. J., Gill, N., Hennessy, L., Kemp, S., Lambert, M., Nichol, R., Mellalieu, S. D., Piscione, J., Stadelmann, J., & Tucker, R. (2017). Managing player load in professional rugby union: A review of current knowledge and practices. *British Journal of Sports Medicine, 51*(5), 421-427. https://doi.org/10.1136/bjsports-2016-096191

Quarrie, K. L., Cantu, R. C., & Chalmers, D. J. (2002). Rugby union injuries to the cervical spine and spinal cord. *Sports Medicine, 32*(10), 633-653. https://doi.org/10.2165/00007256-200232100-00003

Read, P. J., Michael Auliffe, S., Wilson, M. G., & Graham-Smith, P. (2020). Lower limb kinetic asymmetries in professional soccer players with and without anterior cruciate ligament reconstruction: Nine months is not enough time to restore “functional” symmetry or return to performance. *The American Journal of Sports Medicine, 48*(6), 1365-1373. https://doi.org/10.1177/0363546520912218

Reboursiere, E., Bohu, Y., Retière, D., Sesboüé, B., Pineau, V., Colonna, J. P., Hager, J. P., Peyrin, J. C., & Piscione, J. (2018). Impact of the national prevention policy and scrum law changes on the incidence of rugby-related catastrophic cervical spine injuries in French rugby union. *British Journal of Sports Medicine, 52*(10), 674-677. https://doi.org/10.1136/bjsports-2016-096122

Rezasoltani, A., Ahmadi, A., Nehzate-Khoshroh, M., Forohideh, F., & Ylinen, J. (2005). Cervical muscle strength measurement in two groups of elite Greco-Roman and free style wrestlers and a group of non-athletic subjects. *British Journal of Sports Medicine, 39*(7), 440-443. https://doi.org/10.1136/bjsm.2004.013961

Roberts, S. P., Trewartha, G., England, M., Shaddick, G., & Stokes, K. A. (2013). Epidemiology of time-loss injuries in English community-level rugby union. *BMJ Open, 3*(11), e003998. https://doi.org/10.1136/bmjopen-2013-003998

Roberts, S. P., Trewartha, G., Higgitt, R. J., El-Abd, J., & Stokes, K. A. (2008). The physical demands of elite English rugby union. *Journal of Sports Sciences, 26*(8), 825-833. https://doi.org/10.1080/02640410801942122

Roebroeck, M. E., Harlaar, J., & Lankhorst, G. J. (1993). The application of generalizability theory to reliability assessment: An illustration using isometric force measurements. *Physical Therapy, 73*(6), 386-395. https://doi.org/10.1093/ptj/73.6.386

Ross, E., Gupta, L., & Sanders, L. (2018). When research leads to learning, but not action in high performance sport. *Progress in Brain Research, 240*(1), 201-217. https://doi.org/10.1016/bs.pbr.2018.08.001

Ryan, S., Kempton, T., Pacecca, E., & Coutts, A. J. (2019). Measurement properties of an adductor strength-assessment system in professional Australian footballers. *International Journal of Sports Physiology and Performance, 14*(2), 256-259. https://doi.org/10.1123/ijspp.2018-0264

Salmon, D. M., Handcock, P. J., Sullivan, S. J., Rehrer, N. J., & Niven, B. E. (2015). Reliability of repeated isometric neck strength and endurance testing in a simulated contact posture. *Journal of Strength and Conditioning Research, 29*(3), 637-646. https://doi.org/10.1519/JSC.0000000000000689

Salmon, D. M., Sullivan, S. J., Handcock, P., Rehrer, N. J., & Niven, B. (2018). Neck strength and self-reported neck dysfunction: What is the impact of a season of rugby union? *Journal of Sports Medicine and Physical Fitness, 58*(7), 1078-1089. https://doi.org/10.23736/S0022-4707.17.07070-0

Salmon, D. M., Handcock, P. J., Sullivan, S. J., Rehrer, N. J., & Niven, B. E. (2018). Can neck strength be measured using a single maximal contraction in a simulated contact position? *Journal of Strength and Conditioning Research, 32*(8), 2166-2173. https://doi.org/10.1519/jsc.0000000000001874

Sarto, F., Impellizzeri, F. M., Spörri, J., Porcelli, S., Olmo, J., Requena, B., Suarez-Arrones, L., Arundale, A., Bilsborough, J., Buchheit, M., Clubb, J., Coutts, A., Nabhan, D., Torres-Ronda, L., Mendez-Villanueva, A., Mujika, I., Maffiuletti, N. A., & Franchi, M. V. (2020). Impact of potential physiological changes due to COVID-19 home confinement on athlete health protection in elite sports: A call for awareness in sports programming. *Sports Medicine, 50*(8), 1417-1419. https://doi.org/10.1007/s40279-020-01297-6

Sato, H. (2015). Rugby-related spinal cord injuries in Japan and prevention methods: The catastrophic injuries reports of the Japan Rugby Football Union. *Neurotraumatology, 38*(2), 94-99. https://doi.org/10.32187/neurotraumatology.38.2_94

Schmidt, J. D., Guskiewicz, K. M., Blackburn, J. T., Mihalik, J. P., Siegmund, G. P., & Marshall, S. W. (2014). The influence of cervical muscle characteristics on head impact biomechanics in football. *The American Journal of Sports Medicine, 42*(9), 2056-2066. https://doi.org/10.1177/0363546514536685

Schneider, K., Emery, C. A., Kang, J., & Meeuwisse, W. (2014). Are clinical measures of cervical spine strength and cervical flexor endurance risk factors for concussion in elite youth ice hockey players? *British Journal of Sports Medicine, 48*(7), 659. https://doi.org/10.1136/bjsports-2014-093494.264

Schoenfeld, B. J. (2010). The mechanisms of muscle hypertrophy and their application to resistance training. *Journal of Strength and Conditioning Research, 24*(10), 2857-2872. https://doi.org/10.1519/JSC.0b013e3181e840f3

Schwab, L. M., McGhee, D., Franettovich Smith, M. M., Mendis, M. D., & Hides, J. (2020). Pre-season screening of the upper body and trunk in Australian football players: A prospective study. *Physical Therapy in Sport, 46*(1), 120-130. https://doi.org/10.1016/j.ptsp.2020.06.013

Sedeaud, A., Marc, A., Schipman, J., Tafflet, M., Hager, J. P., & Toussaint, J. (2012). How they won Rugby World Cup through height, mass and collective experience. *British Journal of Sports Medicine, 46*(8), 580-584. https://doi.org/10.1136/bjsports-2011-090506

Sedeaud, A., Vidalin, H., Tafflet, M., Marc, A., & Toussaint, J. F. (2013). Rugby morphologies: "Bigger and taller", reflects an early directional selection. *The Journal of Sports Medicine and Physical Fitness, 53*(2), 185-191. https://www.ncbi.nlm.nih.gov/pubmed/23584326

Selistre, L. F. A., Melo, C. d. S., & Noronha, M. A. d. (2021). Reliability and validity of clinical tests for measuring strength or endurance of cervical muscles: A systematic review and meta-analysis. *Archives of Physical Medicine and Rehabilitation, 102*(6), 1210-1227. https://doi.org/10.1016/j.apmr.2020.11.018

Seminati, E., Cazzola, D., Preatoni, E., & Trewartha, G. (2017). Specific tackling situations affect the biomechanical demands experienced by rugby union players. *Sports Biomechanics, 16*(1), 58-75. https://doi.org/10.1080/14763141.2016.1194453

Sharples, A. M., Galloway, S. D., Baker, D., Smith, B., & Black, K. (2021). Barriers, attitudes, and influences towards dietary intake amongst elite rugby union players. *Frontiers in Sports and Active Living, 3*(1), 789452. https://doi.org/10.3389/fspor.2021.789452

Sim, J., & Wright, C. (2000). *Research in health care: concepts, designs and methods*. Stanley Thornes.

Snodgrass, S. J., Osmotherly, P. G., Reid, S. A., Milburn, P. D., & Rivett, D. A. (2018). Physical characteristics associated with neck pain and injury in rugby union players. *The Journal of Sports Medicine and Physical Fitness, 58*(10), 1474-1481. https://doi.org/10.23736/S0022-4707.17.07255-3

Sobue, S., Kawasaki, T., Hasegawa, Y., Shiota, Y., Ota, C., Yoneda, T., Tahara, S., Maki, N., Matsuura, T., Sekiguchi, M., Itoigawa, Y., Tateishi, T., & Kaneko, K. (2018). Tackler's head position relative to the ball carrier is highly correlated with head and neck injuries in rugby. *British Journal of Sports Medicine, 52*(6), 353-358. https://doi.org/10.1136/bjsports-2017-098135

Sport Scotland. (2018). *If in doubt, sit them out: Scottish sports concussion guidance.* https://sportscotland.org.uk/media/3382/concussionreport2018.pdf

Stark, T., Walker, B., Phillips, J. K., Fejer, R., & Beck, R. (2011). Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review. *Physical Medicine and Rehabilitation, 3*(5), 472-479. https://doi.org/10.1016/j.pmrj.2010.10.025

Stewart, W., McNamara, P. H., Lawlor, B., Hutchinson, S., & Farrell, M. (2016). Chronic traumatic encephalopathy: A potential late and under recognized consequence of rugby union? *Quarterly Journal of Medicine, 109*(1), 11-15. https://doi.org/10.1093/qjmed/hcv070

Stone, M. H. (1993). Literature review: Explosive exercises and training. *National Strength and Conditioning Association Journal, 15*(3), 7-15. https://journals.lww.com/nsca-scj/Abstract/1993/05000/POSITION_STATEMENT__Explosive_Exercise_and.2.aspx

Stoop, R., Hohenauer, E., Rucker, A. M. L., & Clijsen, R. (2018). Anthropometric properties versus physical performance in rugby union forwards and backs: A systematic review. *Annals of Applied Sport Science, 6*(2), 1-13. https://doi.org/10.29252/aassjournal.6.2.1

Streiner, D. L., Norman, G. R., & Cairney, J. (2014). *Health measurement scales: a practical guide to their development and use* (5th ed.). Oxford University Press. https://doi.org/10.1093/med/9780199685219.001.0001

Strimpakos, N., Sakellari, V., Gioftsos, G., & Oldham, J. (2004). Intratester and intertester reliability of neck isometric dynamometry. *Archives of Physical Medicine and Rehabilitation, 85*(8), 1309-1316. https://doi.org/10.1016/j.apmr.2003.08.104

Sukari, A. A. A., Sarwinder, S., Bohari, M. H., Idris, Z., Ghani, A. R. I., & Abdullah, J. M. (2021). Examining the range of motion of the cervical spine: Utilising different bedside instruments. *Malaysian Journal of Medical Sciences, 28*(2), 100-105. https://doi.org/10.21315/mjms2021.28.2.9

Swain, M. S., Lystad, R. P., Pollard, H., & Bonello, R. (2011). Incidence and severity of neck injury in rugby union: A systematic review. *Journal of Science and Medicine in Sport, 14*(5), 383-389. https://doi.org/10.1016/j.jsams.2010.10.460

Swartz, E. E., Floyd, R. T., & Cendoma, M. (2005). Cervical spine functional anatomy and the biomechanics of injury due to compressive loading. *Journal of Athletic Training, 40*(3), 155-161. https://www.ncbi.nlm.nih.gov/pubmed/16284634

Taylor, A. E., Kemp, S., Trewartha, G., & Stokes, K. A. (2014). Scrum injury risk in English professional rugby union. *British Journal of Sports Medicine, 48*(13), 1066-1068. https://doi.org/10.1136/bjsports-2013-092873

Tee, J. C., Ashford, M., & Piggott, D. (2018). A tactical periodization approach for rugby union. *Strength and Conditioning Journal, 40*(5), 1-13. https://doi.org/10.1519/SSC.0000000000000390

Tierney, G. J., & Tucker, R. (2022). The role of player mass and contact speed on head kinematics and neck dynamics in rugby union tackling. *Scandinavian Journal of Medicine & Science in Sports, 32*(2), 298-312. https://doi.org/10.1111/sms.14090

Tortora, G. J., & Derrickson, B. H. (2017). *Tortora's principles of anatomy and physiology* (15th ed.). Wiley.

Trewartha, G., Preatoni, E., England, M. E., & Stokes, K. A. (2015). Injury and biomechanical perspectives on the rugby scrum: A review of the literature. *British Journal of Sports Medicine, 49*(7), 425-433. https://doi.org/10.1136/bjsports-2013-092972

Tucker, R., Lancaster, S., Davies, P., Street, G., Starling, L., de Coning, C., & Brown, J. (2021). Trends in player body mass at men's and women's Rugby World Cups: A plateau in body mass and differences in emerging rugby nations. *BMJ Open Sport and Exercise Medicine, 7*(1), e000885. https://doi.org/10.1136/bmjsem-2020-000885

Tucker, R., Raftery, M., Fuller, G. W., Hester, B., Kemp, S., & Cross, M. J. (2017). A video analysis of head injuries satisfying the criteria for a head injury assessment in professional rugby union: A prospective cohort study. *British Journal of Sports Medicine, 51*(15), 1147-1151. https://doi.org/10.1136/bjsports-2017-097883

Tucker, R., Raftery, M., Kemp, S., Brown, J., Fuller, G., Hester, B., Cross, M., & Quarrie, K. (2017). Risk factors for head injury events in professional rugby union: A video analysis of 464 head injury events to inform proposed injury prevention strategies. *British Journal of Sports Medicine, 51*(15), 1152-1157. https://doi.org/10.1136/bjsports-2017-097895

Tudini, F., Myers, B., & Bohannon, R. (2019). Reliability and validity of measurements of cervical retraction strength obtained with a hand-held dynamometer. *Journal of Manual and Manipulative Therapy, 27*(4), 222-228. https://doi.org/10.1080/10669817.2019.1586167

Ullucci, P. A., Tudini, F., & Moran, M. F. (2019). Reliability of smartphone inclinometry to measure upper cervical range of motion. *Journal of Sport Rehabilitation, 28*(1)https://doi.org/10.1123/jsr.2018-0048

UNC Women's Rugby. (n.d.). *About rugby.* UNC Women's Rugby. Retrieved November 4, 2022, from https://rugby.web.unc.edu/about-rugby

Uremović, M., Cvijetić, S., Pasić, M. B., Serić, V., Vidrih, B., & Demarin, V. (2007). Impairment of proprioception after whiplash injury. *Collegium Antropologicum, 31*(3), 823-827. https://hrcak.srce.hr/26897

VALD Performance. (n.d.). *ForceFrame strength testing system.* VALD Performance. Retrieved April 14, 2023, from https://valdperformance.com/forceframe

van Mechelen, W., Hlobil, H., & Kemper, H. C. (1992). Incidence, severity, aetiology and prevention of sports injuries: A review of concepts. *Sports Medicine, 14*(2), 82-99. https://doi.org/10.2165/00007256-199214020-00002

Vannebo, K. T., Iversen, V. M., Fimland, M. S., & Mork, P. J. (2018). Test-retest reliability of a handheld dynamometer for measurement of isometric cervical muscle strength. *Journal of Back and Musculoskeletal Rehabilitation, 31*(3), 557-565. https://doi.org/10.3233/BMR-170829

Verdera, F., Champavier, L., Schmidt, C., Bermon, S., & Marconnet, P. (1999). Reliability and validity of a new device to measure isometric strength in polyarticular exercises. *The Journal of Sports Medicine and Physical Fitness, 39*(2), 113-119. https://pubmed.ncbi.nlm.nih.gov/10399418

Verhagen, E. A. L. M., van Stralen, M. M., & van Mechelen, W. (2010). Behaviour, the key factor for sports injury prevention. *Sports Medicine, 40*(11), 899-906. https://doi.org/10.2165/11536890-000000000-00000

Versteegh, T., Beaudet, D., Greenbaum, M., Hellyer, L., Tritton, A., & Walton, D. (2015). Evaluating the reliability of a novel neck-strength assessment protocol for healthy adults using self-generated resistance with a hand-held dynamometer. *Physiotherapy Canada, 67*(1), 58-64. https://doi.org/10.3138/ptc.2013-66

Viviers, P. L., Viljoen, J. T., & Derman, W. (2018). A review of a decade of rugby union injury epidemiology: 2007-2017. *Sports Health, 10*(3), 223-227. https://doi.org/10.1177/1941738118757178

Vriend, I., Gouttebarge, V., Finch, C. F., van Mechelen, W., & Verhagen, E. A. L. M. (2017). Intervention strategies used in sport injury prevention studies: A systematic review identifying studies applying the Haddon matrix. *Sports Medicine, 47*(10), 2027-2043. https://doi.org/10.1007/s40279-017-0718-y

Walsh, D. (2022, July 30). Siobhan Cattigan: "They fixed her broken bones but turned their back on her broken brain". *The Times* https://www.thetimes.co.uk/article/they-fixed-siobhan-s-broken-bones-but-turned-their-back-on-her-broken-brain-n668rkwlt

West, S. W., Starling, L., Kemp, S., Williams, S., Cross, M., Taylor, A., Brooks, J. H. M., & Stokes, K. A. (2021). Trends in match injury risk in professional male rugby union: A 16-season review of 10,851 match injuries in the English Premiership (2002–2019): The Professional Rugby Injury Surveillance Project. *British Journal of Sports Medicine, 55*(12), 676-682. https://doi.org/10.1136/bjsports-2020-102529

West, S. W., Williams, S., Kemp, S. P. T., Cross, M. J., & Stokes, K. A. (2019). Athlete monitoring in rugby union: Is heterogeneity in data capture holding us back? *Sports, 7*(5), 98. https://doi.org/10.3390/sports7050098

Williams, S., Trewartha, G., Kemp, S. P. T., Brooks, J. H. M., Fuller, C. W., Taylor, A. E., Cross, M. J., & Stokes, K. A. (2016). Time loss injuries compromise team success in Elite Rugby Union: A 7-year prospective study. *British Journal of Sports Medicine, 50*(11), 651-656. https://doi.org/10.1136/bjsports-2015-094798

Windle, W. F. (Ed.). (1980). *The spinal cord and its reaction to traumatic injury: anatomy, physiology, pharmacology, therapeutics*. M. Dekker.

World Rugby. (2017). *Concussion guidance.* https://resources.world.rugby/worldrugby/document/2021/01/28/4bc618b4-845a-4ee3-9ea2-8afe69f1e163/World_Rugby_Concussion_Guidance_EN.pdf

World Rugby. (2021a). *10 facts you need to know about international Wheelchair Rugby.* World Rugby. Retrieved November 3, 2022, from https://www.world.rugby/news/579811

World Rugby. (2021b). *Year in Review 2021.* http://publications.worldrugby.org/yearinreview2021/en/1-1

World Rugby. (2022). *Global law trials.* World Rugby. Retrieved March 18, 2023, from https://www.world.rugby/the-game/laws/global-law-trials

World Rugby. (n.d.). *World Rugby Charter: Introduction.* World Rugby. Retrieved November 3, 2022, from https://www.world.rugby/the-game/laws/charter/introduction

Yahia, L., & Newman, N. (1993). A scanning electron microscopic and immunohistochemical study of spinal ligaments innervation. *Annals of Anatomy, 175*(2), 111-114. https://doi.org/10.1016/S0940-9602(11)80162-7

Zanrosso, E. M., Coghetto, G., Rabello, R., da Ros, J. L., & Rodrigues, R. (2022). Physical and performance indicators between backs and forwards in a subelite rugby union team. *The Journal of Sports Medicine and Physical Fitness, 62*(11), 1435-1439. https://doi.org/10.23736/S0022-4707.21.12953-6

Appendices

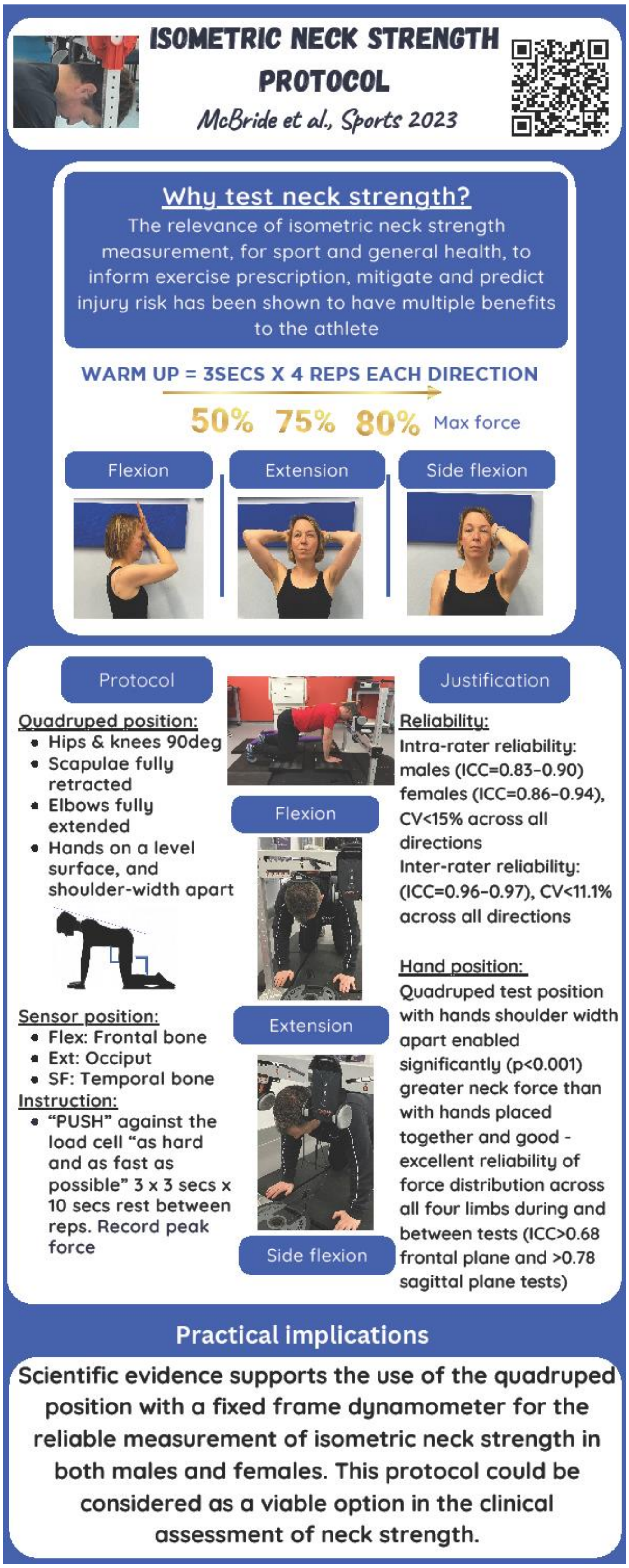
Appendix 1: Questionnaire

https://drive.google.com/file/d/1AVOmWDqxsCaFvpVENHViqvwFpDRUXKLk/view?usp=sharing

Appendix 2: Publication

https://drive.google.com/file/d/1ieKdigTkG2DkTbA3Day8PulRSZsEPHH_/view?usp=sharing

Appendix 3: Infographic of protocol



Appendix 4: Participant information sheet and Informed consent (Chapters 4–5)

Reliability study of the GroinBar™ dynamometer for measuring cervical spine isometric strength

PARTICIPANT INFORMATION SHEET
Ethics reference number: P93801

You are being invited to take part in research on cervical spine strength measurements. Lesley McBride, Assistant Professor at Coventry University, is leading this research. Before you decide to take part it is important you understand why the research is being conducted and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?
The purpose of the study is to establish the reliability of the equipment as seen in figure 1 below – a dynamometer called a ForceFrame which measures muscle strength, to measure neck strength in 4 directions (flexion, extension, left and right side flexion). This equipment is already in use in the sports industry for testing strength in the hip, knee, shoulder and ankle joints.

Figure 1- The ForceFrame equipment **Figure 2 – All 4s test position**

Why have I been chosen to take part?
You are invited to participate in this study because you are able to complete the testing protocol and are over the age of 18 and under the age of 50 years. You do not currently have any neck pain, and have not sustained a previous neck injury which has resulted in ongoing pain or neurological deficit. You also do not have any diagnosis which may be made worse by this testing. You must let the researcher know if either of these issues pertain to you.

What are the benefits of taking part?
By sharing your experiences with us, you will be helping Lesley McBride and Coventry University to better understand how to reliably measure neck strength.

Are there any risks associated with taking part?
This study has been reviewed and approved through Coventry University's formal research ethics procedure. There are no significant risks associated with participation.

Do I have to take part?
No – it is entirely up to you. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research, and that you are happy to participate. Please note down your participant number (which is on the Informed Consent Form) and provide this to the lead researcher if you seek to withdraw from the study at a later date. You are free to withdraw your information from the project data set at any time until the data is fully anonymised in our records. You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to this date and so you are advised to contact Coventry University at the earliest opportunity should you wish to withdraw from the study. If you consent a photograph may be taken of the positioning of the testing – but if this is used in any publications it will be anonymised. To withdraw, please contact the lead researcher (contact details are provided below). Please also contact the Research Support Office email ethics.hls@coventry.ac.uk; so that your request can be dealt with promptly in the event of the lead researcher's absence. You do not need to give a reason. A decision to withdraw, or not to take part, will not affect you in any way.

What will happen if I decide to take part?
You will sign an informed consent sheet. You will be asked to complete a warm up and familiarise yourself with the equipment by pushing with your neck at 80% of your maximal force against the ForceFrame equipment in all the test positions (flexion, extension and left/right side flexion) as clearly instructed by the researcher. You will then be asked to push with a maximal voluntary contraction into flexion, extension and left/right side flexion against the ForceFrame equipment. You will push 3 x 5 seconds each and the scores will be recorded by the equipment. Whilst completing the test you will be kneeling on all 4s on force platforms to ensure that you are only activating your neck muscles. You will be asked to repeat the test twice – once with hands together and once with hands apart. You will then be asked to wait 10 minutes and will be retested by another researcher to ensure that both researchers collect the same data. You will need to return for repeated measuring on 1 more occasion at least 72 hours after this first visit.

Data Protection and Confidentiality
Your data will be processed in accordance with the General Data Protection Regulation 2016 (GDPR) and the Data Protection Act 2018. All information collected about you will be kept strictly confidential. Unless they are fully anonymised in our records, your data will be referred to by a unique participant number rather than by name. If you consent to being audio recorded, all recordings will be destroyed once they have been transcribed. Your data will only be viewed by the researcher/research team. All electronic data will be stored on a password-protected computer file on an encrypted laptop held by Lesley McBride. Your consent information will be kept separately from your responses in order to minimise risk in the event of a data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before September 2021

Data Protection Rights
Coventry University is a Data Controller for the information you provide. You have the right to access information held about you. Your right of access can be exercised in accordance with the General Data Protection Regulation and the Data Protection Act 2018. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner's Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - enquiry.ipu@coventry.ac.uk

What will happen with the results of this study?
The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name.

Making a Complaint
If you are unhappy with any aspect of this research, please first contact the lead researcher, Lesley McBride on hsx205@coventry.ac.uk. Or contact ethics.hls@coventry.ac.uk

Participant No.

INFORMED CONSENT FORM:
Ethics reference number: P93801

Reliability study of the ForceFrame dynamometer for measuring cervical spine isometric strength

You are invited to take part in this research study for the purpose of determining the reliability of the ForceFrame to measure neck strength

Before you decide to take part, you must **read the accompanying Participant Information Sheet.**

Please do not hesitate to ask questions if anything is unclear or if you would like more information about any aspect of this research. It is important that you feel able to take the necessary time to decide whether or not you wish to take part.

If you are happy to participate, please confirm your consent by circling YES against each of the below statements and then signing and dating the form as participant.

1	**I confirm that I have read and understood the Participant Information Sheet for the above study and have had the opportunity to ask questions**	**YES**	**NO**
2	**I understand my participation is voluntary and that I am free to withdraw my data, without giving a reason, by contacting the lead researcher and the Research Support Office at any time until the date specified in the Participant Information Sheet**	**YES**	**NO**

3	**I have noted down my participant number (top left of this Consent Form) which may be required by the lead researcher if I wish to withdraw from the study**	**YES**	**NO**
4	**I understand that all the information I provide will be held securely and treated confidentially**	**YES**	**NO**
5	**I am happy for the information I provide to be used (anonymously) in academic papers and other formal research outputs**	**YES**	**NO**
6	**I consent to have my photograph taken whilst undergoing the testing on the equipment. I understand that these photographs may be used in publications but that they will be anonymised**	**YES**	**NO**
7	**I agree to take part in the above study**	**YES**	**NO**

Thank you for your participation in this study. Your help is very much appreciated.

Participant's Name	**Date**	**Signature**
Researcher	**Date**	**Signature**
Lesley McBride		

Appendix 5: Gate keeper letter (Chapter 6)

Lesley McBride

School of Health and Life Sciences

Coventry University

CV1 5FB

02476885036

Date

Dear Head of medical services

My name is Lesley McBride and I'm currently undertaking a research project at Coventry University, towards the qualification of a PhD, to explore the neck strength of professional rugby players.

Subject to approval by Coventry University Ethics this study will be using the VALD Groinbar™, a fixed frame dynamometer, in order to measure the neck strength of players registered at your club.

I'm writing to ask your permission to be allowed access to your players. This testing itself involves the player pushing their head into a load cell to generate their maximum neck force, and takes a maximum of 10 mins per player to complete. The study can be conducted at a convenient time and date for your players and staff. I will need a small space, probably in the gym, where the equipment can be situated for the duration of the testing.

Each player involved will have the right to withdraw at any time, and will need to sign an informed consent form to be eligible to take part. All results will subsequently be anonymised and are kept strictly confidential and the results will be reported in a research paper available to all participants on completion.

If this is possible, please could you E-mail me at hsx205@coventry.ac.uk to confirm that you are willing to allow access to the players providing they agree to take part?

Yours sincerely

Lesley McBride,

Assistant Professor Physiotherapy

Neck strength measurements of professional rugby players (P93396)

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on cervical spine strength measurements. Lesley McBride, Assistant Professor at Coventry University is leading this research. Before you decide to take part it is important you understand why the research is being conducted and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?
The purpose of the study is to collect measurements of neck strength in 4 directions (flexion, extension, left and right side flexion) using the Groinbar equipment in order to get a baseline measurement of your strength. This will allow us to generate bespoke exercises for you based on the measurements gained.

Why have I been chosen to take part?
You are invited to participate in this study because you are a professional rugby player.

What are the benefits of taking part?
By sharing your experiences with us, you will be helping Lesley McBride and Coventry University to better understand the definition of a "strong" neck and its relevance to injury prevention and prevention of pain.

Are there any risks associated with taking part?
This study has been reviewed and approved through Coventry University's formal research ethics procedure. There are no significant risks associated with participation.

Do I have to take part?
No – it is entirely up to you. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research, and that you are happy to participate. Please note down your participant number (which is on the Consent Form) and provide this to the lead researcher if you seek to withdraw from the study at a later date. You are free to withdraw your information from the project data set at any time until the data is fully anonymised in our records on 16/09/19. You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to this date and so you are advised to contact the university at the earliest opportunity should you wish to withdraw from the study. To withdraw, please contact the lead researcher (contact details are provided below). Please also contact the Research Support Office email ethics.hls@coventry.ac.uk; so that your request can be dealt with promptly in the event of the lead researcher's absence. You do not need to give a reason. A decision to withdraw, or not to take part, will not affect you in any way.

What will happen if I decide to take part?
You will be asked to complete a neck strength test by pushing with a maximal voluntary contraction in flexion, extension and side flexion against a load cell on the Groinbar equipment. You will push 3 x 5 seconds each and the highest score will be recorded.

Data Protection and Confidentiality
Your data will be processed in accordance with the General Data Protection Regulation 2016 (GDPR) and the Data Protection Act 2018. All information collected about you will be kept strictly confidential. Unless they are fully anonymised in our records, your data will be referred to by a unique participant number rather than by name. If you consent to being audio recorded, all recordings will be destroyed once they have been transcribed. Your data will only be viewed by the researcher/research team. All electronic data will be stored on a password-protected computer file on an encrypted laptop held by Lesley McBride. Your consent information will be kept separately from your responses in order to minimise risk in the event of a data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before September 2021

Data Protection Rights
Coventry University is a Data Controller for the information you provide. You have the right to access information held about you. Your right of access can be exercised in accordance with the General Data Protection Regulation and the Data Protection Act 2018. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner's Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - enquiry.ipu@coventry.ac.uk

What will happen with the results of this study?
The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name.

Making a Complaint
If you are unhappy with any aspect of this research, please first contact the lead researcher, Lesley McBride on hsx205@coventry.ac.uk. Or contact ethics.hls@coventry.ac.uk

Participant No.

INFORMED CONSENT FORM (P93396)
Neck strength measurements for professional rugby players

You are invited to take part in this research study for the purpose of collecting data on neck strength measurements of professional rugby players

Before you decide to take part, you must **read the accompanying Participant Information Sheet.**

Please do not hesitate to ask questions if anything is unclear or if you would like more information about any aspect of this research. It is important that you feel able to take the necessary time to decide whether or not you wish to take part.

If you are happy to participate, please confirm your consent by circling YES against each of the below statements and then signing and dating the form as participant.

1	**I confirm that I have read and understood the Participant Information Sheet for the above study and have had the opportunity to ask questions**	**YES**	**NO**
2	**I understand my participation is voluntary and that I am free to withdraw my data, without giving a reason, by contacting the lead researcher and the Research Support Office at any time until the date specified in the Participant Information Sheet**	**YES**	**NO**
3	**I have noted down my participant number (top left of this Consent Form) which may be required by the lead researcher if I wish to withdraw from the study**	**YES**	**NO**
4	**I understand that all the information I provide will be held securely and treated confidentially**	**YES**	**NO**
5	**I am happy for the information I provide to be used (anonymously) in academic papers and other formal research outputs**	**YES**	**NO**
6	**I agree to take part in the above study**	**YES**	**NO**

Thank you for your participation in this study. Your help is very much appreciated.

Participant's Name	**Date**	**Signature**
Researcher	**Date**	**Signature**
Lesley McBride		

Appendix 7: Declaration of co-authors

A version of Chapter 4 has previously been published: McBride L., James R.S., Alsop S. and Oxford S.W. (2023). Intra and inter-rater reliability of a novel isometric test of neck strength. *Sports 11*(1), 2. DOI: 10.3390/sports11010002.

The co-authors – Robert S. James (R.S.J.), Siân Alsop (S.A.) and Samuel W. Oxford (S.W.O.) – have all given their consent for the findings published in this paper to be reproduced here in an alternative form for the purposes of the thesis.

With regard to the specific contributions of the individual authors, the following has been copied from the published paper (McBride et al., 2022, p. 7):

"Author Contributions: Conceptualization, S.W.O. and L.M.; methodology, S.W.O. and L.M.; software, S.W.O. and L.M.; validation, S.W.O., L.M. and R.S.J.; formal analysis, S.W.O., L.M. and R.S.J.; investigation, S.W.O. and L.M.; data curation, L.M., S.W.O. and R.S.J.; writing—original draft preparation, L.M., S.W.O. and S.A.; writing—review and editing, R.S.J., S.W.O., L.M. and S.A.; supervision, S.W.O., R.S.J. and S.A. All authors have read and agreed to the published version of the manuscript."

Signed,

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Robert S. James	Siân Alsop	Samuel W. Oxford