Combining evidence and practice to optimise neck training aimed at reducing head acceleration events in sport: a systematic review and Delphi-consensus study

FOWNES-WALPOLE, Molly <http://orcid.org/0009-0001-9010-7519>, HEYWARD, Omar <http://orcid.org/0000-0002-7390-6511>, TILL, Kevin <http://orcid.org/0000-0002-9686-0536>, MACKAY, Lois, STODTER, Anna <http://orcid.org/0000-0002-1037-9398>, AL-DAWOUD, Marwan, BUSSEY, Melanie Dawn <http://orcid.org/0000-0002-5746-3861>, GORDON, Leigh <http://orcid.org/0000-0002-0455-6204>, HAIRSINE, James, KIRK, Chris <http://orcid.org/0000-0002-6207-027X>, MADDEN, Rob, MCBRIDE, Lesley, MCDANIEL, Alexander, MCKNIGHT, Pete, MILL, Nathan, PEEK, Kerry <http://orcid.org/0000-0002-2194-3353>, PRATT, Gavin, RYAN, Des, SALMON, Danielle, SCHROEDER, Lindsey, TWENTYMAN, Craig, VERSTEEGH, Theo, WILLIAMS, Elisabeth and JONES, Ben <http://orcid.org/0000-0002-4274-6236>

Citation:

FOWNES-WALPOLE, Molly, HEYWARD, Omar, TILL, Kevin, MACKAY, Lois, STODTER, Anna, AL-DAWOUD, Marwan, BUSSEY, Melanie Dawn, GORDON, Leigh, HAIRSINE, James, KIRK, Chris, MADDEN, Rob, MCBRIDE, Lesley, MCDANIEL, Alexander, MCKNIGHT, Pete, MILL, Nathan, PEEK, Kerry, PRATT, Gavin, RYAN, Des, SALMON, Danielle, SCHROEDER, Lindsey, TWENTYMAN, Craig, VERSTEEGH, Theo, WILLIAMS, Elisabeth and JONES, Ben (2025). Combining evidence and practice to optimise neck training aimed at reducing head acceleration events in sport: a systematic review and Delphi-consensus study. British Journal of Sports Medicine. [Article]

Combining Evidence and Practice to Optimise Neck Training aimed at Reducing Head Acceleration Events in Sport: A Systematic Review and Delphi-Consensus Study

Molly Fownes-Walpole[1,2], Omar Heyward[1,3,4], Kevin Till1[1,2], Lois Mackay[1,5], Anna Stodter[1,6], Marwan Al-Dawoud[1], Melanie Bussey[7], Leigh Gordon[8], James Hairsine[4], Christopher Kirk[9], Lesley McBride[10], Alexander McDaniel[11], Nathan Mill[12], Pete McKnight, Rob Madden[13], Gavin Pratt[14], Kerry Peek[15], Des Ryan[16], Danielle Salmon[17,18], Lindsey Schroeder[11], Craig Twentyman[19], Elisabeth Williams[20], Theo Versteegh[21], Ben Jones[1, 5, 8, 22, 23]

Affiliations

1. Carnegie Applied Rugby Research (CARR) centre, Carnegie School of Sport, Leeds Beckett University, Leeds, UK
2. Leeds Rhinos Rugby League Club, Leeds, UK
3. Rugby Football Union, Twickenham, UK
4. Premiership Rugby, London, UK
5. England Netball, Loughborough, UK
6. Centre for Sport Coaching, Carnegie School of Sport, Leeds Beckett University, Headingley Campus, Leeds, UK.
7. University of Otago, Dunedin, New Zealand
8. Division of Physiological Sciences, Department of Human Biology, Faculty of Health Sciences, University of Cape Town and the Sports Science Institute of South Africa, Cape Town, South Africa
9. Sport and Human Performance Research Group, School of Sport and Physical Activity, Sheffield Hallam University, Sheffield, UK
10. University of Leicester, Leicester, UK
11. University of North Carolina Wilmington, Wilmington, NC, USA
12. Saint Helens R.F.C, Merseyside, UK
13. Team Antony Joshua, UK
14. Ultimate Fighting Combat Performance Institute, Las Vegas, USA
15. Sydney School of Health Sciences, The University of Sydney, Sydney, New South Wales, Australia
16. University of Galway, Galway, Ireland
17. International Rugby Players Association, Dublin, Ireland
18. Sport Injury Prevention Research Centre, University of Calgary, Calgary, Canada
19. New Zealand Sevens, New Zealand Rugby, Wellington, New Zealand
20. Applied Sports, Technology, Exercise and Medicine Research Centre (A-STEM), Faculty of Science and Engineering, Swansea University, Wales, UK
21. TopSpin Technologies Ltd, ON, Canada
22. England Performance Unit, Rugby Football League, Manchester, UK

[23.] School of Behavioural and Health Sciences, Faculty of Health Sciences, Australian Catholic University, Brisbane, QLD, Australia

Corresponding author: Molly Fownes-Walpole, m.fownes-walpole@leedsbeckett.ac.uk

Contributors: MFW, KT, OH, AS, and BJ conceptualised and designed the research project. MFW, LM and KT completed the systematic review. MFW constructed the Round 2 and 3 surveys and completed the inductive content analysis. MFW and OH completed the GRADE. MFW, KT, OH, AS, and BJ constructed the Delphi-consensus-Round-1 survey. OH reviewed the statements and text. MFW was responsible for the interpretation of results and drafted the manuscript. Other authors contributed towards the consensus statements and all authors critically reviewed and edited the manuscript prior to submission. MFW is the guarantor for this study.

Acknowledgements: We would like to acknowledge Dr. Isla Shill for her guidance in the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) process.

Funding: No funding was received to undertake this study.

Competing interests: One author (TV) works for a company that designs and sells a neuromuscular neck training device. All other authors have no competing interests to declare, however, due to the nature of the study many of the authors work in research or practice involving neck training or other interventions to reduce concussion/head acceleration events in sports.

Ethical Approval: This project was approved by Leeds Beckett University, Local Ethics Committee (117157)

Patient and public involvement: Patients and/or the public were not involved in the design, conduct, reporting or dissemination of this research.

Data Sharing: All data relevant to the study are included in the article or uploaded as supplementary information.

Total Word Count: including abstract and title: 7947

Combining Evidence and Practice to Optimise Neck Training aimed at Reducing Head Acceleration Events in Sport: A Systematic Review and Delphi Consensus Study

Abstract

Head acceleration events (HAEs) can potentially have adverse consequences for athlete brain health. In sports in which head injuries have the highest incidence, identifying strategies to reduce HAE frequency and magnitude is a priority. Neck training is a potential strategy to mitigate against the magnitude of HAEs. This two-part study aimed to I) systematically review the literature of neck training interventions in sport; and II) undertake an expert Delphi consensus on the best practices for neck training implementation to reduce HAEs in sport. Part I - a systematic search of four databases was undertaken from the earliest records to September 2024. The PRISMA guidelines were followed, and a quality assessment was completed using a modified Downs and Black assessment tool and the GRADE. Papers were eligible if they both i) implemented a reproducible exercise intervention targeting the neck within collision, combat or motor sport, and ii) assessed outcomes relating to either: the physical profile of the neck; head/neck injury incidence; and/or HAEs. Part II - Eighteen international experts, with experience in research and/or applied practice of neck exercise training, concussion, and/or HAEs, reviewed the part I findings before completing a three-round Delphi consensus process. Part I included 21 papers, highlighting the heterogeneity of existing interventions. Part II resulted in 57 statements coded into five categories: contextual factors (n=17), neck training periodisation (n=12), training adaptations (n=10), neck training content (n=15), and athlete adherence (n=3). This study presents recommendations for neck exercise training aiming to reduce HAEs in sport, supporting both practice and future research.

Key Messages

What is already known on this topic

- The reduction of head acceleration events in sport is a current priority due to the potential impact on athlete brain health.
- There is mixed evidence that greater neck strength may be a protective factor against concussion and head acceleration events.

What this study adds

- A comprehensive overview of all neck training interventions that have been implemented within sports where HAEs may be common was conducted.
- Studies showed variation in design, intervention, outcome assessment, and effectiveness.
- A set of 57 statements achieved consensus to help guide future research and practice.

How this study might affect research, practice or policy

- The consensus recommendations produced from this study may be used by researchers and practitioners to inform future neck training interventions for research and applied purposes.

1. Introduction

Head acceleration events (HAEs) are caused by an external force applied either directly to the head or indirectly through inertial loading of the body.[1] Head acceleration events can result in acute injury (eg, concussion),[2,3] with some developing evidence linking repeat non-concussive HAEs to possible long-term health consequences (eg, neurodegenerative disease).[4–11] Head acceleration events can occur repeatedly during combat and collision sports as well as in motor sports.[12–23] Therefore, the development of interventions to reduce the incidence and/or magnitude of HAEs is important for sport as this may mitigate the impact on athlete brain health.[3,24–27] Aspects of the neck musculature (eg, maximal strength, rate of force development [RFD]) may have a protective factor.[28–36] Improvements in neck strength and muscle function could improve trunk-neck-coupling and neck stability upon collision,[29] increasing the capacity to 'brace for impact' and potentially reducing the HAE magnitude.[37] However, current research demonstrates mixed effects of neck training interventions across sporting populations, specifically those that focus on muscle-strengthening interventions, and literature reviews are limited by small sample sizes of included studies (n≤8),[38–40] single sport cohorts,[38] inclusion of non-athletic populations,[41] focus only on sport-related concussion/injury incidence,[39,40,42] and a lack of longitudinal studies. To date, no study has systematically reviewed all scientific literature on the implementation of neck training interventions on neck characteristics (ie, the neck physical profile), head/neck injury, and/or head kinematics in sports where HAEs may frequently occur.

In practice, sport-specific resources such as the Ultimate Fighting Championship (UFC Performance Institute) "Neck Strengthening Matrix"[45] and World Rugby's "Contact Confident"[46] have been designed and implemented but their effects have not been evaluated in scientific peer-reviewed studies. Additionally, the results of peer-reviewed literature are conflicting and there is a lack of consensus on what constitutes an evidence-based neck training intervention, demonstrating a disconnect between applied practice and research. Expert knowledge of neck training interventions can be captured using a Delphi technique, which, alongside the current evidence base can inform future neck training interventions, in addition to policy and practice aimed at reducing HAE magnitudes and their potential effects. This is therefore an important research direction. Thus, this two-part study aimed to 1) systematically review the scientific literature and present an overview of all current neck training interventions with neck characteristics, head kinematics and head/neck injury surveillance outcomes in collision and combat sport, and 2) undertake a Delphi consensus on the best practices for neck training implementation from a panel of experts with the aim of reducing HAEs in sport.

2. Methods

2.1. Overview of Parts I and II

2.2. Part I: A systematic review of neck training interventions in collision and combat sport

2.2.1. Study design and research strategy

A systematic review of the literature was conducted in accordance with the updated Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[47] and guidance for implementing PRISMA in Exercise, Rehabilitation, Sport Medicine and Sports Science (PERSiST).[48] Before initiating the review process, the protocol was registered on the International Prospective Register of Systematic Reviews (PROSPERO) database (ref: CRD42023421370). A systematic review of four databases (CINHAL, PubMed, SCOPUS, and SPORTDiscus) was conducted to identify primary research. The initial search was completed on 19/06/2023, no date filter was applied. Due to the time required to complete the study, the search was repeated to identify additional papers between 01/01/2023 and 25/09/2024. Boolean operators were used to combine search terms relating to the neck, training, and sport. Keywords were combined for each term using the "OR" operator, and the final search phrase was constructed using the "AND" operator for all search concepts. Table 1 presents an example search strategy, including all search terms used. The exact search for all databases can be found in Supplementary Material 1. The neck muscles were identified as keywords and confirmed by an experienced sports medicine physician. Title and abstract searches were completed with filters for 'Human participants', 'Full text', and 'English language' selected, where appropriate. Bibliographic screening and forward citation searching (via Google Scholar) of included articles and previous systematic reviews on neck training interventions were conducted by 30 August 2023. The original systematic review protocol and any changes made can be found in Supplementary Material 1. Changes included expanding and refining the literature search (eg, populations <16 years of age were included due to the volume of papers published within youth athletes), improvements in the reporting of study results (eg, use of PERSIST[48] guidelines), accounting for the different study design.e.ie, the use of a modified Downs and Black assessment tool),[49] and providing more information regarding the quality of the evidence (ie, the addition of a Grading of Recommendations, Assessment, Development and Evaluation (GRADE)[50] assessment).

Table 1. Sample search strategy terminology

Search terms	Keywords
Neck	Cervical OR Capitis OR Colli OR Cervicis OR Platysma OR Sternocleidomastoid OR Hyoid OR Trapezius OR Levator scapulae OR Scalene* OR Splenius* OR Multifidus OR Interspinales OR Intertransversarii
Training	Training OR Strength OR Power OR Endurance OR Conditioning OR Intervention OR Rehabilitation OR Exercise* OR Stability OR Proprioception
Sport	Sport* OR Player* OR Athlete*

2.2.2. Study Selection

Duplicate records were identified and removed prior to screening the remaining studies against inclusion and exclusion criteria (Table 2).

Table 2. Study inclusion and exclusion criteria for the systematic review

Inclusion criteria	Exclusion criteria
The study included healthy participants participating in combat, collision and/or motor sports	Participants were >40 years of age
The study included an exercise intervention targeting the neck muscles	Participants had experienced a head, neck, or back injury within six months of the intervention
Study outcomes included changes in the physical profile of the neck (eg, strength) and/or changes in head kinematics or head/neck injury incidence	Participants were not from an athletic population or did not participate in a sport where HAEs may be common
The study was published in a peer-reviewed academic journal	There were not sufficient details regarding the intervention to replicate it (eg, repetition and set numbers were missing)
The study was original research	Pre- and post-testing methodologies were not described
English language, full text was available.	

HAEs = Head acceleration events

The screening process was completed independently by two researchers (MFW and LM) and involved two phases. In phase one, study abstracts and titles were screened against the eligibility criteria. Studies deemed eligible then progressed to full-text screening in phase two. Reviewers remained blind to the other's vote on individual papers until both had voted. Following the completion of the screening process, the reviewers met to discuss and resolve any conflicts for both study selection and exclusion reasoning. Where papers were excluded, the exclusion reasoning was that which occurred first in the paper. For any papers where a conflict could not be resolved, a third reviewer (KT) made the final decision. Study selection and screening were completed using the Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia).

2.2.3. Quality Assessment

A modified version of the Downs and Black checklist[49] (Supplementary Material 2), which has been validated for use to assess both randomised and non-randomised trials and demonstrates adequate psychometric properties such as internal consistency, test-retest reliability, and criterion validity, was used to assess the quality of each study. This checklist has been ranked in the top six quality assessment tools suitable for use in systematic reviews.[51] The checklist consists of 27 items that address the following methodological domains: reporting, external validity, internal validity (bias and confounding), and power. This modified version involves rating the final question '1' or '0', rather than '5', to indicate whether sample size power analyses were conducted a priori and has been used in previous reviews.[52,53] Therefore, all questions are scored '1' or '0', other than question 5, which can be scored '2'. Additionally, question 14 (*Was an attempt made to blind study subjects to the intervention they have received?*) was removed as it is not possible to blind participants to the introduction of a physical training intervention. This results in a maximum score of 27 for each study. Studies have previously been categorised as poor (≤14), fair (15-19), good (20-25), and excellent (26-28).[54] With the removal of question 14, studies were therefore categorised as poor (≤13), fair (14-18), good (19-24), and excellent (25-27). Quality assessment was completed independently by the two reviewers (MFW and LM) using Covidence. Following completion, all conflicts were resolved through a virtual meeting. Certainty of evidence for the effect of a neck training interventions on key outcomes with more than three studies were assessed using GRADE. Evidence was downgraded based on the risk of bias, inconsistency, indirectness, imprecision and risk of publication bias.[50] The GRADE was completed by two members of the primary group (MFW and OH) and differences were resolved in person.

2.2.4. Data extraction

Data extraction was completed using a standardised template designed in Covidence (Supplementary Material 3). The template included publication details, study type, participant characteristics, intervention content and methods, outcomes of interest (ie, neck characteristics, head kinematics, head/neck injury surveillance), methods of assessment, and study findings. Both reviewers (MFW and LM) completed data extraction independently. Extracted data were compared to ensure all relevant study information was extracted and then exported to Microsoft Excel (Microsoft® Excel®, Version 2202). All conflicts were resolved through an in-person meeting.

The authors of three studies with missing intervention details were asked to provide missing information via email.[55–57] Two authors provided the necessary information.[55,56] The data from these studies were extracted separately following the completion of the Delphi rounds. These studies are identified by an asterisk (*). Studies extracted following the updated search were not included in the Delphi consensus part of the study and are identified by a double asterisk (**).

2.2.5. Data Analysis

No formal data analyses took place as the systematic review aimed to inform the Delphi consensus in Part II of this study. Additionally, the data were expected to be heterogenous in nature; therefore, no summary measures, data exploration or additional quantitative analysis took place.[58,59] Data presented are alphabetical by author and describe the intervention protocols used and changes in outcome variables for individual studies. Individual intervention designs are reported including intervention duration, neck exercise direction, muscle contraction types, exercise sets and repetitions, resistance and loads used, and intervention weekly frequency. Outcome variables (eg, neck strength) and how they were assessed (eg, hand-held dynamometer) are also reported.

2.3. Part II: Consensus on guidelines for neck training interventions to reduce HAEs in sport

2.3.1. Expert Panel

The Delphi-consensus process was guided by the recommendations for the Conducting and Reporting of Delphi Studies (CREDES).[60] A minimum of 10 experts are required for reliable results, but including a greater number increases reliability.[61,62] For the purpose of this study, experts were defined as either; (1) a practitioner with a minimum of five-years' experience implementing neck training interventions within sports where HAEs or concussions are relatively common (eg, soccer, rugby, combat sports), or (2) a researcher in the area of concussion prevention, HAEs or neck training, who has at least one peer-reviewed published article. The primary research group (MFW, AS, BJ, KT, OH) invited twenty-six potential experts via purposive sampling techniques, involving the selection of knowledgeable individuals with expertise in neck training and/or HAE/concussion. Additionally, invited experts were asked to recommend other potential experts who might fit the expert criteria. A total of 30 experts were invited to form the panel and 18 completed the Delphi survey. One expert was unable to complete Round 2 but completed Round 3. The panel provided consent for the use of the data collected through the Delphi. The expert panel development process and characteristics are displayed in Figure 1.

2.3.1.1. Equity, Diversity and Inclusion Statement

Consideration was given to forming a diverse and inclusive panel representing different performance/medical applied and research roles. Emphasis was given to recruiting experts from multiple countries, especially female researchers/practitioners. The primary research group included three male and two female researchers with the lead author being an early-career, female researcher.

*** Insert Figure 1 near here ***

2.3.2. Round 1

The primary research group guided the construction of survey questions for all Delphi rounds. The surveys were constructed and distributed using Qualtrics online software (Qualtrics, Provo, USA), and Round 1 was divided into four sections. Section 1 provided a study overview and included questions regarding expert demographics. In section 2, the panel was asked to read a summary of the results from the systematic review (ie, Part I) as an overview of existing, published neck training interventions. In section 3, the panel provided important considerations for neck interventions within four overarching themes determined by the steering group (macrocycles (eg, annual), mesocycles (eg, monthly), microcycles (eg, weekly) and training sessions), as well as any information that did not fit these themes. In section 4, the panel provided considerations for contextual factors (biological age, training age, sex, sport, and any other contextual factors). Experts were given two weeks to complete this round, with email reminders sent one week and then two days before the deadline. A one-week extension was granted for experts who were recommended following the initial survey distribution and those who requested extra time.

2.3.3. Round 2

Round 1 survey answers were extracted from Qualtrics as a Microsoft Excel file. Responses were grouped by question, and inductive content analysis was performed by the primary researcher (MFW) to identify themes that were common across answers. Statements for Round 2 were constructed from the content of each response and grouped by category. Duplicate and similar responses were combined. Statements were reviewed by a second member of the steering group (OH) to ensure all information was captured in the final statements. All steering group members agreed on the final statements. The panel was asked to rank their agreement with statements on a five-point Likert scale (1=strongly disagree, 2=disagree, 3=neither agree nor disagree, 4=agree, 5=strongly agree). Consensus was defined as 70% expert agreement[58,63–69]. Statements that reached consensus for agree/strongly agree (score of 4 or 5) were said to have reached agreement consensus. Statements that reached consensus for disagree/strongly disagree (score of 1 or 2) were said to have reached disagreement consensus. Experts were given 10 days to complete Round 2 with an email reminder sent out four days before; however, more time was provided if requested.

2.3.4. Round 3

Round 2 results were extracted and summarised in Microsoft Excel before distribution through Qualtrics. Statements that met consensus were not included in Round 3. Additional comments from

Round 2 were used to modify existing statements or create additional statements, as appropriate (eg, clarify statement meaning). Modified and new statements were highlighted to the panel. Experts were asked to re-rate the statements that did not meet consensus along with new/modified statements, using the same 5-point Likert scale. Descriptive feedback was presented with median and interquartile ranges of statements previously rated to enable reflection before expressing a final opinion[58]. An additional five questions were included to collect demographic data from the panel. Experts were given 10 days to provide their final responses, with an email reminder sent four days before the deadline. The response rates in this Delphi from all contacted experts (n=30) were 63% (n=19; Round 1), 57% (n=17; Round 2), and 60% (n=18; Round 3). The expert retention rate was 95%. The surveys for all rounds of the Delphi process can be found in Supplementary Materials 4-6.

3. Results

3.1. Part I. A systematic review of neck training interventions in collision and combat sport

3.1.1. Overview

Figure 2 shows the schematic for the PRISMA search and data extraction process. In total, 19 studies were included in the initial review. Two studies were added following the repeated search.[70,71] Full study details and extracted data can be found in Supplementary Material 7. Table 3 lists the included studies.

Study designs included randomised-control trials (n=9),[72–80] non-randomised control trials (n=6),[56,81–85] pre-post trials (n=3),[55,71,86] cluster-randomised-control trials (n=1),[87] cluster-non-randomised control trials (n=1),[70] and retrospective pre-post trials (n=1).[88] The included studies represented a total of 980 participants, of which 653 (67%) were male and 327 (33%) were female. A single study accounted for 364 participants (female, n=138).[70] Data collection took place across multiple countries, including the USA (n=5),[56,72,78,80,85] Australia (n=5),[55,70,75,87,88] UK (n=4),[71,73,74,82] Canada (n=2),[84,86] Germany (n=2),[81,83] Italy (n=1),[77] New Zealand (n=1),[76] and Japan (n=1).[79] Participants were involved in multiple sports, including soccer (n=10),[56,70,75,78,80,81,83,85–87] rugby union (n=8),[55,71,73,74,76,77,82,88] judo (n=1),[79] Australian rules football (n=1),[75] and American Football (n=1).[84] A single study described participants as partaking in 'contact and collision sport'.[72] Athletes participated at school/junior (U18) (n=9),[56,70,72–74,83,85–87] university (n=5),[71,78–80,84] professional/elite, (n=4)[55,75,82,88] amateur senior (n=3),[77,81,83] academy/scholarship (n=1),[76] and semi-professional (n=1)[82] standards/levels. Eight studies included both male and female participants,[70,72,78,80,83,85–87] ten included male participants only,[55,73,74,76,77,79,81,82,84,88] and three studies included female participants only.[56,71,75] Full participant characteristics are displayed in Supplementary Material 7.

3.1.2. Study Interventions

Study interventions were heterogeneous in nature. Intervention durations varied from five to 27 weeks in length with most interventions lasting 12 weeks or less (n=15, 71%).[56,72–82,84,85,87] Of these, seven were implemented for six weeks or less.[74,76,80–82,85,87] Six studies were implemented between 14 and 27 weeks.[55,70,71,83,86,88] Sessions took place between two and three times a week for all but two studies which took place between two and four times a week[70] and progressed from daily sessions to three-to-four sessions a week.[85] Studies varied in exercise movement planes (ie, sagittal, frontal, transverse), training modalities (eg, eccentric, isometric), and exercise sets and repetitions (eg, 1x1 to 3x10). The majority of studies (n=13, 62%) used interventions including exercises in two planes[55,56,70,71,73,75,76,80,82,85–88] (eg, frontal and sagittal), four included exercises across all planes[72,74,77,83] and three studies included exercises in a single plane (eg, extension/flexion only).[78,79,81] One study implemented a single, repeated multiplanar circumduction movement[84]. Studies varied in training modality with most interventions (n=13, 62%) implementing isometric- (n=7) or isotonic-only (n=5) interventions.[55,56,71–75,78–80,82,84,88] Six studies implemented a combination of isometric and isotonic modalities[76,77,81,83,85,86] and two studies implemented a 'Quasi-isometric' intervention,[70,87] whereby the participant had to keep their head and neck still during body movement. Studies specify that the interventions were led/overseen by a strength and conditioning coach (n=6),[72,73,76,80,82,86] other club/school staff (n=4),[55,74,86,87] coach (n=3),[70,71,86] research group members (n=3),[56,71,78] physiotherapist (n=2),[70,74] and "expert operators" (n=1).[77] One study utilised web-based videos[85] and another study was self-directed by participants who were monitored for adherence by the research team.[75] Other studies (n=6) did not identify who led/oversaw the intervention.[79,81,83,84,88] Studies took place outside of the competitive season (eg, pre-season, off-season) (n=5),[73,78,82,84,87] during the competitive season (n=4),[70,76,77,83] and during both pre-season and competition (n=4).[55,71,85,88] Two studies stated that the intervention took place “over the course of one soccer season”[56] and started “at the beginning of the season preparation”.[81] A single study stated the intervention aligned with the “pre-season and/or in-season”[75]. Five studies did not specify where in the season the intervention took place.[72,74,79,80,86] Ten studies report monitoring of intervention completion,[70,73–75,77,78,84–87] adherence was encouraged by the researcher in one study[71] and reported in five studies.[73,77,84–86] A single study excluded players who were unable to complete all training sessions.[81]

3.1.3. Study Outcome Measures

All but one study[70] assessed maximal neck strength. Maximal isometric neck strength was assessed in nineteen studies[55,56,71–85,87,88] and a single study assessed the maximal possible load during concentric and eccentric neck flexion and extension.[86] Half the studies assessing neck strength (n=10) used a head harness/strap attached to a load cell/force transducer/dynamometer[55,72–74,76,81,82,85,87,88] which was fixed to a rack/wall or held by a tester to determine changes in isometric strength. Other studies used manually applied handheld-dynamometers (HHD) (n=5),[56,75,78,80,84] specific devices (eg, cervical extension machine) (n=3),[71,79,83] a custom-made ergometer (n=1),[77] and the application of external weights (n=1).[86] Fourteen studies[72–79,82,84,85,87,88] conducted maximal neck strength assessments in seated positions, four[56,80,81,86] completed testing in prone/supine positions, two[55,83] studies conducted assessments in both seated and standing positions and one study conducted the assessment in a rugby-specific prone position.[71] Four studies investigated changes in neck size.[56,72,75] Three studies assessed changes in neck girth using a measuring tape [56,72,75] and two studies assessed changes in cervical muscle cross-sectional area by scanning (ie, ultrasound, magnetic resonance imaging) (n=2).[72,79] Neck range of motion was assessed in three studies utilising a bi-axial electrogoniometer (n=1)[77] or specific cervical range of motion devices (ie, CROM basic; n=2).[74,83] Head kinematics were assessed in eight studies utilising accelerometers (n=3),[56,81,83] inertial measurement units (n=3),[80,86,87] or a video-capture marker system (eg, PEAK motus motion analysis system; n=2).[72,78] Three studies investigated changes in injury incidence using the Orchard Sport Injury and Illness Classification System (n=1),[88] by comparing team injury statistics (n=1),[55] and via a self-reported survey.[70] Neuromuscular changes (ie, fatiguability, changes in electromyography [EMG] activity, head-neck segment stiffness) were investigated in five studies using EMG sensors (n=3),[72,77,78] a neuromuscular training device (n=1),[84] a load cell (n=2),[74,78] and the PEAK motion analysis system (n=1).[78]

3.1.4.Quality Assessment

Of the 21 studies, two (10%) were rated "poor", eight (38%) "fair", 11 (52%) "good" and none were rated "excellent". The results of the quality assessment can be found in Table 3. The certainty of evidence for the effect of neck training on neck strength, head kinematics, head/neck injury incidence and neuromuscular activity is presented in the summary of findings (Table 4). The GRADE evidence profile can be found in Supplementary Material 8. Overall, there was very low certainty in the evidence for the effect of neck training interventions on neck strength, head kinematics, head/neck injury incidence or neuromuscular activity.

*** Insert Figure 2 near here **

Table 3. Quality assessment of studies using a modified Downs and Black[49] tool.

Reference	Reporting (/11)	External Validity (/3)	Internal Validity – bias (/6)	Internal Validity – confounding (/6)	Power (/1)	Total Score	Rating
Attwood et al.[73]	10	3	5	4	1	23/27	Good
Barrett et al.[74]	10	2	6	6	0	24/27	Good
Becker et al.[81]	9	1	5	0	1	16/27	Fair
Deng et al.[75]	11	1	6	5	0	23/27	Good
Eckner et al. [72]	7	1	4	1	0	13/27	Poor
Geary, Green & Delahunt[82]	8	1	5	0	0	14/27	Fair
* Gillies et al.[55]	11	2	5	1	0	19/27	Good
Hamlin et al.[76]	9	1	4	3	0	16/27	Fair
Le Flao et al.[86]	11	1	5	2	0	16/27	Fair
Maconi et al.[77]	8	1	5	3	1	18/27	Fair
Mansell et al.[78]	9	0	5	5	1	20/27	Good
Müller & Zentgraf [83]	11	1	5	3	1	19/27	Good
Naish et al. [88]	11	2	4	2	0	19/27	Good
Peek et al.[87]	11	2	6	2	1	22/27	Good
** Peek et al.[70]	10	2	5	2	1	20/27	Good

** Petrie et al.[71]	9	2	5	4	0	20/27	Good
Tsuyama et al. [79]	3	0	4	3	0	10/27	Poor
Versteegh et al. [84]	11	0	5	4	0	20/27	Good
* Wahlquist et al. [56]	8	1	4	1	0	14/27	Fair
Waring et al.[80]	7	2	5	4	0	18/27	Fair
Wilson et al. [85]	9	2	4	2	1	18/27	Fair

* Indicates study was included following contact with corresponding authors and was not presented to the expert panel; ** Indicates the study was included following the updated search, therefore was not included in Phase II.

Table 4. GRADE Summary of Findings

Outcome of interest	Studies (n)	Participants (n)	Certainty (Quality of Evidence)	Report of Adverse Effects
Neck Strength	20	609	⨁○○○ Very Low [a]	None
Head Kinematics	8	218	⨁○○○ Very Low [a]	None
Head/Neck Injury Incidence	3	430	⨁○○○ Very Low [b]	None
Neuromuscular Activity	4	83	⨁○○○ Very Low [c]	None

High quality: We are very confident that the true effect lies close to that of the estimate of the effect. Moderate quality: We are moderately confident in the effect estimate: The true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different. Low quality: Our confidence in the effect estimate is limited: The true effect may be substantially different from the estimate of the effect. Very low quality: We have very little confidence in the effect estimate: The true effect is likely to be substantially different from the estimate of effect.

[a] inconsistencies and indirectness across interventions, assessment methods and results

[b] inconsistency and imprecision in injury definitions

[c] use of exploratory analysis and proxy measurements

3.1.5. Intervention Outcomes

A synopsis of the findings from all studies included in the systematic review can be seen in Supplementary material 7.

3.1.5.1. Neck Strength

Intervention effects on increases in maximal neck strength were demonstrated in 16 of the 20 (80%) studies assessing neck strength.[55,56,71,73,75–80,82–87] Moderate to large effects of the intervention were reported for total/composite neck strength (n=3).[73,84,87] Absolute and/or relative lateral neck strength increases were demonstrated in 10 studies.[55,71,73,75,76,80,82,83,85,87] Five studies reported moderate to very large effects[71,73,82,83,87], with other studies demonstrating significant change (ie, $p<0.05$).[55,75,76,80,85] Rotational neck strength significantly increased compared to the control group[77] and with a large effect.[84] Significant p-values ($p<0.05$) and small to large effects were found for both the impact of an intervention on neck flexor strength (n=8)[55,71,77,78,82,83,85–87] and neck extensor strength (n=10).[71,73,76–79,82,83,85–87] Additionally, changes in the flexor/extensor ratio within a single study exceeded minimal detectable change in rugby forwards (n=1).[55] Functional neck strength and neck strength endurance significantly improved following a neck flexor/extensor targeted intervention with large effects in a single study.[83] Improvements in neck strength were found in soccer (n=8),[56,75,78,80,83,85–87] rugby (n=6),[55,71,73,76,77,82] judo (n=1),[79] Australian rules football (n=1),[75] and American football (n=1).[84]

Of the studies that demonstrated favourable effects of the intervention on neck strength, most interventions lasted ≥8 weeks (n=10, 63%)[55,56,71,73,75,77–79,83,86] using isometric (n=6, 38%),[55,56,71,73,75,82] isotonic (n=4, 25%),[78–80,84] quasi-isometric (n=1, 6%),[87] and mixed (n=5, 31%)[76,77,83,85,86] training modalities. Intervention exercises involved neck flexors (n=15, 94%),[55,56,71,73,75–78,80,82–87] extensors (n=16, 100%),[55,56,71,73,75–80,82–87] lateral flexors (n=12, 75%),[55,56,71,73,76,77,80,82–85,87] and rotators (n=5, 31%)[75,77,83,84,86] with four studies utilising exercises and/or isometric holds in all directions (ie, extension, flexion, left/right lateral flexion, left/right rotation).[55,77,83,84] Two of these studies implemented interventions with a neuromuscular focus,[84,87] two were performed alongside existing injury prevention programmes (ie, GetaHEAD Safely Soccer™, FIFA 11+)[56,87], three included exercises targeting other body parts (eg, trunk, core)[56,83,87] and one included a passive stretching protocol.[77]

Of the four studies that did not find significant effects of the intervention,[72,74,81,82] three lasted <8 weeks. Interventions used isometric (n=2),[74,82] isotonic (n=1)[72] and mixed (n=1)[81] training modalities across one (n=1),[81] two (n=1),[82] and three planes (n=2).[72,74] All interventions involved neck flexors and extensors, three involved lateral flexors,[72,74,82] and three involved neck rotators.[72,74,88] Training frequency of both successful and unsuccessful interventions were implemented between two and three times a week. One study progressed from daily sessions to three-to-four times a week.[85]

3.1.5.2. Head Kinematics

Head acceleration outcome data were reported in eight studies.[56,72,78,80,81,83,86,87] Significant decreases in the magnitude of peak linear head accelerations were reported in two studies,[83,86] whereby one of these studies also found a significant reduction in pitch (angular ROM in the sagittal plane). Both studies had no control group. A third, cluster-RCT demonstrated medium effects (η^2=0.08) of the intervention on reductions in peak linear and peak angular head acceleration (p=0.04)[87], exceeding the meaningful detectable change for both variables, during heading. Interventions were >14 weeks in length for two of the studies[83,86] with the third lasting five weeks.[87] All interventions included exercises involving neck flexors and extensors. One intervention included lateral flexors,[87] the second included neck rotators[86] and one intervention utilised movements across all planes targeting all muscle groups.[83] Two were mixed modality interventions[83,86] and the final was quasi-isometric.[87]

No significant changes in head kinematics were reported in four studies.[56,72,80,81] A 40% increase in head-neck acceleration during post-intervention testing in both the intervention and control group was reported in a single study.[78] Three of the studies that did not report a beneficial change in head kinematics, reported an increase in neck strength upon testing following the intervention[56,78,80]; none of these interventions included rotation exercises.

A single study investigating changes in head-neck displacement found that during forced flexion and extension, when the force-application was known, the magnitude of displacement was significantly lower[78] ($p<0.001$). However, there was no effect of the intervention.

Seven of the studies investigating changes in head kinematics involved soccer athletes[56,78,80,81,83,86,87] with the final study involving athletes from organised contact or collision sport.[72] Studies involved youth (n=5),[33,56,83,86,87] amateur (n=2),[81,83] and university, (n=2)[78,80] athletes. Four studies investigated changes in head kinematics during purposeful heading,[80,81,83,87] three investigated changes in response to an external load/perturbation[72,78,86] with the final study investigating changes in head kinematics within soccer games.[56]

3.1.5.3. Cervical ROM and Neck Size

Significant changes were found in two of three studies investigating changes in cervical ROM. One study showed a small (-1.13%) but significant reduction in ROM into right rotation in the intervention group compared to the control group.[74] The other showed significant increases in flexion, rotation and side-bending ROM.[77] Significant increases in neck muscle cross-sectional area were found in one study,[79] with no intervention effects found on neck size (ie, neck girth and/or neck muscle cross-sectional area), in four studies.[56,72,78,81]

3.1.5.4. Neuromuscular Activation and Neck Stiffness

Beneficial effects of an intervention were found on neuromuscular activation[77] ($p<0.05$) and neuromuscular device performance parameters[84] (Hedges $d\geq1.55$). One study demonstrated a knowledge x session x group interaction for male participants ($p=0.029$) for head-neck segment stiffness[78] during extension with no effect of the intervention on muscle onset latency or on muscle activity.[78] A final study found descriptive changes in muscle activation during exploratory analyses.[72] Study interventions were ≥7 weeks in length and implemented either isotonic (n=3)[72,78,84] or mixed (n=1)[77] training modalities with one implementing flexion and extension exercises alone[78] and three using movements across all planes of motion.[72,77,84]

3.1.5.5. Cervical Spine and Head Injuries

Significant reductions in cervical spine match-related injuries following the introduction of the neck training intervention were found in a single study[88] (from 11 to 2, p=0.03). The second study reported non-significant reductions in all head/neck and sport-related concussion injuries of 11-45% (incidence rate ratio (IRR): 0.55-0.89)[55] and the third reported a worthwhile effect on possible concussive events[70] (IRR: 0.38; 95% CI 0.14-0.90, $p \leq 0.05$). These interventions lasted 26,[88] 27,[55] and 16[70] weeks respectively, and were comprised of isometric exercises which targeted neck extensors, flexors, lateral flexors and rotators[55,88] and a quasi-isometric exercise.[70]

3.2. Part II. Consensus Guidelines for a Neck Training Intervention to reduce HAEs in sport

Figure 3 presents the Delphi-consensus process. Fifty-seven statements achieved consensus and were coded and categorised into five themes: "Contextual Factors" (n=17), "Neck Training Periodisation" (n=12), "Target Adaptation" (n=10), "Neck Training Content" (n=15), and "Athlete Adherence" (n=3). Seven statements achieved 100% consensus. All statements are presented in Tables 5-9. Statements that did not reach consensus are included in Supplementary Material 9.

*** Insert Figure 3 near here***

Table 5. Neck training intervention guidelines categorised under the theme of "Contextual Factors"

T5	Statement	Consensus (%)	Median	Interquartile Range
S1	Neck training to reduce HAEs should be specific to the athlete (eg, playing position, playing level, skill level, maturation, age, training age).	100	4	1
S2	Neck training to reduce HAEs should consider athlete access to coaching and equipment prior to design and implementation.	100	4	1
S3	The content and aims of neck training to reduce HAEs will be similar across sports but may differ due to various contextual factors (eg, age, sporting demands).	100*	4	0
S4	Neck training with youth athletes should follow principles for other resistance training (eg, LTAD, avoiding heavy weights, plyometrics and eccentric activities, competency based physical development framework).	94	4	1
S5	Neck training to reduce HAEs with younger or less experienced athletes should begin with unloaded exercises and a lower exercise volume with focus on technical mastery and greater time spent in individual mesocycles (eg, monthly) before progressing load and intensity.	94	4	0
S6	Neck training to reduce HAEs should be specific to the demands and training requirements of the athlete's sport.	94	5	1
S7	Youth athletes (ie, athletes <18 years of age) should include neck training to reduce head acceleration events.	89*	4	1
S8	Neck training may be beneficial in the reduction of HAEs within sport.	88	5	0
S9	Neck training to reduce HAEs should be implemented with all athletes in sports where HAEs may occur.	88	5	1
S10	Head impacts and training fatigue accumulated through other training modalities (eg, sparring, field sessions, wrestle) should be monitored to guide neck training.	88	4	1

S11	Neck training to reduce HAEs within female athletes should equally consider rotation, flexion, extension, lateral extension, and lateral flexion.	83*	4	1
S12	Neck training to reduce HAEs should only be implemented for players with a history of neck/head injury.	82†	1	1
S13	Neck training to reduce HAEs should be specific to the head acceleration mechanism of the sport (eg, force vectors, injury mechanisms, contact mechanisms [striking vs tackle; anticipated vs unanticipated]).	82	4	1
S14	Neck training to reduce HAEs should be aligned with the overall training periodisation (ie, resistance training goals).	76	4	0
S15	Neck training to reduce HAEs in younger athletes (eg, junior, scholarship, academy athletes) should initially follow isometric exercises.	72*	4	0.25
S16	Neck training to reduce HAEs within older athletes requires increased caution due to degenerative effects of age and accumulation of contact.	71	4	1
S17	Neck training to reduce HAEs should currently be implemented the same for male and female athletes (provided maturation and training age are accounted for).	71	4	2

No * indicates consensus was achieved in Round 2; * Achieved consensus in Round 3; † disagreement consensus; HAEs = head acceleration events; the median and interquartile ranges presented are the Round 3 agreement ratings for each statement.

507 **Table 6. Neck training intervention guidelines categorised into the theme of "Neck Training Periodisation"**

T6	Statement	Consensus (%)	Median	Interquartile Range
S1	Neck training to reduce HAEs should utilise regular (valid and reliable) testing and/or normative data (eg, target strength ratios) to determine changes from baseline, periodisation, and prescription.	100	5	1
S2	Neck training to reduce HAEs should follow traditional strength and conditioning principles (eg, Overload principles, Specific adaptation to imposed demand).	94	4	1
S3	Within neck training, deloading of exercise intensity and volume should occur periodically throughout the macrocycle (eg, yearly) and prior to competition/matches.	94*	4	0
S4	The duration of all mesocycles used within neck training to reduce HAEs should be determined by testing/retesting the athlete throughout the programme in conjunction with the period in the sporting calendar (eg, pre-season).	94*	4	0
S5	Neck training to reduce HAEs should be periodised across the macrocycle (eg, yearly) in line with the sport-specific calendar (eg, general preparation phase, hypertrophy phase, max strength phase, maintenance phase).	89*	4	0.25
S6	Neck training to reduce HAEs should be implemented throughout the year (ie, as an annual macrocycle).	88	4	1
S7	Neck training mesocycles (eg, monthly) to reduce HAEs should be periodised and progressive (eg, isometric to dynamic exercises, bodyweight to resisted exercises, foundational to complex movements, technique to loaded exercise).	88	4	0
S8	Sessions for neck training to reduce HAEs should be periodised through the week (eg, high, low, medium sessions)	83*	4	1
S9	Neck training to reduce HAEs should be included in pre-contact-session activation/warm-up (eg, prior to field sessions, wrestle sessions, sparring).	82	4	1

S10	Neck training should continue during in-season/competition phases for maintenance, as opposed to physical adaptation.	78*	4	1
S11	Neck training to reduce HAEs should be completed 2-3 times a week during development phases (eg, general physical preparation phases, off-season/pre-season).	76	4	1
S12	Neck training to reduce HAEs should be integrated into existing weights sessions alongside primary exercises (eg, as a superset, as a circuit at the end of the session).	71	4	1

No * indicates consensus was achieved in Round 2; * Achieved consensus in Round 3; † disagreement consensus; HAEs = head acceleration events; the median and interquartile ranges presented are the Round 3 agreement ratings for each statement.

Table 7. Neck training intervention guidelines categorised into the theme of "Target Adaptations"

T7	Statement	Consensus (%)	Median	Interquartile Range
S1	Neck training to reduce HAEs should target physiological adaptations (eg, hypertrophy, maximal strength, rate of force development) determined through baseline testing.	100*	4	1
S2	Neck training to reduce HAEs should target neuromuscular improvements.	94	5	1
S3	Neck training to reduce HAEs should target static strength, slow dynamic, fast dynamic, and reactive strength.	88	4	1
S4	Neck training to reduce HAEs should target multiple physiological adaptations throughout the macrocycle (eg, yearly) (eg, hypertrophy, maximal strength, rate of force development, endurance, neck stiffness).	76	4	1
S5	Neck training to reduce HAEs should target both superficial and deep muscles.	76	4	1
S6	Neck training to reduce HAEs should include a mesocycle (eg, monthly) targeting neck muscle maximal strength.	72*	4	0.25
S7	Neck training to reduce HAEs should include a mesocycle (eg, monthly) targeting neck muscle rate of force development.	72*	4	0.5
S8	Neck training to reduce HAEs should include a mesocycle (eg, monthly) targeting neck muscle muscular endurance.	71	4	1
S9	Neck training to reduce HAEs should target primary stabilisers.	71	4	2
S10	Neck training to reduce HAEs should aim to minimise muscle imbalances.	71	4	1

No * indicates consensus was achieved in Round 2; * Achieved consensus in Round 3; † disagreement consensus; HAEs = head acceleration events; the median and interquartile ranges presented are the Round 3 agreement ratings for each statement.

529 **Table 8. Neck training intervention guidelines categorised into the theme of "Neck Training Content"**

T8	Statement	Consensus (%)	Median	Interquartile Range
S1	Neck training to reduce HAEs should include exercises in all planes (ie, sagittal, frontal, and transverse).	94	5	1
S2	Neck training to reduce HAEs should include oscillatory movements and external perturbations/challenges to stability.	94	4	1
S3	Neck training to reduce HAEs should safely utilise a range of concentric velocities in rotation.	89*	4	0
S4	Neck training to reduce HAEs should include varied exercise positions across the week, specific to sporting demands (eg, seated, standing, four-point hold).	88	4	1
S5	Neck training to reduce HAEs should include exercises targeting neck flexion, extension, and lateral flexion.	88	5	1
S6	Neck training to reduce HAEs only requires isometric exercises.	82†	1	1
S7	Neck training with isometric exercises alone is not sufficient to reduce HAEs.	82	5	1
S8	Neck training to reduce HAEs should include individual exercises that are both dynamic and multiplanar (eg, head circumduction with flexion, extension and lateral flexion).	82	4	1
S9	Neck training to reduce HAEs only requires dynamic or isotonic exercises.	78*†	2	1.25
S10	Neck training to reduce HAEs should include exercises targeting mobility and range of motion.	78*	4	0.5
S11	Neck strength training should incorporate both lower (eg, 2/5s) and higher (eg, 15/30s) repetitions/isometric hold duration, depending on the phase of training.	78*	4	1.25
S12	Neck training to reduce HAEs should include neurocognitive approaches (eg, visual tasks, reaction time tasks, response inhibition tasks, balance tasks, coordination tasks).	76	5	1

S13	Neck training to reduce HAEs should include isometric and isotonic/dynamic exercises.	71	5	2
S14	Neck training should incorporate both lower (eg, 30% max, RPE 5) and higher (eg, 80% max, RPE 8+) efforts, depending on the phase of training.	71	4	2
S15	Loads for neck training to reduce HAEs should be prescribed from maximal voluntary isometric contraction tests.	71	4	1

No * indicates consensus was achieved in Round 2; * Achieved consensus in Round 3; † disagreement consensus; HAEs = head acceleration events; the median and interquartile ranges presented are the Round 3 agreement ratings for each statement.

Table 9. Neck training intervention guidelines categorised into the theme of Athlete Adherence

T9	Statement	Consensus (%)	Median	Interquartile Range
S1	Athletes should be educated on neck training to reduce HAEs to support buy-in and adherence.	100	5	0
S2	Neck training adherence should be monitored.	100	5	1
S3	Neck training to reduce head acceleration should encourage athlete autonomy (eg, some exercise self-selection) to support buy-in and adherence.	82	4	1

No * indicates consensus was achieved in Round 2; * Achieved consensus in Round 3; † disagreement consensus; HAEs = head acceleration events; the median and interquartile ranges presented are the Round 3 agreement ratings for each statement.

4. Discussion

This two-part systematic review and Delphi-consensus study reviewed the existing literature on neck training interventions implemented within sports where HAEs may frequently occur (ie, collision, combat and motor sport) and developed an expert-consensus on guidelines to inform future neck training interventions for the potential reduction of HAEs, and their potential injurious consequences, in sport. The systematic review identified 21 studies highlighting the heterogeneity of previous research in study design, intervention, assessment methodology and equipment, outcomes, and effectiveness. Most of the literature demonstrated an increase in assessed neck strength following the intervention in differing muscle groups (eg, neck flexors vs lateral flexors), predominantly within soccer and rugby athletes. Changes in neck strength did not always translate into alterations in head kinematics and/or neuromuscular changes. The Delphi consensus included an international group of researchers and practitioners and, producing guidelines to influence future neck training interventions aimed at reducing HAEs in sport. Expert consensus was achieved for 57 statements categorised as "Contextual Factors", "Neck Training Periodisation", "Target Adaptations", "Neck Training Content" and "Athlete Adherence". Seven statements achieved 100% consensus. These statements provide guidance for future research and practitioners when designing and implementing neck training interventions to reduce HAEs.

4.1. Neck Training Guidelines: Contextual Factors

Seventeen statements that achieved consensus were coded as 'Contextual Factors' (Table 5). Three achieved 100% consensus, including two that emphasised the importance of individualising the intervention to an athlete's contextual factors (eg, age, sporting demands, playing level) (Table 5; Statements 1&3). For example, a flexor/extensor ratio of <0.60 has been associated with a greater prevalence[89] and incidence[55] of concussion in male rugby players. Determining this at baseline testing may help individualise the programme and help avoid loads that may be a detriment to the athlete. Furthermore, individualisation of programming aligns with other statements in this category and other established training principles.[90] The third statement to reach 100% highlighted the need to consider access to coaching and equipment (Table 5; Statement 2). Of the studies included in the review, seven interventions required no equipment,[56,70,73,75,82,85,87] nine studies included equipment readily available in gyms (eg, resistance bands, dumbbells),[55,71,72,76,77,81,83,88] five required head harnesses (with/without elastic cords),[55,74,76,83,88] one used a scrum machine,[88] and three required specific (eg, a cervical extension machine) equipment.[79,80,84] Interventions that are implemented using little and readily available equipment may be more effective in applied settings than those that require additional equipment.

Experts believed neck training should be implemented across athletes in sports where HAEs may occur and may be beneficial in the reductions of HAEs (Table 5; Statements 8,9 & 12); however, one expert disagreed as they believed there was currently insufficient evidence. Current reviews investigating the relationship between assessed neck strength (ie, maximal isometric strength, peak isokinetic strength, neck muscle endurance) and head/neck injuries agree that current evidence is limited and conflicting,[29,38,40,42,91] although many of these reviews are limited by small sample sizes of studies within sporting populations ($n \leq 8$). Additionally, previous reviews on neck training interventions have primarily focused on neck strength to reduce sport-related concussion as opposed to HAEs.[29,39,40] A recent meta-analysis on four eligible prospective studies in invasion sports[29] suggested very-low certainty evidence for a small, non-significant relationship between greater neck strength and reduced rates of sport-related concussions ($r=0.008 - 0.14$). In agreement with the current study, the results showed large study heterogeneity ($I^2= >90$). Additionally, no studies in the present review were rated as ‘excellent’ following the methodological quality assessment, only half (52%) were rated as ‘good’, and the overall certainty in the evidence following the GRADE assessment was “very-low”. Further methodologically robust, high-quality studies are required to support and establish the relationship between neck strength and beneficial outcomes and the benefits of interventions targeting neck strength within multiple populations.[29,38,40,41] Importantly, none of the studies reported any adverse effects as a consequence of the neck training intervention.

Of note, experts believed that currently, male and female athletes should complete similar neck training when other factors (eg, training age) are accounted for (Table 5; Statement 17). While 10 of the studies included in the review involved solely male participants,[55,73,74,76,77,79,81,82,84,88] only three interventions were implemented in a female population.[56,71,75] Of the eight studies completed with both male and female participants, six involved youth athletes.[70,72,83,85–87] This highlights a lack of research within senior female populations. It may be that the requirements of neck training for male and female athletes will differ, however, further research is needed to determine this.

4.2. Neck Training Guidelines: Neck Training Periodisation

Twelve statements that achieved consensus were coded as 'Neck Training Periodisation' (Table 6). Regular valid and reliable neck strength testing methods to monitor the effect of a neck training intervention, achieved 100% consensus (Table 6; Statement1). Whilst this indicates that testing should aid intervention as well as evaluation, only three studies in this review completed strength testing at more than two time points.[55,75,85] A recent narrative summary by Peek (2022)[92] highlighted how different testing protocols, equipment (eg, HHD or load cells using compression vs tension evaluation) and techniques (eg, make vs break techniques; standing vs seated) result in different values, which is important given the lack of consensus on best practice neck testing techniques in real-world settings. For example, the 'break' (ie, the tester exerts enough incremental force to break the isometric contraction to induce head movement) vs 'make' (ie, the athlete is asked to complete a maximal effort against a fixed or stationary resistance) technique yields greater maximal isometric neck strength values. Only three studies in this review, specify use of the 'break' technique.[55,82,87] This is important if prescribing loads and highlights the need for consistent testing methodologies to assess change. Consistent testing protocols should be implemented, and all muscles groups should be tested under the same conditions, to allow for standardisation and aid comparisons.[92] Sport-specific testing positions may then have additional benefits[92].

A further three statements with >90% consensus aligned to an overarching theme that neck training should follow principles of traditional resistance training (eg, periodisation, progressive overload)[90,93] (Table 6; Statements 2,5&7). Fourteen[55,71,72,74,76–81,83–85,88] of the included studies involved interventions that were designed to be progressive (eg, by changes in repetitions, sets, loads used, and exercises introduced); however, none described progression between stimulus or targeted training adaptation (eg, progressing from a hypertrophy or strength focus to fast dynamic or RFD focus). Only five studies included in the review that assessed neck strength implemented interventions that lasted more than 12 weeks[55,71,83,86,88] and five were completed across both pre-season and in-season phases.[55,71,75,85,88] Of the interventions that lasted >12 weeks, all studies found a significant change in neck strength following the intervention. It could be hypothesised that longer intervention durations are more conducive to beneficial training effects. Longitudinal studies would help develop an understanding of the required neck-training dose and the longer-term outcomes of neck training interventions.

4.3. Neck Training Guidelines: Target Adaptations

Ten statements that achieved consensus were coded as "Target Adaptations" (Table 7). A single statement reached 100% consensus (Table 7; Statement 1) reiterating the importance of testing, athlete specificity, and considering multiple outcomes. Experts agreed that neuromuscular improvements should be targeted through neck training (Table 7; Statement 2). In the present study, three of the five studies that did not report a beneficial effect of the intervention on head kinematics demonstrated increases in maximal isometric strength.[56,78,80] A suggested explanation for this is that neuromuscular changes (eg, RFD), were not assessed and that interventions lacked a dynamic/stability/perturbation component.[29,38,39,42,91] However, whilst many testing devices have demonstrated reliability for measuring maximal isometric strength, many are unable to assess RFD[92] meaning that maximal isometric strength is a more accessible outcome variable to determine. This limits interpretation of the current literature as intervention effects on RFD are rarely reported.

A single-cohort study of 16 college-male athletes demonstrated significant increase in neck extensor and left-lateral flexor strength with trends towards increased neck flexor and right-lateral flexor strength. However, there was no effect on EMG activity or head kinematic data during an American football tackle.[94] This study was excluded from the review as the participants had "previous high school football" experience but the study did not specify if they were currently engaged in collision or combat sports; therefore, the effects of the intervention could not be separated from those of a normal training/playing programme. However, to the author's knowledge, this is the only study to have investigated the effects of neck training during a tackle. These results support the premise that increases in isometric strength alone may not be sufficient to impact changes in head kinematics,[56,78,85] but further research within collision-sport athletes is required.

Additionally, Mansell and colleagues (2005)[78] demonstrated a greater head-neck displacement and reduced sternocleidomastoid peak activity when force-application was unknown compared to known during forced-flexion and/or extension following an intervention. It is possible that when force is anticipated, there is a pre-activation of neck muscles allowing for the development of greater peak force over less time. Gilchrist et al.,[91] highlighted in their review the importance of short-latency strength developed before impact as key in the modification of post-impact head kinematics. Whilst they could not present consistent evidence for a protective effect of higher peak neck strength on head-neck kinematics after impact, they found an attenuating effect of short-latency isometric neck muscle tension from studies comparing anticipated and unanticipated impacts. They suggested targeting increased gains in short-latency RFD could be an important, modifiable component to target for the reduction of concussion risk. Furthermore, it highlights the need for research in collision sports where impact may be unanticipated (eg, rugby tackle) compared to anticipated contact (eg, soccer heading). Additionally, in American football, athletes with higher cervical stiffness had reduced odds of sustaining moderate (OR, 0.77; 95% CI, 0.61-0.96) and severe (OR, 0.64; 95% CI, 0.46-0.89) HAEs than athletes with lower cervical stiffness[95] and, whilst the effect on HAEs has yet to be explored, deep neck flexor endurance test time showed a clinically significant relationship with recovery from concussion ($R=0.47$; $p=0.001$).[96] This highlights that consideration should be given to multiple components of the neck musculature, not just maximal strength. Both static and dynamic strength should be targeted by a neck intervention to reduce HAEs (Table 7; Statement 3).

4.4. Neck Training Guidelines: Neck Training Content

Thirteen statements that achieved consensus were coded as “Neck Training Content” (Table 8). Two statements achieved >90% (Table 8, Statements 1&2) supporting the use of dynamic exercises targeting stability and not just maximal strength and the inclusion of exercises in all planes. Eleven studies[55,56,73,76,78–82,85,87] included in the review only utilised exercises in the frontal and/or sagittal planes, neglecting the transverse plane. Including rotational movements may be important for neck training to reduce HAEs as both linear and rotational acceleration are important components and a high magnitude of both/either may influence concussion and future brain health.[2,97] The present study supports this as the interventions that resulted in increases in neck strength without impacting head acceleration did not include cervical rotation; however further research is required to investigate this. Additionally, it has biomechanical studies have suggested that rotational acceleration may be the primary contributor of concussion and persisting symptoms associated with concussion.[2,97,98]

Two statements achieved a disagreement consensus (Table 8; Statements 6&9). These, along with a third statement that achieved agreement consensus, (Table 8; Statement 7), highlight the recommendation for a combination of isometric and isotonic exercises. Of the studies included in the review, twelve utilised either isometric or isotonic exercises individually[55,56,72–75,78–80,82,84,86,88] and one utilised quasi-isometric exercises.[87] Including mixed training modalities across a programme may allow for change in multiple components of strength as recommended in the previous statements.

4.5. Neck Training Guidelines: Athlete Adherence

Three statements that reached consensus were coded as 'Athlete Adherence' (Table 9). Two reached 100% consensus (Table 9; Statements 1&2) suggesting neck training adherence should be monitored and that athlete buy-in should be facilitated through athlete education. The final statement achieved consensus at 83% with an expert suggesting that whilst athlete autonomy is important, this should be developed once relative targets have been met. Of the studies included in the review, only five reported adherence, with a sixth excluding participants who did not complete all training. Monitoring athlete adherence is important as whilst the intervention may have been efficacious, outcome results may be biased towards the null if implementation is ineffective and athlete adherence is low.

4.6. Clinical and Prevention Implications

Reducing the magnitude and frequency of HAEs may have positive implications for athlete brain health. Improving the ability of neck musculature to produce and resist force presents a potential modifiable factor to reduce the magnitude of HAEs and their potential negative consequences as a result of repeat exposure to HAEs in sport. However, current understanding of the effects of neck training on neck properties, injury incidence, and head kinematics remains limited, partially due to the variation and limitations of the research conducted to date. The consensus statements produced in this study can guide the design of future interventions studies in research to aid understanding of the influence of neck training on neck properties, injury incidence and head kinematics. Additionally, these consensus statements can be used to guide practice in settings where neck training may be new to practitioners and athletes.

4.7. Strengths and Limitations

A limitation of this study is that no quantitative or meta-analyses were conducted due to the heterogeneity in study design, intervention content and assessment methods, making it difficult to fully ascertain the effects of neck training interventions. Furthermore, due to the time required to complete the Delphi process, the systematic review search was repeated and two studies[70,71] were added. Additionally, two studies[55,56] that required correspondence with the lead author were also included following the first round of the Delphi. Therefore, the panel were not presented with these studies during the first round. Additionally, interpretation of the current literature base may be limited by the variation in assessing maximal isometric neck strength. Comparisons between tests using different devices and following different protocols in different body positions cannot be made. Similarly, interpretations of neck training effects on head kinematics may be limited by the assessment methods. Six studies assessed changes in acceleration of the head using IMU or accelerometers attached to the skin or to the head via a band/cap which are susceptible to poor coupling with the skull, potentially leading to erroneous results.[100]

The Delphi consensus included a multidisciplinary panel who were able to offer multiple views and bridge the gap between practical and research settings. There is potential for selection bias due to purposive sampling recruitment meaning that other potential experts did not have the opportunity to contribute; additionally, by allowing experts to recommend other members for the panel, there is potential for confirmation bias due to the recommendation of others with similar views. However, this step was taken to identify experts beyond the primary research group's knowledge. Whilst the aim was to create as diverse a panel as possible, the majority of experts were from the UK and USA and members may therefore not fully represent all possible perspectives (eg, lower-income countries). However, a strength of the panel is their experience across sports and populations from grassroots to elite.

This study is the first to review the effects of all currently published neck training interventions across sports where HAEs may be common on neck characteristics, head/neck injury or head kinematics. Furthermore, to the author's knowledge, this study is the first to have developed a set of guidelines for neck strength training. The broad set of consensus statements produced allows for adaptation across multiple sports, playing levels, and ages increasing the translation into real-world practice. Should neck training have a positive effect on reducing the magnitude of HAEs sustained by an athlete, this may have a positive impact on their brain health. As neck exercise training is a growing research area, in the future, new, sport-specific statements may need to be developed considering new research and intervention publications.

4.8. Future Research

Further high-quality research is still needed to establish a clear relationship between changes in neck characteristics (eg, RFD, maximal strength) and HAEs across multiple sports as indicated by the "very-low" evidence ratings. Only eight of the included studies assessed a priori sample sizes, meaning results may have been underpowered. Future studies should aim to conduct sample size calculation a priori to prevent this. Additionally, future research should consider intervention design to ensure feasibility in practice (ie, use of little/available equipment; completed alongside normal training). All bar one study[79], which was rated as 'poor' quality, in this review presents data from collision-based team sports. This makes it challenging to generalise findings to combat sports, such as mixed martial arts, where the training periodisation and sporting demands are likely to be different. Furthermore, whilst difficult to blind participants to the introduction of a physical intervention, future interventions could look to implement a sham technique alongside the training intervention and the control in order to mitigate a placebo effect. Moreover, the presence of a control group is essential as athletes may experience increases in neck strength throughout the course of a playing season alone.[101] Currently, interventions targeting changes in head kinematics focus on external weight drops and purposeful heading in soccer. Further studies should investigate the effect of neck training on head kinematics in sport-specific situations (eg, rugby tackle and carry), across other sporting populations (eg, boxing, mixed martial arts) where HAEs frequently occur. Additionally, research in more senior amateur/professional, female cohorts and sporting populations other than rugby and soccer (eg, combat sport) is needed to help develop athlete/sport-specific interventions and understand sport-specific mechanisms of HAEs to determine the impact of neck training.

Future intervention studies should consider utilising these guidelines. Interventions of longer durations (eg, >12 weeks, a whole season or macrocycle), that are progressive in nature and target other strength components (eg, RFD), not just maximal strength, would aid future applied practice and develop current understanding of the impact of neck training interventions. This would be aided by the development of a standardised protocol to assess RFD as well as maximal isometric strength. Studies involving the assessment of head kinematics in a greater variation of sport-specific situations would help develop research within these populations, provide normative data, and aid in the individualisation and sport-specification of future neck training programmes. Whilst the link between neck training and HAEs is limited, this may in part be explained by limitations in existing research therefore further research addressing these limitations will allow researchers and practitioners to determine whether neck training can reduce HAEs and possibly link this to brain health. The statements produced in this paper can help to guide this.

4.9. Conclusion

In conclusion, this two-part systematic review and Delphi study summarises existing literature and presents guidelines for future neck training interventions. The systematic review identified 21 studies which were heterogeneous in study design and intervention content. Whilst neck training may play a mitigating role in HAEs, further intervention studies assessing multiple components of neck musculature and head kinematics in multiple sports are required. The Delphi consensus on neck training to reduce HAEs in sport included 18 international experts with applied and research experience. Fifty-seven statements, coded into five categories (ie, contextual factors, neck training periodisation, target adaptations, neck training content, and athlete adherence), achieved consensus ≥70%. These statements can act as guidelines to inform and align the future development and implementation of interventions targeting neck muscle properties to reduce HAEs in both research and applied settings. Whilst recognising the broad nature of these guidelines, they provide the first step in guiding future neck training interventions founded in clinical reasoning and traditional strength and conditioning principles that have yet to be applied in this area within research. Additionally, the broad nature of the guidelines allows for adaptation to different sports and athletes.

References

1. Arbogast KB, Caccese JB, Buckley TA, McIntosh AS, Henderson K, Stemper BD, et al. Consensus Head Acceleration Measurement Practices (CHAMP): Origins, Methods, Transparency and Disclosure. Ann Biomed Eng. 2022 Nov;50(11):1317–45.

2. Tierney G. Concussion biomechanics, head acceleration exposure and brain injury criteria in sport: a review. Sports Biomechanics. 2021 Dec 23;1–29.

3. Stemper BD, Shah AS, Harezlak J, Rowson S, Mihalik JP, Duma SM, et al. Comparison of Head Impact Exposure Between Concussed Football Athletes and Matched Controls: Evidence for a Possible Second Mechanism of Sport-Related Concussion. Ann Biomed Eng. 2019 Oct 1;47(10):2057–72.

4. Manley G, Gardner AJ, Schneider KJ, Guskiewicz KM, Bailes J, Cantu RC, et al. A systematic review of potential long-term effects of sport-related concussion. Br J Sports Med. 2017 Jun;51(12):969–77.

5. Stern RA, Riley DO, Daneshvar DH, Nowinski CJ, Cantu RC, McKee AC. Long-term Consequences of Repetitive Brain Trauma: Chronic Traumatic Encephalopathy. PM&R. 2011;3(10S2):S460–7.

6. Baugh CM, Stamm JM, Riley DO, Gavett BE, Shenton ME, Lin A, et al. Chronic traumatic encephalopathy: neurodegeneration following repetitive concussive and subconcussive brain trauma. Brain Imaging and Behavior. 2012 Jun;6(2):244–54.

7. Bailes JE, Petschauer M, Guskiewicz KM, Marano G. Management of Cervical Spine Injuries in Athletes. Journal of Athletic Training (National Athletic Trainers' Association). 2007 Jan;42(1):126–34.

8. Graham R, Rivara FP, Ford MA, Spicer CM, Youth C on SRC in, Board on Children Y, et al. Neuroscience, Biomechanics, and Risks of Concussion in the Developing Brain. In: Sports-Related Concussions in Youth: Improving the Science, Changing the Culture [Internet]. National Academies Press (US); 2014 [cited 2024 Jan 31]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK185339/

9. Ntikas M, Binkofski F, Shah NJ, Ietswaart M. Repeated Sub-Concussive Impacts and the Negative Effects of Contact Sports on Cognition and Brain Integrity. Int J Environ Res Public Health. 2022 Jun 9;19(12):7098.

10. Daneshvar DH, Nair ES, Baucom ZH, Rasch A, Abdolmohammadi B, Uretsky M, et al. Leveraging football accelerometer data to quantify associations between repetitive head impacts and chronic traumatic encephalopathy in males. Nat Commun. 2023 Jun 20;14:3470.

11. Iverson GL, Castellani RJ, Cassidy JD, Schneider GM, Schneider KJ, Echemendia RJ, et al. Examining later-in-life health risks associated with sport-related concussion and repetitive head impacts: a systematic review of case-control and cohort studies. Br J Sports Med. 2023 Jun;57(12):810–21.

12. Jacobs PL, Olvey SE, Johnson BM, Cohn KA. Physiological responses to high-speed, open-wheel racecar driving: Medicine & Science in Sports & Exercise. 2002 Dec;34(12):2085–90.

13. Tooby J, Weaving D, Al-Dawoud M, Tierney G. Quantification of Head Acceleration Events in Rugby League: An Instrumented Mouthguard and Video Analysis Pilot Study. Sensors (Basel). 2022 Jan 13;22(2):584.

14. Tooby J, Woodward J, Tucker R, Jones B, Falvey É, Salmon D, et al. Instrumented Mouthguards in Elite-Level Men's and Women's Rugby Union: The Incidence and Propensity of Head Acceleration Events in Matches. Sports Med [Internet]. 2023 Oct 31 [cited 2024 Jan 31]; Available from: https://doi.org/10.1007/s40279-023-01953-7

15. Lamond LC, Caccese JB, Buckley TA, Glutting J, Kaminski TW. Linear Acceleration in Direct Head Contact Across Impact Type, Player Position, and Playing Scenario in Collegiate Women's Soccer Players. Journal of Athletic Training. 2018 Feb;53(2):115.

16. Wilcox BJ, Machan JT, Beckwith JG, Greenwald RM, Burmeister E, Crisco JJ. Head-Impact Mechanisms in Men's and Women's Collegiate Ice Hockey. Journal of Athletic Training. 2014 Aug;49(4):514.

17. Lota KS, Malliaropoulos N, Blach W, Kamitani T, Ikumi A, Korakakis V, et al. Rotational head acceleration and traumatic brain injury in combat sports: a systematic review. British Medical Bulletin. 2022 Jan 28;141(1):33.

18. Fife GP, O'sullivan DM, Lee SY. Rotational and linear head accelerations from taekwondo kicks and punches. Journal of Sports Sciences. 2018 Jul;36(13):1461–4.

19. Le Flao E, Lenetsky S, Siegmund GP, Borotkanics R. Capturing Head Impacts in Boxing: A Video-Based Comparison of Three Wearable Sensors. Ann Biomed Eng. 2024 Feb;52(2):270–81.

20. Tierney GJ, Kuo C, Wu L, Weaving D, Camarillo D. Analysis of head acceleration events in collegiate-level American football: A combination of qualitative video analysis and in-vivo head kinematic measurement. Journal of Biomechanics. 2020 Sep;110:109969.

21. Bussey MD, Salmon D, Romanchuk J, Nanai B, Davidson P, Tucker R, et al. Head Acceleration Events in Male Community Rugby Players: An Observational Cohort Study across Four Playing Grades, from Under-13 to Senior Men. Sports Med [Internet]. 2023 Sep 7 [cited 2024 Jan 31]; Available from: https://link.springer.com/10.1007/s40279-023-01923-z

22. Basinas I, McElvenny DM, Pearce N, Gallo V, Cherrie JW. A Systematic Review of Head Impacts and Acceleration Associated with Soccer. International Journal of Environmental Research and Public Health. 2022 Jan;19(9):5488.

23. Kirk C, Childs C. Combat Sports as a Model for Measuring the Effects of Repeated Head Impacts on Autonomic Brain Function: A Brief Report of Pilot Data. Vision (Basel). 2023 May 4;7(2):39.

24. Rowson S, Duma SM. Brain Injury Prediction: Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration. Ann Biomed Eng. 2013 May 1;41(5):873–82.

25. Rowson S, Campolettano ET, Duma SM, Stemper B, Shah A, Harezlak J, et al. Accounting for Variance in Concussion Tolerance Between Individuals: Comparing Head Accelerations Between Concussed and Physically Matched Control Subjects. Annals of Biomedical Engineering. 2019 Jul 24;47(10):2048.

26. Eliason PH, Galarneau JM, Kolstad AT, Pankow MP, West SW, Bailey S, et al. Prevention strategies and modifiable risk factors for sport-related concussions and head impacts: a systematic review and meta-analysis. Br J Sports Med. 2023 Jun;57(12):749–61.

27. Patricios JS, Schneider KJ, Dvorak J, Ahmed OH, Blauwet C, Cantu RC, et al. Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport–Amsterdam, October 2022. Br J Sports Med. 2023 Jun;57(11):695–711.

28. Collins CL, Fletcher EN, Fields SK, Kluchurosky L, Rohrkemper MK, Comstock RD, et al. Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. Journal of Primary Prevention. 2014;35(5):309–19.

29. Garrett JM, Mastrorocco M, Peek K, Den Hoek DJV, Mcguckian TB. The Relationship Between Neck Strength and Sports-Related Concussion in Team Sports: A Systematic Review With Meta-analysis. Journal of Orthopaedic & Sports Physical Therapy. 2023 Oct;53(10):585–93.

30. Caccese JB, Buckley TA, Tierney RT, Arbogast KB, Rose WC, Glutting JJ, et al. Head and neck size and neck strength predict linear and rotational acceleration during purposeful soccer heading. Sports Biomechanics. 2018 Nov;17(4):462–76.

31. Peek K, Elliott JM, Orr R. Higher neck strength is associated with lower head acceleration during purposeful heading in soccer: A systematic review. J Sci Med Sport. 2020 May;23(5):453–62.

32. Versteegh T. 327 Lower dynamic neck strength is associated with history of concussion in varsity female soccer players. In: Poster Presentations [Internet]. BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine; 2021 [cited 2024 Jan 31]. p. A125.2-A125. Available from: https://bjsm.bmj.com/lookup/doi/10.1136/bjsports-2021-IOC.299

33. Eckner JT, Oh YK, Joshi MS, Richardson JK, Ashton-Miller JA. Effect of Neck Muscle Strength and Anticipatory Cervical Muscle Activation on the Kinematic Response of the Head to Impulsive Loads. American Journal of Sports Medicine. 2014 Mar;42(3):566–76.

34. Farley T, Barry E, Sylvester R, De Medici A, Wilson MG. Poor isometric neck extension strength as a risk factor for concussion in male professional Rugby Union players. British Journal of Sports Medicine [Internet]. 2022; Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85129641912&doi=10.1136%2fbjsports-2021-104414&partnerID=40&md5=4ab227ec1a3a8b935d185e33e2615984

35. Dezman ZDW, Ledet EH, Kerr HA. Neck Strength Imbalance Correlates With Increased Head Acceleration in Soccer Heading. Sports Health: A Multidisciplinary Approach. 2013 Jul;5(4):320–6.

36. Bretzin AC, Mansell JL, Tierney RT, McDevitt JK. Sex Differences in Anthropometrics and Heading Kinematics Among Division I Soccer Athletes. Sports Health: A Multidisciplinary Approach. 2017 Apr 3;9(2):168–73.

37. Le Flao E, Brughelli M, Hume PA, King D. Assessing Head/Neck Dynamic Response to Head Perturbation: A Systematic Review. Sports Med. 2018 Nov;48(11):2641–58.

38. Chavarro-Nieto C, Beaven M, Gill N, Hébert-Losier K. Neck strength in Rugby Union players: a systematic review of the literature. Phys Sportsmed. 2021 Nov;49(4):392–409.

39. Elliott J, Heron N, Versteegh T, Gilchrist IA, Webb M, Archbold P, et al. Injury Reduction Programs for Reducing the Incidence of Sport-Related Head and Neck Injuries Including Concussion: A Systematic Review. Sports Med. 2021 Nov;51(11):2373–88.

40. Daly E, Pearce AJ, Ryan L. 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 & Kinesiology. 2021 Mar;6(1):1–15.

41. Hrysomallis C. Neck Muscular Strength, Training, Performance and Sport Injury Risk: A Review. Sports Med. 2016 Aug;46(8):1111–24.

42. Garnett D, Patricios J, Cobbing S. Physical Conditioning Strategies for the Prevention of Concussion in Sport: a Scoping Review. Sports Medicine - Open [Internet]. 2021;7(1). Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85106244831&doi=10.1186%2fs40798-021-00312-y&partnerID=40&md5=ab1d32383787eab7bf97e0527e0dfca2

43. Coutts AJ. Working Fast and Working Slow: The Benefits of Embedding Research in High-Performance Sport. International Journal of Sports Physiology and Performance. 2016 Jan 1;11(1):1–2.

44. Jones B, Till K, Emmonds S, Hendricks S, Mackreth P, Darrall-Jones J, et al. Accessing off-field brains in sport; an applied research model to develop practice. Br J Sports Med. 2019 Jul;53(13):791–3.

45. Neck training to improve performance and injury outcomes [Internet]. Sportsmith. [cited 2024 Nov 6]. Available from: https://www.sportsmith.co/articles/neck-training-to-improve-performance-and-injury-outcomes/

46. World Rugby Passport - Contact Confident [Internet]. [cited 2024 Oct 23]. Available from: https://passport.world.rugby/injury-prevention-and-risk-management/tackle-ready/contact-confident/

47. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021 Mar 29;n71.

48. Ardern CL, Büttner F, Andrade R, Weir A, Ashe MC, Holden S, et al. Implementing the 27 PRISMA 2020 Statement items for systematic reviews in the sport and exercise medicine, musculoskeletal rehabilitation and sports science fields: the PERSiST (implementing Prisma in Exercise, Rehabilitation, Sport medicine and SporTs science) guidance. Br J Sports Med. 2022 Feb;56(4):175–95.

49. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Community Health. 1998 Jun;52(6):377–84.

50. Balshem H, Helfand M, Schünemann HJ, Oxman AD, Kunz R, Brozek J, et al. GRADE guidelines: 3. Rating the quality of evidence. Journal of Clinical Epidemiology. 2011 Apr 1;64(4):401–6.

51. Deeks J, Dinnes J, D'Amico R, Sowden A, Sakarovitch C, Song F, et al. Evaluating non-randomised intervention studies. Health Technol Assess [Internet]. 2003 Sep [cited 2023 Oct 10];7(27). Available from: https://www.journalslibrary.nihr.ac.uk/hta/hta7270/

52. Trac MH, McArthur E, Jandoc R, Dixon SN, Nash DM, Hackam DG, et al. Macrolide antibiotics and the risk of ventricular arrhythmia in older adults. CMAJ. 2016 Apr 19;188(7):E120–9.

53. Korakakis V, Whiteley R, Tzavara A, Malliaropoulos N. The effectiveness of extracorporeal shockwave therapy in common lower limb conditions: a systematic review including quantification of patient-rated pain reduction. Br J Sports Med. 2018 Mar;52(6):387–407.

54. Hooper P, Jutai JW, Strong G, Russell-Minda E. Age-related macular degeneration and low-vision rehabilitation: a systematic review. Canadian Journal of Ophthalmology. 2008 Apr;43(2):180–7.

55. Gillies L, McKay M, Kertanegara S, Huertas N, Nutt S, Peek K. The implementation of a neck strengthening exercise program in elite rugby union: A team case study over one season. Physical Therapy in Sport. 2022;55:248–55.

56. Wahlquist VE, Glutting JJ, Kaminski TW. Examining the influence of the Get aHEAD Safely in Soccer™ program on head impact kinematics and neck strength in female youth soccer players. Research in Sports Medicine [Internet]. 2022; Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85131047182&doi=10.1080%2f15438627.2022.2079982&partnerID=40&md5=0775ebef57b48e2e9c03c07e59332bd9

57. Liu J. Effect of strength training on neck injuries prevention in martial arts athletes. Revista Brasileira de Medicina do Esporte. 2022;28(5):523–4.

58. Heyward O, Emmonds S, Roe G, Scantlebury S, Stokes K, Jones B. Applied sport science and medicine of women's rugby codes: a systematic-scoping review and consensus on future research priorities protocol. BMJ Open Sport & Exercise Medicine. 2021 Jul 1;7(3):e001108.

59. Ryan T, Nagle S, Daly E, Pearce AJ, Ryan L. A Potential Role Exists for Nutritional Interventions in the Chronic Phase of Mild Traumatic Brain Injury, Concussion and Sports-Related Concussion: A Systematic Review. Nutrients. 2023 Aug 25;15(17):3726.

60. Jünger S, Payne SA, Brine J, Radbruch L, Brearley SG. Guidance on Conducting and REporting DElphi Studies (CREDES) in palliative care: Recommendations based on a methodological systematic review. Palliat Med. 2017 Sep 1;31(8):684–706.

61. Vergouw D, Heymans MW, de Vet HC, van der Windt DA, van der Horst HE. Prediction of persistent shoulder pain in general practice: Comparing clinical consensus from a Delphi procedure with a statistical scoring system. BMC Family Practice. 2011 Jun 30;12(1):63.

62. Delbecq A, Ven A, Gustafson D. Group Techniques for Program Planning: A Guide to Nominal Group and Delphi Processes. Glenview, Illinois: Scott Forman and Co. 1986 Jan 1;

63. Diamond IR, Grant RC, Feldman BM, Pencharz PB, Ling SC, Moore AM, et al. Defining consensus: A systematic review recommends methodologic criteria for reporting of Delphi studies. Journal of Clinical Epidemiology. 2014 Apr;67(4):401–9.

64. Van Der Horst N, Backx F, Goedhart EA, Huisstede BM. Return to play after hamstring injuries in football (soccer): a worldwide Delphi procedure regarding definition, medical criteria and decision-making. Br J Sports Med. 2017 Nov;51(22):1583–91.

65. Kleynen M, Braun SM, Bleijlevens MH, Lexis MA, Rasquin SM, Halfens J, et al. Using a Delphi Technique to Seek Consensus Regarding Definitions, Descriptions and Classification of

Terms Related to Implicit and Explicit Forms of Motor Learning. De Lussanet MHE, editor. PLoS ONE. 2014 Jun 26;9(6):e100227.

66. Verhagen AP, Boers M, Bouter LM, Knipschild PG. The Delphi List: A Criteria List for Quality Assessment of Randomized Clinical Trials for Conducting Systematic Reviews Developed by Delphi Consensus. 1998;

67. Paton BM, Court N, Giakoumis M, Head P, Kayani B, Kelly S, et al. London International Consensus and Delphi study on hamstring injuries part 1: classification. Br J Sports Med. 2023 Mar;57(5):254–65.

68. Paton BM, Read P, Van Dyk N, Wilson MG, Pollock N, Court N, et al. London International Consensus and Delphi study on hamstring injuries part 3: rehabilitation, running and return to sport. Br J Sports Med. 2023 Mar;57(5):278–91.

69. Plastow R, Kerkhoffs GMMJ, Wood D, Paton BM, Kayani B, Pollock N, et al. London International Consensus and Delphi study on hamstring injuries part 2: operative management. Br J Sports Med. 2023 Mar;57(5):266–77.

70. Peek K, Versteegh T, Veith S, Whalan M, Edwards S, McKay M, et al. Injury-Reduction Programs Containing Neuromuscular Neck Exercises and the Incidence of Soccer-Related Head and Neck Injuries. Journal of Athletic Training (Allen Press). 2023 Jun;58(6):519–27.

71. Petrie FJ, Williams EMP, Mackintosh KA, Starbuck C, McNarry MA. Assessing the feasibility of a neck-strength training intervention in university women's rugby. European Journal of Sport Science. 2024;24(4):466–73.

72. Eckner JT, Goshtasbi A, Curtis K, Kapshai A, Myyra E, Franco LM, et al. Feasibility and Effect of Cervical Resistance Training on Head Kinematics in Youth Athletes: A Pilot Study. American Journal of Physical Medicine & Rehabilitation. 2018 Apr;97(4):292–7.

73. Attwood MJ, Hudd LJW, Roberts SP, Irwin G, Stokes KA. Eight Weeks of Self-Resisted Neck Strength Training Improves Neck Strength in Age-Grade Rugby Union Players: A Pilot Randomized Controlled Trial. Sports Health: A Multidisciplinary Approach. 2022 Jul;14(4):500–7.

74. Barrett MD, McLoughlin TF, Gallagher KR, Gatherer D, Parratt MTR, Perera JR, et al. 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. 2015 May;6:137–47.

75. Deng CL, Pearce AJ, Mentiplay BF, Middleton KJ, Clarke AC. An isometric neck strengthening program does not improve neck strength in elite women's football-code athletes: A randomised controlled trial. J Sci Med Sport. 2022 Apr;25(4):327–33.

76. Hamlin MJ, Deuchrass R, Elliot CE, Raj T, Promkeaw D, Phonthee S. Effect of a 6-week exercise intervention for improved neck muscle strength in amateur male rugby union players. JSES [Internet]. 2020 [cited 2024 Jan 29];4(1). Available from: https://protect-eu.mimecast.com/s/Wgl5CYQEkcL7K98FA5fbt?domain=jses.net

77. Maconi F, Venturelli M, Limonta E, Rampichini S, Bisconti AV, Monti E, et al. 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. 2016;12(3):443–52.

78. Mansell J, Tierney RT, Sitler MR, Swanik KA, Stearne D. Resistance Training and Head-Neck Segment Dynamic Stabilization in Male and Female Collegiate Soccer Players. Journal of Athletic Training (National Athletic Trainers' Association). 2005 Oct;40(4):310–9.

79. Tsuyama K, Yamamoto Y, Nakazato K, Nakajima H. The effect of neck muscle training on the isometric cervical extension strength and cross-sectional area of the neck extensor muscles: Combined training for neck extensor muscles using a cervical extension machine-. In 2006. p. 1–5. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-33751295385&doi=10.7600%2fjspfsm.55.s1&partnerID=40&md5=286eb850734f4e6b2e34a449fac4f750

80. Waring KM, Smith ER, Austin GP, Bowman TG. Exploring the Effects of a Neck Strengthening Program on Purposeful Soccer Heading Biomechanics and Neurocognition. International Journal of Sports Physical Therapy. 2022 Nov;17(6):1043–52.

81. Becker S, Berger J, Backfisch M, Ludwig O, Kelm J, Fröhlich M. Effects of a 6-Week Strength Training of the Neck Flexors and Extensors on the Head Acceleration during Headers in Soccer. Journal of Sports Science & Medicine. 2019 Dec;18(4):729–37.

82. Geary K, Green BS, Delahunt E. Effects of neck strength training on isometric neck strength in rugby union players. Clin J Sport Med. 2014 Nov;24(6):502–8.

83. Müller C, Zentgraf K. Neck and Trunk Strength Training to Mitigate Head Acceleration in Youth Soccer Players. Journal of Strength & Conditioning Research. 2021 Dec 3;35:S81–9.

84. Versteegh TH, Dickey JP, Emery CA, Fischer LK, MacDermid JC, Walton DM. Evaluating the effects of a novel neuromuscular neck training device on multiplanar static and dynamic neck strength: a pilot study. Journal of Strength & Conditioning Research. 2020 Mar;34(3):708–16.

85. Wilson JC, Levek C, Daoud AK, Brewer M, Brooks K, Sochanska A, et al. Web-based exercise program increases cervical strength in adolescent athletes. Journal of Strength & Conditioning Research. 2021 Apr;35(4):1149–55.

86. Le Flao E, Pichardo AW, Ganpatt S, Oranchuk DJ. An Accessible, 16-Week Neck Strength Training Program Improves Head Kinematics Following Chest Perturbation in Young Soccer Athletes. Journal of Sport Rehabilitation. 2021 Nov;30(8):1158–65.

87. Peek K, Andersen J, McKay MJ, Versteegh T, Gilchrist IA, Meyer T, et al. The Effect of the FIFA 11 + with Added Neck Exercises on Maximal Isometric Neck Strength and Peak Head Impact Magnitude During Heading: A Pilot Study. Sports Med. 2022 Mar;52(3):655–68.

88. Naish R, Burnett A, Burrows S, Andrews W, Appleby B. 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 & Medicine. 2013 Sep;12(3):542–50.

89. Nutt S, McKay MJ, Gillies L, Peek K. Neck strength and concussion prevalence in football and rugby athletes. Journal of Science and Medicine in Sport. 2022 Aug;25(8):632–8.

90. Pearson D, Faigenbaum A, Conley M, Kraemer WJ. The National Strength and Conditioning Association's Basic Guidelines for the Resistance Training of Athletes. Strength and Conditioning Journal. 2000;

91. Gilchrist I, Storr M, Chapman E, Pelland L. Neck Muscle Strength Training in the Risk Management of Concussion in Contact Sports: Critical Appraisal of Application to Practice. J Athl Enhancement [Internet]. 2015 [cited 2024 Feb 6];04(02). Available from:

http://scitechnol.com/neck-muscle-strength-training-in-the-risk-management-of-concussion-in-contact-sports-critical-appraisal-of-application-to-practice-7JSo.php?article_id=3427

92. Peek K. The measurement of neck strength: A guide for sports medicine clinicians. Physical Therapy in Sport. 2022;55:282–8.

93. Kraemer WJ, Ratamess NA. Fundamentals of Resistance Training: Progression and Exercise Prescription: Medicine & Science in Sports & Exercise. 2004 Apr;36(4):674–88.

94. Lisman P, Signorile JF, Rossi GD, Asfour S, Eltoukhy M, Stambolian D, et al. Investigation of the Effects of Cervical Strength Training on Neck Strength, EMG, and Head Kinematics during a Football Tackle. 2012;

95. Schmidt JD, Guskiewicz KM, Blackburn JT, Mihalik JP, Siegmund GP, Marshall SW. The Influence of Cervical Muscle Characteristics on Head Impact Biomechanics in Football. American Journal of Sports Medicine. 2014 Sep;42(9):2056–66.

96. Baker M, Quesnele J, Baldisera T, Kenrick-Rochon S, Laurence M, Grenier S. Exploring the role of cervical spine endurance as a predictor of concussion risk and recovery following sports related concussion. Musculoskeletal Science and Practice. 2019;42:193–7.

97. Meaney DF, Smith DH. Biomechanics of Concussion. Clinics in Sports Medicine. 2011 Jan;30(1):19–31.

98. Rowson S, Bland ML, Campolettano ET, Press JN, Rowson B, Smith JA, et al. Biomechanical Perspectives on Concussion in Sport. Sports Medicine and Arthroscopy Review. 2016;24(3):100–7.

99. McKay CD, Verhagen E. 'Compliance' versus 'adherence' in sport injury prevention: why definition matters. Br J Sports Med. 2016 Apr;50(7):382–3.

100. Wu LC, Nangia V, Bui K, Hammoor B, Kurt M, Hernandez F, et al. In vivo evaluation of wearable head impact sensors. Ann Biomed Eng. 2016 Apr;44(4):1234–45.

101. Salmon DM, Sullivan SJ, Handcock P, Rehrer NJ, Niven B. Neck strength and self-reported neck dysfunction: what is the impact of a season of Rugby Union? J Sports Med Phys Fitness [Internet]. 2018 Jun [cited 2025 Feb 12];58(7–8). Available from: https://www.minervamedica.it/index2.php?show=R40Y2018N07A1078