Risk factors and effective assessment of concussion in an athletic population

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‘I, xx xxxx confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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"Appreciation is a wonderful thing. It makes what is excellent in others belong to us as well." - Voltaire

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Abstract

Background

Concussion is one of the highest burden injuries within contact sports and comes with a high health and financial cost. Inadequet evidence exists identifying intrinsic risk factors to concussion, leaving sports medicine departments with limited options to reduce injury incidence.

Common comorbidities to concussion include dysfunction of the vestibular-oculomotor system and are commonly assessed as part of sideline concussion tests. Physical exertion is known to have a delirious impact on many bodily functions but it is unclear what impact high intensity exercise, akin to sporting participation, has on the vestibular-oculomotor system.

Aims

The aims of this thesis were to investigate whether two different measure of neck function, strength and proprioception, are associated with concussion incidence in male professional rugby players

and

To investigate the impact of high intensity exercise on the vestibular-oculomotor system in a mixed gender and activity group.

Methods

Neck strength and proprioception was assessed in 390 professional players and concussion incidence and exposure data were collected to analyse associations with concussion risk through a full season.

The Vestibular-Oculomotor Screening (VOMS) tool was assessed pre and post high intensity exercise in 75 participants. Deterioration of test scores was used as a marker of declining vestibular-oculomotor function.

Results

Significant associations were found between both neck strength and proprioception, and concussion rates leading to the identification of two risk factors to concussion in male professional rugby players.

The impact of high intensity exercise on VOMS was shown to be significant in all groups including, different genders, activity levels and sports participated in.

Conclusion

The evidence surrounding the assessment of concussion and its risk factors are important lines of investigation within sports medicine research and work must continue in order to open the door to interventional studies that may eventually reduce the risk of this high impact injury.

Impact statement

The work undertaken in this thesis was designed to positively enhance clinical decision making on a global scale. The identification of risk factors for concussion within the populations investigated has provided a foundation for future research including the replication of methods to investigate different populations including professional female, elite academy, and amateur rugby players. Furthermore, these methods should be extended to other high-risk contact sports, such as boxing, taekwondo, and mixed-martial arts. The identification of modifiable risk factors linked to concussion provide a basis for interventional studies that focus on the implementation of physical conditioning strategies designed to improve neck strength and cervical proprioception, with the aim being a reduction in concussion through a prospective randomised control trial.

Clinically, the studies that have identified modifiable intrinsic risk factors for concussion will help clinicians to identify which professional male rugby players are most at risk of concussion throughout a rugby season and guide strategies to enhance neck strength and proprioception. It is worth noting that the benefit of these interventions can be exponential and therefore valuable to all athletes, regardless of their physical starting point.

The study investigating the impact of high-intensity exercise on vestibular and oculomotor function provides avenues for further research; including the impact of different types of exercise as well as how improvements in cardiovascular and vestibular-oculomotor function interact with post-exertion symptoms. Clinically, these findings should act as a warning that exertion has a negative impact on vestibular and oculomotor function regardless of gender, sport played or activity level. This is important when considering the timing of assessment as well as highlighting that athlete's with poor vestibular and oculomotor function may increase their risk of injury as their somatosensory function deteriorates further.

The three reliability studies in this thesis provide clinical confidence through the demonstration of excellent inter and intra-rater reliability for the assessment techniques used. In some cases, to the authors knowledge, this is the first time that the reliability of these assessment techniques has been investigated and therefore supports their application clinically and academically. I demonstrate that repeated assessment are reliable and accurate either between examiners or within the same examiner.

Due to the techniques and simple hand-held equipment employed for data collection within this thesis, the methods can be employed globally. Commonly available equipment were purposely used to allow replication of methods and utilisation in multiple settings, regardless of budget.

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Chapter One- Introduction and literature review

Sports-related concussion (SRC) has become one of the highest burden injuries within professional and amateur sports(1-4) accounting for significant time loss from competition(5, 6), with evidence demonstrating a high risk of musculoskeletal injuries upon return to play(6-10). Sports commonly associated with high velocity impacts have begun to quantify the injury burden of concussion with seemingly increasing incidence(1, 6). These trends may in part reflect improvements in identification over time(1, 2, 6), however also highlight a significant public health concern that must be addressed with measures to reduce incidence and improve identification and management of the injury(11, 12).

Concussion incidence

Concussion incidence is most commonly expressed as the number of injuries per unit of playing time or per frequency of athlete exposures (AEs) where an exposure equates to one player participating in one training session or match(2). More recently, an alternate method of quantifying concussion risk has been proposed which presents risk as a likelihood of the injury occurring for a given sport, in a given team, over a given time period, usually a season. Risk can then be presented as a percentage(13).

Sports most commonly associated with SRC include American football which, in the top tier of the sport between 2012/13 and 2013/14 seasons, saw 480 games played, resulting in 292 concussions. This resulted in a concussion rate of 0.61 concussions per game (95% CI, 0.54-0.68) or 6.61 concussions per 1000 AEs (95% CI, 5.85-7.37)(14). In this study defensive backs (11.76/1000) and tight ends (11.11/1000) had the highest concussion incidence rates per AE, whereas defensive linemen (3.13/1000) and fullbacks (3.13/1000) had the lowest concussion incidence rate, demonstrating a significant positional difference in concussion risk. A similar pattern can be seen within Irish Rugby Union. A study of four clubs playing within the county's top professional league during the 2016/17 season found 60 recorded concussions across 47 players, an incidence rate of 18.4/1000 player-match-hours, ranging from 17.8 in backs compared to 19.0 in forwards(5). The same study found an increase in concussion incidence as the seasons progressed, with 35.7 concussions/1000 player-

match-hours in the last month of the season(5). These results are consistent with elite level Welsh Rugby Union, with one study over a four-year period spanning the 2012/12 to 2015/16 seasons finding a concussion incidence ranging between 7.9 (95% CI 5.1 to 11.7) to 21.5 concussions/1000 player-match-hours (95% CI 16.4 to 27.6). Further analysis revealed that, after 25 games, a player was more likely than not to suffer a concussion(6). Over two seasons between 2012/13 and 2013/14, elite English Rugby Union had a concussion incidence of 8.9/1000 per player match hours (95% CI 7.7 to 10.3)(7).These results are contrasted by those in elite level amateur boxing. Over a five-year study period, an incidence of 0.53 concussions/1000 hours was recorded amongst the GB men and women's squad(15). Concussion incidence in professional boxing has been demonstrated to be higher, ranking as the second most common injury amongst professional Australian boxers and accounting for 11.7% of all injuries across an eight and a half year period(4).

The results from professional sport are contrasted by those from youth and amateur levels that demonstrate a significantly lower concussion incidence. A nine-month study across under 9-17-year old rugby players found a incidence of 1.8 concussions/1000 hours(16), though it is worth noting that in this study diagnosis was made by non-medical professionals provided with pre-season injury identification training. Further studies investigating youth rugby in England found that level of play has a significant impact on concussion rate. Over a three-year period (2012-15) elite level schoolboy rugby (mean age 17.5) had a incidence of 20 concussions/1000 hours compared to the second tier whose players suffered an incidence of 4 concussions/1000 hours(17). A different picture can be seen in men's community rugby in England. In a study spanning five seasons, an incidence of 1.46 concussions/1000 hours was recorded(18), demonstrating a mixed concussion incidence across different age groups and levels of rugby. This picture is consistent with college American football where a four-year study (2009/10-2013/14) across the NCAA league established an incidence of 3 concussions per 1000 athletic match exposures(19); significantly less than that at the elite level but, higher than the concussion incidence in high school American football at 1.04 concussions per 1000 AEs over four years between the 2013–2014 and 2017–2018 seasons(20).

The evidence for concussion incidence in high-impact women's sports is at present inadequate, with limited data existing for women's American football and only a small body of evidence looking at female rugby. Available evidence does point towards a comparable incidence with male rugby players(21, 22), although a large epidemiology study of U.S mixed student athletes observed an increased concussion risk in female athletes, noting females were 1.9 times more likely to suffer a concussion than their male counterparts(23).

Defining concussion

The term concussion has been taken from the Latin "concussus," which means "to shake violently(24). The terminology related to head injury causes confusion to patients, medical practitioners, and lay commentators alike. The terms concussion, mild mTBI, mild head injury, cerebral concussion, and post-concussion syndrome are often used interchangeably to describe the mechanism of injury, the pathological processes and the immediate and long-term symptoms of the injury(25).

It has been proposed that concussion should be 'retired' in favour of the adoption of the term mTBI(26). It is argued that the adoption of the Mayo TBI Classification System should be used in the context of concussion however even this classification falls short of encompassing all symptoms and does not define the pathophysiology, leaving one to wonder whether the term 'mTBI' offers any distinct advantage over the term 'concussion'. In order for this debate to move forward from its current impasse, groups such as the Concussion in Sport Group (CISG) who, rightly or wrongly corner the market on concussion guidance, will need to be bolder in future statement papers.

Concussion is characterised by the rapid onset of changes in neurological function that can last from minutes to weeks(27). The CISG go on to define concussion as comprising a collection of features that aid diagnosis, including a mechanism of injury 'caused by a direct blow to the head, face, neck or the body'. They go on to say that neurological impairment is rapid and short-lived and resolves spontaneously. The statement concludes that symptoms reflect a functional disturbance rather than a structural injury and can not be explained by pharmacological or alcohol use, or the presence of injury to the peripheral vestibular system or cervical spine(27).

The definition as it is set out by the CISG provides a level of insight to a lay reader that helps to increase their understanding of the injury without unduly worrying them.

Unfortunately this definition and indeed the term ‘concussion’ provides scant insight to the clinician who needs a deeper understanding of the pathophysiology of the injury in order provide effective assessment and treatment of the condition.

The CISG consensus paper is currently the go-to document for clinicians looking to gain a deeper understanding of concussion and is the resource that the majority of world and international sporting governing bodies base their own guidance and return to play protocols on(28, 29). This provides certain dangers for best practice. The vagueness in which concussion is defined in this statement serves only to minimise the injury to a self-resolving collection of symptoms that do not need to be actively addressed. Active management of concussion remains a rare approach to the injury that unlike any other sporting injury(30), a wait and watch approach followed by a graduated return to play is still common practice, even at the elite level(27). Should the CISG group more clearly define the pathophysiology of concussion in future statements this could provide clinicians with a deeper understanding of the injury, a clearer dialogue with multi-disciplinary colleagues and a stronger lean towards active management, all likely to improve outcomes(30-32).

The starting point of any concussion diagnosis, management plan or injury risk reduction programme is a thorough understanding of the pathophysiology of concussion, allowing for appropriate and targeted interventions(33). The diagnosis of concussion is a multi-pathology diagnosis involving a range of functional and microstructural changes (27, 34), for which a degree of consensus exists within the literature. Imbalance of the brain’s chemical and ionic homeostasis is believed to be one of the first functional changes to occur following a mechanical shake to the brain(31, 33). Disruption of cellular membranes results in an efflux of extra-cellular potassium through voltage-gated channels leading to neuronal depolarisation. The indiscriminate release of glutamate further proliferates this potassium release. Additionally, the binding of this glutamate to N-methyl-d-aspartate (NMDA) receptors opens sodium and calcium channels, allowing for unrestricted flow of these ions in to the cell membrane(33). This leads to intracellular accumulation of calcium and additional cellular damage and mitochondria impairment(35). This period of excitation is followed by neuronal depression and a metabolic mismatch as mitochondria attempt to increase ATP production to meet the metabolic demands of the cell(35, 36). Glycolysis is activated in an attempt to reverse the ionic imbalance leading to excess

lactate accumulation and acidosis and eventual breakdown of the blood brain barrier and cerebral oedema in extreme cases(36). The net result of these processes is an abnormally high glucose metabolism within the brain and a reduction in connectivity leading to many of the symptoms commonly seen in concussion(35, 36).

It is broadly accepted that a concussive event leads to functional dysautonomia(37), however it is not known whether this is a result of damage to an area of the brain directly responsible for autonomic control, or whether it is the result of diffuse brain injury(31). The primary autonomic nervous system is housed within the brain stem, specifically, the Medulla Oblongata. It is responsible for maintaining the function of the cardiac and pulmonary systems(31, 37) including heart rate, blood pressure, orthostatic pressure, respiratory rate, vasoconstriction and dilation(31, 38, 39). Recent studies have demonstrated that a change in the cerebral blood flow (CBF) exists following a concussion(33, 38-40). A study of concussed male university athletes in the U.S found CBF to be significantly reduced at 0-3 days and 13 days post-concussion versus age-matched controls. This was consistent with clinical symptoms of concussion. Furthermore, a trend towards a reduction in CBF beyond clinical recovery was demonstrated(40). In non-concussed individuals CBF is influenced by the pressure of arterial carbon dioxide (PaCO2), with an increase in PaCO2 leading to an increase in CBF and, conversely, a decrease in PaCO2 reducing CBF, with PaCO2 being inversely proportional to pulmonary ventilation(31, 37). Under normal circumstances, raised PaCO2 leads to a metabolic acidosis that results in a compensatory hyper-ventilation known as the ventilatory threshold. This is governed by the autonomic nervous system's CO2 sensitivity(38, 39). Studies have shown that in concussed individuals this ventilatory threshold is altered, leading to a PaCO2 level out of proportion to exercise intensity and subsequent abnormal CBF. It is thought that this failed mechanism contributes to symptoms of dizziness, headaches and exercise intolerance commonly associated with concussion(39).

Diffuse axonal injury is a common consequence of concussive injuries occurring most commonly at the grey-white matter junction, corpus collosum, thalamus and brain stem(33). Deformation of the brain causes shear stress and tension resulting in cytoskeletal disruption. In the majority of cases primary axonotomy (axonal disconnection) does not occur. Instead, the disruption of membrane ionic homeostasis

discussed above leads to secondary axonotomy(41, 42) through cytoskeletal damage and eventual Wallerian degeneration resulting in impaired signal conduction(33). Axonal degeneration leads to myelin loss as well as demyelination of intact axons, with the neuroinflammatory response furthering these processes and reducing signal conduction(42).

Local inflammatory responses, regulated by microglial infiltration of the area around the injured axons stimulate cytokine, free radical and proteases release and increase peripheral immune cell accumulation through the increased permeability of the blood-brain barrier (43, 44). In addition to the protective and restorative value of the inflammatory response it is theorised that the metabolic disturbance created may lead to more chronic neurodegenerative disease and associated neurocognitive changes(45).

The impact of concussion on cognition

The impact of concussion on cognitive function is well documented(26, 46, 47). Neuroimaging modality studies have attempted to correlate neurocognitive deficits with structural injury(47) and in doing so have demonstrated a range of micro structural and functional changes that correlate directly with diminished ability when performing cognitive tasks(48, 49). Studies looking at these parameters are not without their methodological limitations however and are based on the comparison of concussed individuals with age matched controls. Baseline cognitive function is not commonly taken and therefore while inferences can be drawn, we still await stronger levels of evidence in the area.

The pathophysiological processes discussed above are known to lead to a range of impairments most commonly associated with frontal lobe dysfunction, including slow processing, language deficits, forgetfulness and inability to concentrate(50, 51). The impact of SRC on both short and long-term cognitive changes has been demonstrated throughout the literature. In a group of 28 college-age athletes who suffered SRC, speed of information processing immediately post injury was observed to be significantly slower than age-matched controls ($p=0.005$). The same study identified group differences in information processing speed to be significantly different on day 1 post-concussion ($p= 0.003$), compared to day 2 ($P = 0.001$), day 3 ($P = 0.012$), and day 10 ($P = 0.017$), indicating a progressive recovery in this cohort (52).

Collins(53) investigated the relationship between concussion and neurocognitive performance in college American football players. Based on testing conducted 24 hours post injury, the test battery spanning verbal learning, delayed memory, visual scanning and executive functioning, attention and concentration resulted in an overall 89.5% correct classification rate when distinguishing between concussed athletes and those in the non-injured control group. In the study, 87.5% of players were correctly classified for concussions, with a 90% correct classification for the control subjects, indicating a strong link between neurocognitive performance and a current concussion. The same study observed a relationship between a history of concussion and neurocognitive test results, demonstrating a significant relationship between overall neurocognitive performance and a history of one or more concussions ($p=0.009$). Unfortunately in this study, only p-values are presented from the statistical analysis and the inclusion of confidence intervals would have provided a deeper understanding of the causal relationship between concussion history and cognition.
The theme of long-term cognitive dysfunction following concussion is present throughout the literature. In a review of computerised cognitive assessments of athletes suffering from SRC, Collie and colleagues reported that the effects of concussion have also been shown to be cumulative and that repeated exposure to head injury may therefore result in progressively deteriorating cognitive function(54). These findings are consistent with those observed by Guskiewicz(55) whose survey of 2552 retired NFL players found that former players with three or more concussions during their playing career had a fivefold greater risk of a mild cognitive impairment diagnosis after the age of 50 compared with those with no prior concussions.

Cognitive function is central to sporting performance (56, 57) and it is commonly accepted that signs and symptoms of reduced on-field performance are an integral part of making a pitch side concussion diagnosis(58). Although it is difficult to formally assess the impact of concussion on immediate post-injury performance due to the need to instantly and permanently remove concussed athletes from the field of play(27), the link between concussive injury and sporting performance upon return to play has been investigated(59-61). In a study of concussed professional ice hockey players, no significant association with pre and post-concussion performance metrics at return to play (RTP) was observed, this included points per 60 minutes, shooting

rates, scoring chances per 60 minutes, penalties taken and drawn, and save percentage(59). Using different performance metrics in the same athlete group, Van Pelt and colleagues observed no significant difference when comparing concussed player performance with those missing the same amount of playing time for reasons of musculoskeletal (MSK) injury(61). These results are again consistent with those observed in a population of NFL players(60). Comparison of pre and post-concussion performance metrics (a measure of a player's game contribution) revealed no significant difference when compared to a control group of players absent from competition for reasons other than head and neck injuries. Interestingly, the same study revealed that a significant decline in players performance metrics was observed two weeks and one week prior to their concussive event, leading to suggestions of possible involvement of the somatosensory or MSK systems. A drop in performance is often associated with central and peripheral fatigue(62), which may point towards MSK fatigue being a possible contributing factor to concussion risk with the MSK system providing less protection for the head and neck.

The impact of concussion on musculoskeletal injury

While these results suggest that concussion does not have a detrimental impact on sporting performance following a recovery period, the link between concussion history and MSK injury upon return to play is now well established(63). A number of studies have demonstrated this association with the impact linked to multiple injury sites and MSK structures(6). In a four-year prospective cohort study, Rafferty(6) observed a 38% greater MSK injury risk in professional male Rugby Union players than those who did not sustain a concussion (HR 1.38; 95% CI 1.21 to 1.56). Injury risk to individual body sites compared to players who did not suffer a concussion were quantified by hazard ratios (HR) and demonstrated an increased risk to the lower limb (leg, ankle and foot, HR 1.60; 95% CI 1.21 to 2.10), pelvic region (buttock and groin, HR 2.07; 95% CI 1.18 to 3.65), head and neck (HR 1.34; 95% CI 1.06 to 1.70) and upper limb (shoulder and arm, HR 1.59; 95% CI 1.19 to 2.12). Although the increased risk reported by Rafferty and colleagues was significant, it was lower than the 60% reported by Cross(7). In this study conducted over two seasons, professional male rugby players suffering a concussion were 1.6 (95% CI 1.4 to 1.9) times more likely to suffer a match injury of any type upon return to play than players who had not sustained a concussion. Both of these studies have collected high quality data using

the league recording systems for each respective RFU. Although reliant on injury reporting from individual clubs within their unions, this is a methodologically strong form of data collection given the centrality of the recording and the size of the populations involved.

Central to understanding the mechanism of this increased risk are the findings of this study demonstrating no association between length of injury and re-injury rate. Subsequent injury incidence was not significantly different in players who returned from concussion in 14 days or less (116.1/1000 h; 95% CI 94.5 to 144.6) compared to players with a prolonged (>14 days) recovery (152.5/1000 h; 95% CI 108.9 to 213.4; IRR 1.3 95% CI 0.9 to 2.0) suggesting that deconditioning through inactivity was not a factor.

These findings are consistent with those of other studies investigating different sporting populations and age groups. The risk of subsequent injury has been found to be 50% greater in a cohort of elite male association football players(10). In this prospective cohort study conducted over eleven seasons, concussion was associated with an increased risk of sudden onset injuries rather than those categorised as overuse injuries. Further analysis revealed that in the year preceding the concussive event, the risk of all injuries was approximately two times greater than in players that did not sustain a concussion. When considering this data more closely, only 66 out of 1599 players were concussed over 11 seasons, demonstrating low numbers of concussion relative to the sample size. Furthermore, given the length of the study, the same athletes will have been followed over a number of seasons which could add bias to the results reported. Finally, the confidence intervals presented are large and therefore these results should be viewed with greater uncertainty.

In a study of division one collegiate men's American football and women's association football, basketball and lacrosse players(8) the concussed and non-concussed players were matched by sport, position played, and starting status. Results revealed the odds of sustaining a lower extremity MSK injury were 3.39 times higher in concussed, compared to non-concussed athletes (OR = 3.39; 95% CI = 1.90, 6.05; $p < 0.01$). When adjusted for sex, the odds of sustaining a lower extremity MSK injury were 3.72 times higher in male athletes with concussion, (OR = 3.72; 95% CI = 1.84, 7.54; $p < 0.01$) whereas in female athletes, the odds of sustaining a lower extremity MSK injury were 2.75 times higher in athletes with concussion (OR = 2.75; 95% CI = 0.98, 7.69;

p = 0.05). The youngest age group to demonstrate increased MSK risk following a concussion is a study of 18216 mixed sex high school athletes (age 14-15)(9). In this prospective cohort study the odds of sustaining a time-loss lower extremity injury following a concussion increased by 34% (odds ratio [OR] 1⁄4 1.34; 95% confidence interval [CI] 1⁄4 1.13, 1.60) following a concussion. In comparison, for every previous lower limb injury, an established MSK injury risk(64, 65), the odds of sustaining a subsequent time-loss lower extremity injury increased by only 13% (OR 1⁄4 1.13; 95% CI 1⁄4 1.04, 1.23).

The results of these studies demonstrate the link between concussion incidence and MSK injury risk however, the mechanism of this increased risk has not yet been established. As discussed above, Cross(7) observed no relationship between length of time out from training and competition and subsequent injury incidence, suggesting that other mechanisms may be at play. Tremblay(66) compared 14 previously concussed athletes (mean age 23) against age-matched controls and observed a significantly delayed primary motor response in the concussed group up to one year following injury, while somatosensory processing and sensorimotor integration was unaffected. Although age matched controls were used rather than pre-season baselines, these results indicate that movement planning and execution may be slower in athletes following SRC and that a disconnect between the primary motor cortex and the MSK systems may contribute to injury(67). Evidence suggestive of this mechanism has been demonstrated in a group of 177 youth ice hockey players(68). Reed and colleagues observed that athletes who experienced a concussion achieved significantly lower maximal squat jump scores when symptoms were elevated compared to baseline (p=0.003), which continued following symptom resolution (p=0.03). The study also found that dominant hand max grip strength was significantly lower following a concussion (p=0.02), but not when symptoms had resolved. Although these are closed skill tasks, unlike the athlete's sport and methods do not account for athlete symptoms and motivation, it suggests a change in motor execution amongst concussed individuals.

Buckley and colleagues attempted to identify clinical predictors of post-concussion MSK injuries in collegiate athletes using a multifaceted battery of eight tests including measures of symptom severity, postural control, reaction time and vestibular-

oculomotor function(69). While the results of this study agreed that concussed athletes were more likely to suffer an MSK injury in the year after their concussion than the control participants (HR 1.78; 95% confidence interval (CI), 1.12-2.84; p= 0.015), post hoc testing failed to identify any individual predictors to subsequent MSK injury. The association between concussion and elevated MSK injury risk is a recent finding(10, 69) and consequently the clinical predictors of the risk are limited.

Comorbid conditions

Comorbid conditions such as cervical, oculomotor and vestibular system dysfunction are a common presentation following concussive injuries(70-72) and if unidentified, can lead to an increase in severity of symptoms and prolonged recovery(72-74). Dysfunction of these systems have been found to be present in between 55.8% and 81% of concussed patients(70, 72, 73) and may contribute a range of overlapping symptoms such as dizziness, headaches, blurred vision and nausea(73, 75), confusing the clinical picture.

The vestibular-oculomotor system includes a network of peripheral sensory organs with connections to the brain stem, cerebellum, cerebral cortex, ocular system, and postural muscles, providing information of head position for balance and visual control(73, 76). The vestibular component is made up of three semi-circular canals which detect rotational acceleration across three axis and the otolith organs, the utricle and saccule, responsible for detecting linear acceleration(77). The VIII cranial nerve projects these signals to the vestibular nuclei of the brain stem where information is processed. These are then projected onwards to control, posture, balance and eye movement(77). This output functions as two distinct units, the vestibulo-ocular (VOR) and optokinetic reflexes (OKD) and the vestibulo-spinal (VSR) and vestibulocollic reflexes (VCR), responsible for gaze stability and postural control respectively. Both the VOR and OKD are responsible for focusing the retina on a visual target. The VOR becomes functionally relevant at high head movement frequencies where the gain of the OKD is declined, and contributes considerably to retinal image stabilisation only when the visual scene is stationary, whereas the OKD focuses gaze on a moving target(78). The VSR and VCR contribute to the control of postural orientation. They continuously collaborate with reflexes elicited by stimulation of vestibular and oculomotor apparatus to provide postural responses in muscles stabilising the trunk

(VSR) and the neck (VCR), thus maintaining head position and subsequently gaze stabilisation(79)

The oculomotor system, responsible for eye movement, is comprised of two sets of six muscles that control each eye, the recti superior, inferior, medialis and lateralis and the obliqui, superior and inferior(80). These six complimentary pairs interact to provide three degrees of movement. Movement of the intra-ocular and extra-ocular muscles is controlled by the oculomotor nerve with assistance from the trochlea and abducens nerves. A key component of the oculomotor system is its opposition to stimulus from the vestibular system through the vestibulo-ocular reflex and the ability to stabilise gaze during head movement(80).

An important point of note should be raised when considering whether dysfunction of the vestibular and oculomotor systems should be considered as 'co-morbidities' or part of a diagnosis of concussion. As previously described in this chapter, concussion is defined by the CISG as an injury resulting in symptoms that 'cannot be explained by peripheral vestibular dysfunction'(27)
Disorders of the peripheral vestibular system involve the peripheral vestibular apparatus and the vestibular nerve whereas central vestibular disorders involve the vestibular nuclei, flocculus, and vermis of the cerebellum, thalamus, midbrain parietoinsular vestibular cortex, visual cortex or projections between these regions(81). Due to the highly integrative nature of the vestibular system both centrally and peripherally, injury to one location is likely to have a significant impact on the other. Further, although reflexes such as the VOR and VSR utilise the function of the peripheral vestibular apparatus, differing central tracts are employed, illustrating the likelihood of central vestibular mechanisms in SRC. This is further complicated by the coexistence of central oculomotor dysfunction with post-traumatic vestibular dysfunction, suggesting a centrally mediated vestibular impairment(82) and demonstrating how attempting to separate these systems, both centrally and peripheral may be futile.

Cervical afferents have a complex relationship with the sensory and motor nuclei of the brainstem. Within the cerebellum, cervical somatosensory information is integrated with ocular and vestibular information for adaptive postural and oculomotor

regulation(83). Cervical afferents interact with the vestibular nuclei, the superior colliculi and central cervical nuclei, concerned with coordinating gaze stabilisation and postural stability(84) allowing anticipatory ocular and postural adjustments during functional movements(85). When cervical afferents interact with the superior colliculi they produce the cervico-ocular (COR) reflex and supplement the vestibular ocular reflex, responsible for gaze stabilisation, smooth pursuit and saccadic control during scanning and tracking. They also project through the dorsal column to the thalamus and primary somatosensory cortex for perception of head and body position(83) via the cervicocollic (CCR) and cervicospinal (CSR) reflexes.

Dysfunction of the upper cervical spine (C0-3) and subsequent interruption of cervical afferents can lead to a disruption of information from muscles spindles, joint and pain receptors leading to symptoms of headache, dizziness and vertigo(86). Aberrant somatosensory information directly impacts cervical reflexes, the CCR, COR, and CSR(83). Vestibular reflexes and ocular responses may then be abnormal when altered cervical signals converge with vestibular and ocular information through a change in input to the vestibular nuclei and the superior colliculi(83).

Risk factors to concussion

Sport-related concussion is defined by the 2016 Consensus Statement on Concussion in Sport as a traumatic brain injury induced by biomechanical forces(27). Linear and rotational head accelerations are hypothesised to be the primary mechanism leading to concussion(87) although even when the head does not move, kinetic energy from the trunk can still be transferred through the skull, resulting in injury(87), with force and duration of impact known to influence the magnitude of impact(88). Although this is well accepted, there is minimal evidence to support individual injury-prevention strategies addressing intrinsic risk factors for SRC(27) despite the most recent consensus statement by the Concussion in Sport Group stating that a clear understanding of the potentially modifiable risk factors required to design, implement and evaluate appropriate injury risk reduction strategies is needed(27).

Evidence does exist either directly or indirectly to suggest that the intrinsic risk factors to SRC can be mitigated. Increasing neck muscle strength is a commonly accepted concussion risk reduction strategy(89, 90), theorised to reduce head acceleration during an impact(90). Osteoligamentous structures contribute approximately 20% of

the minimally needed mechanical stability of the cervical spine, while nearly 80% is provided by the surrounding neck muscles(91). Only one study has investigated the impact of neck strength on concussion incidence(92). 6704 female and male high school students, across three sports were assessed for neck strength using a head harness attached to a luggage weighing instrument. Data collection was conducted by a convenience sample of Athletic Trainers at participating schools in 25 states over the course of two academic years. 179 (107 girls and 72 boys) concussions were recorded, an incidence rate of 0.49 and 0.25 concussions per 1000 athletic exposures respectively. After adjusting for gender and sport overall neck strength was a significant predictor of concussion (p=0.004). Significantly this study found that for every one pound increase in neck strength, odds of concussion decreased by 5 % (OR = 0.95, 95 % CI 0.92–0.98)(92). No standardisation of methods was possible within this study due to the number and disparate nature of the clinicians measuring neck strength,

Studies investigating the impact of neck strength and stiffness on linear and rotational head acceleration associated with concussion are conflicting. In a study of 49 high school and collegiate American football players' baseline isometric neck strength, muscle size and response to cervical perturbations was compared against head impact biomechanics. Impacts were categorised in to mild, moderate and severe impacts, with no association found between reduced neck strength and the likelihood of sustaining any category of impact, other than linemen who had high lateral and composite neck strength. This group demonstrated an increased chance of experiencing moderate rather than mild head impacts. Players with larger composite muscle size had an increased chance of sustaining moderate and severe head impacts. The only positive association with neck function was those players with greater neck stiffness demonstrating a reduced chance of experiencing moderate and severe neck impacts(90). These results are consistent with those found in youth ice hockey investigating head impact telemetry (HIT)(93). In a year-long study across 37 youth ice hockey players, high pre-season isometric neck strength measures did not demonstrate a reduction in-season head accelerations during impact. The only association found was in athletes categorised as having high upper trapezius strength. These athletes were more likely to experience higher HIT compared to those with average or low upper trapezius strength. The reliability of HIT has been shown to be

variable and dependent of helmet fit with Jadischke(94) reporting error greater than 15% in more than half of the impacts recorded in a lab based study. With the recent proliferation of instrumented mouth guards, greater reliability may be attained when measuring HIT due to the superior fit of the device(95).

The results presented above conflict with a study looking at 46 mixed male and female athletes ranging from 8-30 years. Higher neck strength in all assessed ranges and increased neck stiffness resulted in a reduction of head impulse at the point of impact(96).

The conflicting results concerning mitigating factors to head accelerations are likely a symptom of mixed methods research. Lab and field-based studies have been used for these trials with different methods of neck strength and neck accelerometery assessment. What the literature does demonstrate is that the current assumptions around neck strength as a protective mechanism to concussion are potentially over estimated.

Vestibular, oculomotor and cervical functional assessment

Rehabilitation strategies for the vestibular and oculomotor systems aim to upregulate the vestibular-ocular system to strengthen their interactions, as well as their integration in the balance network(97, 98). Rehabilitation planning following a concussion relies on the ability to correctly assess sensory function and weight dysfunction proportionately to the affected reflex and tract, and thus determine the sensory strategy of an individual(99). Although the concept of sensory reweighting is widely accepted, it is difficult to measure or assess reliably using the tests that attempt to make this differentiation(100).

Much like the assessment of cervical function, the assessment of the vestibular and oculomotor system has a myriad of assessment techniques governed by time, equipment and training(76, 101, 102). The most widely used clinical test for sensory dependence is the Romberg test, initially developed in the late 19th century to assess postural sway in the feet together position in individuals with Tabes dorsalis(98). The Romberg test was later adapted to the sharpened Romberg test to include two additional test positions, semi tandem stance and tandem stance and used more broadly to assess somatosensory function(103). The test relies on the inclusion and exclusion of visual input to determine the reliance on the vestibular and somatosensory systems for balance and postural modulation(104). The Romberg test

is not quantitative and has several limitations, such as low diagnostic sensitivity and specificity(105, 106), furthermore there is no evidence of the clinical utility of the test in the assessment of concussion(98).

The Modified Balance Error Scoring System (mBESS) is another measure of somatosensory function, used as part of the SCAT 5, the standardised tool for assessing concussion(27). In a cohort of non-injured healthy military personnel, the inter-rater reliability and test-retest reliability for the mBESS has been rated as fair (ICCs of 0.61 and 0.74 respectively)(107). When used as a stand-alone test for concussion the mBESS has a diagnostic sensitivity of 14.3–20% in the first 3-5 days and 7.14–15.4% at 3 weeks post-concussion(108) indicating poor diagnostic utility.

The Sensory Organization Test (SOT) was developed to identify the relative contribution of the three main sensory systems involved in balance; vision, vestibular, proprioception(109). The SOT uses laboratory-grade equipment to assess balance performance and therefore is not available in all clinical settings(98). When comparing a group of concussed university athletes and a group of age-matched controls, SOT scores were significantly worse for all test conditions and the composite score ($p=0.02$)(101), indicating that the SOT may have diagnostic utility when investigating the presence of concussion in an athletic group, however no data currently exists for the test diagnostic sensitivity. These results are also tempered by a study investigating SOT reliability. A study of 24 healthy adults (mean age 24 years) demonstrated fair to good test-retest reliability (ICC 0.67) for the SOT composite score between two sessions with an average of 1.7±0.9 days between tests(109). The same study found a significant learning effect across six sessions, indicating that improvement in test results may be in advance of symptom resolution from SRC.

The Vestibular-Oculomotor Screening tool (VOMS) is a test battery made up of five domains designed to assess function of the vestibular and oculomotor system following a mechanism of injury consistent with concussion(76, 110). The test takes approximately five minutes to complete and requires no specialist equipment(76). The VOMS tool was initially proposed by Mucha(76) who in a study of 105 healthy adolescent participants, demonstrated high agreement in total symptom scores across VOMS domains between two trials, with near point convergence (NPC) distance

demonstrating an ICC of 0.95 (95% CI, 0.89-0.98; p= 0.001)(111). A study by Elbin(76) observed high internal consistency between VOMS domains in 63 adolescents suffering from SRC, ranging from 0.44-0.88. Elbin and colleagues also considered the diagnostic utility of VOMS, analysing change scores at 1-7 days and 8-14 days post SRC. Post-hoc univariate analyses revealed that VOMS change scores were significantly higher at 1-7 days post-injury compared to baseline for all VOMS components except smooth pursuits (p=0.75). At the 8–14-day time point, only the vertical VOR (p=0.02), and the VMS (p=0.05) components were significantly different than baseline. Building on the results of this study, Mucha and colleagues observed that all VOMS symptom scores and the NPC distance demonstrated a significant relationship with the likelihood of sustaining a concussion (p=0.01-0.001) and exhibited a close relationship to the Post Concussion Symptom Scale (PCSS)(76).

The results of these studies, while not going as far to comment on the sensitivity and specificity of the VOMS tool at diagnosing SRC, demonstrate that the VOMS tool may serve to complement the diagnosis of SRC. They also demonstrated that the VOMS tool has good test-retest reliability and comment on the test's accessibility in all rehabilitation settings due to the lack of specialist equipment.

Assessing function of the cervical spine is of paramount importance when establishing the root cause of concussion-type symptoms. Provocation of a patient's symptoms during testing can help to direct exercise interventions that aid resolution of symptoms and addressing deficits in function may help target future injury risk reduction strategies. Field-based assessments allow practitioners without lab access to conduct these assessments using time and cost-efficient methods. Evidence for field-based assessment of the cervical spine in relation to concussion is limited and often extrapolated from research in related fields such as neck pain(112, 113).

Within the literature, methods of cervical strength assessment vary greatly between studies with no consensus on ranges of motion assessed, body position, equipment and the source of resistance to the participants test force(92, 114-116). Fixed frame lab-based dynamometry is widely considered to be the gold standard for muscle strength assessment(117) but is highly reliant on specialist equipment and training, not accessible within all rehabilitation settings. In order to provide consistency in

methods, researchers have attempted to custom make apparatus designed to standardise the resistance provided from a HHD and have demonstrated high levels of consistency in one range of neck strength(115). Limitations still exist in this method, including the fabrication of the apparatus used to house the HHD. Strain gauges have been proposed in the assessment of neck strength(92, 118). The use of strain gauges has included utilisation of luggage scales to record force(92) as well as the development of specialist hardware and software(118, 119). Excellent correlation between HHD and luggage scale strain gauge measurements has been observed, with ICC ranging from 0.83 to 0.94 for the four neck strength measurements of flexion, extension and right and left side flexion(92). The same study observed high inter-tester reliability with strong correlation (ICC's >0.80), indicating this low-cost alternative to be a valid method of neck strength assessment. The methods employed in this study were not without limitation. Although five clinicians with a range of experience were included as raters, only one measure of the strain gauge and HDD was taken by each rater and raters were not blinded to their results, increasing the risk for bias.

This said, similar results have been observed in a professional male rugby playing population. Assessment of the intra-rater reliability of the specialist strain gauge ICC values ranged from 0.80-0.90 (95% CI, 0.64-0.94) across all ranges, thus indicating excellent reliability between raters(114). There is however no investigation of consistency against another measure in this study or, crucially, inter-rater reliability which may vary due to an assessor's individual ability to resist force. Versteegh(73) proposed a novel method of self-resisted handheld dynamometry designed to enhance intra and inter-session reliability by removing the potential inconsistency of different raters. Assessing strength to flexion, extension, bilateral side flexion, bilateral rotation, and bilateral side flexion with rotation, this method of neck strength assessment was shown to have an intra-test ICC of between 0.94 and 0.97 across all ranges between trial one and trial two. The inter-test reliability remained good to excellent, between 0.87 and 0.95(120).

The available evidence demonstrates that the assessment of neck strength is a procedure with a lack of standardisation relating to equipment, body position and method of rater force application and is often governed by the equipment available. The literature to date also demonstrates a lack of rigour in analysing reliability including intra and inter-rater reliability, and between sessions. Methods proposed by Versteegh and colleagues(120) provide good to excellent ICC values for within

session and between session reliability. Furthermore, this method has removed the variability provided by an assessor due to the participants self-resisting their neck force. This has important implications when assessing a large group where assessor fatigue may become a factor in the ability to reduce neck force.

Cervical proprioceptors serve to provide afferent feedback from the muscles, ligaments, joints, tendons, and associated mechanoreceptors to the central nervous system about cervical position and movement and activate subsequent and appropriate spinal reflexes that have protective mechanisms for the neck(121, 122). Cervical joint re-positioning error is one marker of this function and has previously been shown to demonstrate greater error in athletes involved in contact sports(121, 123). The Cervical Joint Position Error Test (JPET) was first described by Revel, when examining the difference in cervical proprioception in patients with and without neck pain(124) and has been used extensively in the literature since, demonstrating variability in repositioning accuracy by sport(121) and by injury(124-128). The literature describes varied techniques and equipment with head mounted laser pointers(127, 129), digital inclinometers(122), video capture(130) and computer assisted systems (125) being employed. Studies have found ICC to range from 0.81 for global error, 0.80 for horizontal components and an ICC value of 0.52 for the vertical(129) with reliability considered to be high. Conversely, ICC for the JPET has also been demonstrated between 0.27 and 0.58(131). These results are likely a reflection of mixed methods employed to undertake the JPET. The most reliable of these approaches was investigated by Pinsault(129) who using the methods first described by Revel(124), found some of the highest ICC's within the literature.
Within a clinical setting and significantly a sporting setting where large volumes of assessment may be undertaken, time and cost is an important consideration and will invariably influence methods chosen.

Another component of cervical proprioception described in the literature is the neuromuscular activation and endurance of the longus capitis and longus colli muscles, often described as the Deep Neck Flexors (DNF)(132). These muscles serve to create stability in the upper cervical spine through a feedforward loop that stabilises the upper cervical spine prior to movement(133). There is currently no known association between the DNF and concussion, however the links between cervical

posture and force attenuation are well documented(134). The cranio-cervical flexion test (CCFT) is a reliable test of DNF function with EMG studies demonstrating strong construct validity between the execution of the CCFT and DNF muscle activation(135). Inter and intra reliability for the test has be shown to be high with an ICC of 0.98 and 0.86 respectively(131, 136).

The functional link between strength and proprioception of the neck

Muscle strength is a critical factor impacting on human performance, allowing athletes to overcome external load applied to the body and create movement(137). Proprioception is the sense of position and movement of the body in space and the sense of tension, effort, and balance(138). The nervous system receives information from proprioceptors located in muscles, tendons joints, and the skin, which transmit afferent information to be integrated in the central nervous system to create an output of muscle contraction(139).

Strength and proprioception are two key indices to athletic performance(137) and the link between these two qualities in relation to concussion has been discussed as having the potential to act as a mitigating factor to injury(92, 140, 141). Using video reconstructions of head impacts in professional American football players, Viano(142) demonstrated that neck muscles with greater tensile stiffness reduce translational head displacement, velocity, and acceleration with stiffness of striated muscle linearly proportional to its activation level, or proprioception, and its isometric strength(96). Furthermore, it has been demonstrated that poor proprioception is associated with an inability to gauge the appropriate force of required muscle contraction(139). In attempting to control and reduce external forces during competitive sport, it may be that athletes rely on cervical proprioception and strength in different measures, adopting motor recruitment strategies for task execution dependent on the physical qualities of their muscles and joints and according to their physical strengths(143, 144).

Studies investigating the relationship between strength and proprioception have observed positive correlations between the two physical qualities including a study by Wang(145). In this study of 24 un-injured female college students, Wang and colleagues observe a significant positive correlation between quadricep strength and knee proprioception ($p=0.01$). The positive correlation in this study is contrary to

results observed by Lee and colleagues(146) who investigated whether proprioception, muscle strength, and knee laxity are correlated with dynamic standing balance in 12 athletes (10 male, 2 female, mean age 23.1 years) with anterior cruciate ligament (ACL) deficiency. Results revealed no correlation between quadricep strength and proprioception in the injured or non-injured limb. It is possible that these findings are a symptom of ACL injury and associated sensory reorganisation or a difference in stability strategy between a predominantly male group and the female cohort studied by Wang and colleagues. This considered, a positive association between strength and proprioception has been observed in a group of un-injured male participants (mean age 20.8 years). Salles found a significant improvement ($p=0.01$) in shoulder joint repositioning error following an eight week upper limb resistance training programme(137) indicating that there may be a linear relationship between the two physical qualities.

Understanding an athlete's control strategy may help to optimise concussion risk reduction programmes with more targeted intervention. To the author's knowledge there are no studies to date that directly compare the relationship between cervical proprioception and strength at single or multiple time points, however it is common for these qualities to be studied as part of the same test battery when investigating injury risk reduction strategies for the head and neck(112, 141, 147).

The available literature concerning concussion and the physical qualities that may help to inform our diagnosis and identify high risk athletes provides a mixed picture, due to a lack of homogeneity in methods and outcomes and small participant numbers.

In the first two experimental chapters, this thesis aims to explore the correlation between concussion and two components of neck function; strength and proprioception. The studies will focus on investigating the link in a professional rugby playing cohort using methods that have been shown to be both reliable and accessible to the field.

The third study aims to establish the impact of high intensity exercise on vestibular and oculomotor function using the VOMS test. This study will go further than previously published studies investigating this topic by employing larger study numbers, standardising the time between exercise and testing, employing multiple test rounds

and drawing a comparison between different groups including sex, activity level and sport played.

The inclusion of studies 1-2 and 3 as part of the narrative of this thesis is important to our understanding of the global view concerning concussion risk. The link between the cervical spine and the vestibular and oculomotor systems is well established, as previously highlighted in this chapter(83-85). Understanding the impact of exertion on the provocation of symptoms commonly associated with concussion helps us better diagnose concussive injuries and associated risk factors.
At the current time insufficient evidence exists around the reliability for vestibular and oculomotor testing, and prior to establishing whether this function is associated with concussion injury rate, a strong base of evidence should exist for the reliability of its testing in a clinical setting. Future research should look to investigate the association between vestibular/oculomotor function and concussion, but only when appropriate testing parameters are defined.

Chapter Two- General Methods

Introduction

This chapter describes the materials and methods used frequently in each experimental study. Specific or modified methods are described within the methods section of each study chapter.

Ethical approval

Prior to ethics application submission all studies were registered on the UCL Research Ethics committee home page under the 'New project' tab. A 'New research registration form' was then submitted under the Data Protection Act, 1998 with UCL as the data controller. A data protection number was attained for each study.

Ethical approval was gained from the University College London research ethics committee prior to commencement of recruitment for each study in order to ensure that the research conformed with general ethical principles and standards. A 'Low risk' ethical application was submitted for all studies and granted by the Committee.

Please see appendix B for Notification of Ethics Approvals.

Medical history

Participant medical history was recorded via a health screening questionnaire (appendix C9) and reviewed to ensure that there was no medical reason that they could not participate in the study.

Anthropometry

Height

Height was recorded prior to testing using a mobile SECA® Leicester, Height Measure. Participants were asked to stand barefoot in the anatomical position with their back to the recording device. The SECA® arm was lowered to rest horizontally at the highest point of the participant's head. Height was recorded in centimetres to the nearest 0.1cm.

Weight

Participants weight was recorded prior to testing using SECA® 875 Class III digital flat scales for mobile use. Weight was recorded in kilograms with participants wearing sports kit and socks only.

Chapter Three- Reliability studies

Introduction

This chapter will describe the inter or intra-rater reliability of the three main methods of data collection employed as part of this thesis.

Reliability Study One - Reliability testing for neck strength assessment- inter-rater reliability

Introduction

Muscle weakness is a common finding in the assessment of joint function and biomechanics and is known to be a consistent factor leading to injury(148-150). Poor muscle function has been shown to impact joint loading and muscle activity patterns (151) as well as increase the risk of headaches(113), muscle(152), tendon(153) and fascial(154) injuries, increasing joint degradation and pain(155). A paucity of neck strength assessment protocols exist within the literature(156) with a greater focus on range of motion, proprioception and deep neck flexor activation(132, 157, 158). Within sport much of the focus around neck strength assessment concerns the risk reduction of high force injuries to the cervical spine, commonly associated with rugby(118, 119), ice hockey, wrestling(134, 159) and American football(134). The methods used in the assessment of neck strength in these studies are varied and show little consistency in approach. Proposed methods of neck strength assessment have to date included both isometric(92, 113, 118, 119) and isokinetic(160) assessment and utilised a range of techniques and equipment including both seated(92, 134, 160) and functional positions(113), hand held dynamometers (HHD)(92, 113), strain gauges(92, 119) and fixed frame seated dynamometry(134, 160).

Muscular strength is the magnitude of the torque exerted by a muscle or muscles in a single maximal contraction of unrestricted duration(161). The reference assessment of muscle strength, or peak force, involves fixed laboratory-based dynamometry that is expensive and time consuming and frequently requires regular training to successfully operate(117, 162). This form of neck strength assessment has been investigated for reliability and demonstrates moderate to excellent intra-rater reliability

and excellent inter-rater reliability(161). Digital handheld dynamometry is a convenient and cost-effective method of measuring the strength of a given muscle (117). The reliability of HHD has been investigated across different joints and pathologies and has been shown to be a time-effective and reliable method of measuring muscle strength (117, 162, 163). Mentiplay(162) observed good to excellent intra-rater reliability measures for peak force in seven out of eight peripheral joint ranges and good to excellent inter-rater reliability in six out of eight ranges in a group of non-injured participants, using a tester resisted technique. The group also observed good to excellent reliability between two of the most common HHD brands on the market, the Lafayette Manual Muscle Testing System Model-01165 (Lafayette Instrument Company, Lafayette IN, USA), used in this study, and a Hoggan micro*FET*2 (Hoggan Scientific, LLC, Salt Lake City UT, USA).

When investigating neck strength, HHD testing has been conducted in both lying and seated positions(115, 120, 164). While studies assessing HHD reliability in lying have demonstrated excellent intra-rater and substantial to excellent inter-rater reliability(115, 164) they involve a longer set up time and specialist equipment. It could also be argued that measuring strength using these methods is not representative of functional positions.

One of the challenges of assessing muscle strength using tester resisted hand-held dynamometry is that the strength of the tester may influence results, compromising reliability(120). If the tester is weaker than the athlete being tested results will only be as high as the force generated by the tester. This may also be limited by accumulative tester fatigue when assessing large numbers, further decreasing the reliability of the results. These factors add weight to the use of a participant-resisted isometric testing method described by Versteegh(120). To date this is the only study investigating the reliability of HHD in a seated position that requires no additional equipment. Excellent intra and inter-session reliability was recorded, however inter-rater reliability was not assessed as it was decided to be unnecessary due to the participant resisted methods used(120). This does not though, account for different instructions potentially given by raters.

The use of isometric strength testing is the most common method of assessment used within the literature(113, 118-120), however limited discussion exists as to why this

type of muscle contraction is employed. A systematic review by Hrysomallis(89) found limited evidence that greater isometric strength or dynamic training was associated with better head stabilisation during low-level force application, however an association between neck isometric training and injury risk was observed. The study also concluded that isometric training reduced match-related cervical spine injuries and that greater overall isometric neck strength reduced concussion risk.
This reliability study will examine the inter-rater reliability of two testers using the participant-resisted isometric HHD technique described by Versteegh(120).

Methods

Participants

Participants were recruited from a professional men's rugby team who had previously volunteered to participate in the study through an approach made by their clubs Chief Medical Officer (CMO). Participants were eligible for the trial if they were healthy, non-injured professional male rugby players between the ages of 18 and 35 competing in the Georgian Didi 10 league. Participants were excluded if they had a current concussion, neck or shoulder pain or any other medical condition that precluded them from participating in physical activity or resistance training. Fifteen participants were included in the reliability arm of the study. Participant characteristics are presented in table 2.

Procedure

Upon arrival at the test site, participants were asked to read and sign the participants consent form if they had not brought the completed form with them to testing. Participants then had their height and weight recorded as described in general methods and were taken through a data collection form to record age, position, number of years as a professional player, the level of international competition that they have played at (under 18's, under 20's, full international) and number of previous concussions. They were also asked to complete the health screening form to ensure that there was no known medical reason that they were unable to undertake testing.

Participants were then taken through the testing procedure as described in page 64 by one of the two examiners. The order by which they were tested (examiner one or

two) was randomly allocated through asking each participant to pick a concealed number out of a bowl that related to one of the two examiners.

All participants were tested seated on a treatment bed with their feet firmly planted on the ground in front of a ceiling to wall mirror. They were then taken through a warmup round to each neck range (flexion, extension, right flexion, left flexion, right rotation, left rotation) at 50% of their perceived maximal contraction. Following the warmup, participants were asked to provide three sets of maximal efforts to each range. There was a mandatory one-minute rest between each set. Participants were then invited to take a ten-minute break and move to the second examiner who instructed the participants through the warmup round, followed by three rounds of maximal efforts in an identical test environment. Each examiner was blinded to the scores of the previous round of testing.

Statistical methods

Data were recorded in kilograms of force (kg/f) and analysed using Stata Version 14 (StataCorp,Texas). Inter-rater reliability was measured using the intraclass correlation coefficient (ICC) with 95% confidence intervals (CI). This compares the variability of ratings of the same individual to the total variation of ratings for all individuals. I assumed that individuals and raters are sampled from a larger population (two-way random effects). The results can therefore be generalised to any raters, not just the two who made the measurements. Measurements are averaged over the three trials. The ICC measures the absolute agreement between the raters. Koo and Li(165) suggested the following parameters for interpreting ICC (table 1).

In addition, I calculated the standard error of measurement (SEM) and minimal detectable change (MDC). SEM is calculated using the standard deviation and the reliability coefficient (ICC). With two raters the SEM can also be calculated by dividing the SD for the difference between the two raters by $\sqrt{2}$. where 1.96 corresponds to the level of confidence adopted (in this case, 95%) and $\sqrt{2}$ represents a correction factor for repeated measurements.

Table 1 Koo and Li parameters for interpreting ICC

ICC score	Rating
< 0.50	Poor
0.50-0.75	Moderate
0.75-0.90	Good
> 0.90	Excellent

Results

Participant characteristics

Participant demographics are presented in table 2. There were no significant differences in participant characteristics between those that participated in the reliability arm of this study and the wider group.

Table 2 Participant characteristics

Variable	Study one N=209	Reliability study N=15	P value
Age, mean (SD)	22.9 (4.0)	21.7 (4.1)	0.24
Height, mean (SD)	181.9 (9.67)	183.3 (5.2)	0.57
Weight, mean (SD)	96.6 (15.2)	98.2 (10.7)	0.69
BMI, mean (SD)	29.7 (10.5)	29.2 (3.0)	0.87

Inter-rater reliability

Measurements are averaged over the three trials. The overall agreement was moderate to excellent for all ranges of neck strength measures between two raters (0.705-0.985). Results for individual ranges are presented in table 3.

Table 3 Intra-class correlation coefficient (95% CI) for inter-rater reliability

	ICC (95% CI)			
Range	**Average**	**Trial 1**	**Trial 2**	**Trial 3**
Right rotation	0.972 (0.920-0.991)	0.896 (0.719-0.964)	0.965 (0.899-0.988)	0.890 (0.704-0.962)
Left rotation	0.985 (0.955-0.995)	0.945 (0.845-0.981)	0.945 (0.844-0.981)	0.922 (0.784-0.973)
Extension	0.978 (0.936-0.993)	0.923 (0.786-0.973)	0.888 (0.700-0.961)	0.928 (0.800-0.975)
Flexion	0.869 (0.654-0.954)	0.849 (0.609-0.947)	0.842 (0.593-0.944)	0.706 (0.322-0.891)
Right flexion	0.935 (0.819-0.978)	0.732 (0.368-0.901)	0.847 (0.603-0.946)	0.805 (0.514-0.930)
Left flexion	0.883 (0.689-0.959)	0.889 (0.702-0.961)	0.873 (0.664-0.955)	0.707 (0.323-0.891)

Standard Error of Measurement

The Standard Error of Measurement was used to provide a range around the observed value for each individual. The interval between plus and minus 1 SEM provides a probability of 68% of containing the true value. For ± 2 SEM the probability becomes 95% and for ± 3 SEM it is 99%.

Table 4 Standard Error of Measurement of neck strength measures (HHD)

Range	SEM
Right rotation	1.36
Left rotation	1.09
Extension	1.05
Flexion	2.15
Right flexion	1.22
Left flexion	1.49

Minimal Detectable Change

The Minimal Detectable Change (MDC) is defined as the change in the instrument's score beyond measurement error and provides a value for the minimum change that needs to be observed in order to be confident that the observed change is not a product of measurement error. The MDC individual ranged from 2.90-5.95 and the

MDC group 0.75-1.54 **(**table 5). The MDC individual is used to label individual participants in a study sample as either changed or unchanged. The MDC group provides an aid to the interpretation of mean scores of groups.

The following calculations were used:

$MDC_{ind} = 1.96 * \sqrt{2} * SEM$

MDC_{group} is calculated by dividing the MDC_{ind} by the square root of the number of participants in the sample.

Table 5 Minimal Detectable Change of neck strength measures (HHD)

Range	MDC individual	MDC group
Right rotation	3.77	0.97
Left rotation	3.02	0.78
Extension	2.90	0.75
Flexion	5.95	1.54
Right flexion	3.38	0.87
Left flexion	4.12	1.06

Discussion

The results of this reliability study show moderate to excellent reliability between the two raters across the ranges of right and left rotation, right and left side flexion, forward flexion, and extension, indicating that we can be confident in comparing the results of both raters. My results are consistent with those of Tudini(115) and Kubas(161) who observed excellent inter-rater reliability when assessing isometric neck strength using a HHD. Correlation in both of these studies was assessed by intraclass correlation coefficients (ICCs) (ICC 0.84- 0.974), demonstrating excellent reliability using a HDD. This considered, methods between the current study and those employed by both Tudini and Kubas vary considerably in regard to participants position, ranges assessed and HHD manufacturer. The results of both of these studies do not have the level of agreement found in my study (0.705-0.985) which may be explained by the methods employed. Kubas(161) adopted a method of assessor resisted hand-held dynamometry which relies on consistent counter-pressure applied by the rater, who is susceptible to fatigue and positional error. Tudini(115) relied on a home-made wooden bracket to anchor the HHD, potentially leading to movement of the HHD when pressure was applied. Methods employed in this study, first described by

Versteegh(120), employed a participant resisted technique, removing external confounders such as rater technique, fatigue and bias. Due to the lack of assessor participation in the assessment method, Versteegh and colleagues stated that the assessment of inter and intra-rater reliability was not necessary.

Using 95% confidence intervals my SEM values ranged from 1.05-2.15kgf, further providing evidence of reliability of methods. These results are consistent with those observed by Carnevalli(166) who demonstrated a mean inter-rater SEM of 0.59-0.87kgf. Again, a lack of consistency with the kind of study participants and methods used make comparisons difficult, however certain factors were consistent such as the model of HHD used (Lafayette Manual Muscle Testing System) and prescribed rest between trials. Within the current study MDC individual ranged from 2.90-5.95kgh and the MDC group 0.75-1.54kgf, suggesting a low probability that my results are due to chance. The MDC in this study is smaller than those observed by Carnevalli(164) (1.49kgf to 4.61kgf) and Kubas 2.4kgf to 3.3kgf (converted from Newtons)(161).

A review of the literature assessing the inter-rater reliability of neck strength assessors and the intra-session and inter-session of neck strength assessment reveals a lack of homogeneity in methodology, making comparisons difficult. The application of handheld dynamometry including assessor position, standardisation in participant position, difference in the anatomical placement of the HHD contact pad, instructions given, the build-up of force during a test and participant type is evident. There are also a number of different HHD models used across these studies(114, 115, 117, 120, 166), all of which makes comparisons with my results difficult.

The intra and inter-session reliability of the methods employed in this study was considered by Versteegh(120). Their reliability study demonstrated good to excellent intra-session reliability and excellent inter-session reliability. Due to the nature of working with professional athletes it was not possible to assess and re-assess professional rugby players repeatedly over short time periods and therefore I have used the work by Versteegh and colleagues to inform my own reliability when considering the intra and inter-session reliability and confidence in comparison of results.

Conclusion

Following the completion of this reliability study and informed by the work by Versteegh and colleagues(120), I am highly confident that the results observed in this study are a true reflection of participants' neck strength.

Reliability Study Two - Reliability testing for Joint Position Error Test- inter-rater reliability

Introduction

Orientating head position with respect to the trunk makes use of visual, vestibular, and cervical proprioceptive cues(124). The high density of regional proprioceptors within the muscles and joints of the cervical spine demonstrate the significant proprioceptive role that the region undertakes in orientating the head and neck(167). The Cervical Joint Position Error Test (CJPET) was first described by Revel(124) in order to assess 'cervicocephalic kinesthetic sensibility' in patients with cervical pain, or measure the ability to relocate the head to a starting position following active cervical range of motion(158). Since this time the CJPET has been widely used in a research setting as a measure of cervical proprioception(121, 122, 129, 158), predominantly in the assessment of patients with cervical pain(131, 158). Following the initial test description by Revel and colleagues, methods have changed significantly in an effort to increase the test's objectivity, however this has dictated the use of specialist equipment(122, 168) which is often expensive and requires expert training. Within the current study I have employed the methods described by Revel and colleagues and later studied for reliability by Pinsault(129). This was a conscious decision designed to extend the studies' use to environments that do not have the time and equipment described in lab-based settings and therefore make results applicable to 'real life' scenarios.

Pinsault investigated the test-retest reliability of the methods described by Revel using a cohort of healthy male and female participants. One significant variation in methods existed in this study to those described by Revel. Participants were situated three metres from the target, double the distance used in the earlier Revel paper(124). In spite of this, Pinsault observed a fair to excellent reliability (ICC ranged from 0.52 to 0.81). When the mean across multiple trials was used, the test-retest reliability of this method increased with a larger number of trials. Using the mean of eight trials is sufficient to ensure fair to excellent reliability of the measurements (ICC ranged from 0.39 to 0.78). When 10 trials are used to calculate a participants repositioning errors, analysis of the absolute error shows ICC values superior to 0.75 for both the global

(ICC=0.81) and horizontal (ICC=0.80) components and an ICC value between 0.40 and 0.75 (ICC=0.52) for vertical error. The current reliability study is designed to lend its results to a study assessing the correlation between cervical proprioception and concussion incidence in professional male rugby players and is therefore designed to consider the realities of a field-based study, namely time. Professional athletes' time is dictated by training and competition schedules leading to limited availability for external distractions such as research. With this considered, in the primary CJPET study I determined to adopt the methods described by Revel(124), using the mean of three trials to left and right rotation and extension of the cervical spine. When considering the mean of three trials Pinsault observed ICC values between 0.40 and 0.75 For both the global (ICC=0.55) and horizontal (ICC=0.46) components, an ICC value 0.25 was observed for the vertical component, giving an overall ICC value of poor to moderate. No feedback or physical cues were provided to participants during testing and therefore the assessment of inter-rater reliability was deemed unnecessary.

The inter and intra-rater reliability of the CJPET has previously been assessed by Juul(158) using methods different to those described above. In this study Juul used measuring tape fitted vertically and horizontally to the back of a baseball cap with a laser shone on the back of the head. The participant was then asked to conduct the test movements with the level of error measured in centimetres. This method does not allow for error greater than the size of the back of the cap to be measured and prevents the ability to take measurements of error beyond one plane of error. In spite of this ICC's for intra-rater reliability indicate moderate to excellent reliability, ranking from 0.50 and 0.80. Inter-rater reliability was considered moderate (0.51- 0.57).

The current study is designed to assess the inter-rater reliability of raters using a target with pre-determined points. This was considered necessary due to the location of raters. The author hypothesises that the assessment of raters recording consistency will have good to excellent reliability.

Methods

Participants

Five raters (four physiotherapists and one osteopath) all with over five years of clinical experience were included in this study.

Procedure

The current study was designed as a reliability study for the study investigating the association between cervical proprioception, using the CJPET, and concussion in professional male rugby players. Due to the disparate nature of the participant groups and the individual raters and the ongoing Covid-19 pandemic it was not possible to coordinate all raters to a central location in order to conduct testing. It was therefore decided to send a collection of the same 12 targets (figure1) to each rater.

Each target measured 39cm in diameter and were randomly populated with three points to represent right cervical rotation, three points to represent left cervical rotation and three points to represent cervical extension. These targets were then photocopied on an industrial large-scale photocopier and sent via post to each rater.

In tandem with this process a blank data collection spreadsheet (Figure 2) was emailed to each rater with a set of instructions outlaying how to undertake the data collection and populate the results spreadsheet. The instructions were as follows:

- You have been sent 12 targets, all with three 'R' points (right rotation), three 'L' points (left rotation) and three 'E' points (extension).
- Please measure the horizontal, vertical and gross error for each point and record in the excel sheet attached.
- Please note that in the form all of the three horizontal errors, all of the vertical errors and all of the gross errors are recorded together to allow for calculation of the mean.
- Please record the distance to the nearest 0.5cm.

When all points were measured for the three ranges, the excel spread sheet was emailed back to the primary researcher and results were collated centrally.

Figure 1 Joint position Error Test target

Figure 2 Joint Position Error Test reliability spreadsheet

Athlete	Range	1H	2H	3H	Average	1V	2V	3V	Average	1G	2G	3G	Average
Participant_IRR_01	Right rotation				#DIV/0!				#DIV/0!				#DIV/0!
	Left rotation				#DIV/0!				#DIV/0!				#DIV/0!
	Extension				#DIV/0!				#DIV/0!				#DIV/0!
Participant_IRR_02	Right rotation				#DIV/0!				#DIV/0!				#DIV/0!
	Left rotation				#DIV/0!				#DIV/0!				#DIV/0!
	Extension				#DIV/0!				#DIV/0!				#DIV/0!
Participant_IRR_03	Right rotation				#DIV/0!				#DIV/0!				#DIV/0!
	Left rotation				#DIV/0!				#DIV/0!				#DIV/0!
	Extension				#DIV/0!				#DIV/0!				#DIV/0!

Statistical methods

Data were recorded in centimetres (cm) and analysed using Stata Version 14 (StataCorp,Texas). Inter-rater reliability was measured using the intraclass correlation coefficient (ICC) and 95% confidence intervals (CI). This compares the variability of ratings of the same individual to the total variation of ratings for all individuals. I assumed that individuals and raters are sampled from a larger population (two-way random effects). The results can therefore be generalised to any raters, not just the five that made the 12 measurements. Measurements are averaged over the three trials. The ICC measures the absolute agreement between the raters.

In addition, I calculated the standard error of measurement (SEM) and minimal detectable change (MDC). SEM is calculated using the standard deviation and the reliability coefficient (ICC). With two raters the SEM can also be calculated by dividing the SD for the difference between the two raters by $\sqrt{2}$. where 1.96 corresponds to the level of confidence adopted (in this case, 95%) and $\sqrt{2}$ represents a correction factor for repeated measurements.

Results

Inter-rater reliability

Across five raters measuring the results of 12 charts the overall agreement was moderate to excellent across all ranges (right rotation, left rotation and extension) for horizontal, vertical and gross measures (0.687-1.000). Results for individual ranges are presented in Tables 6, 7 and 8.

Table 6 Inter-rater reliability of JPET: Horizontal

	Horizontal			
	ICC (95% CI)			
Range	Average	Trial 1	Trial 2	Trial 3
Right rotation	0.999 (0.998-1.000)	0.999 (0.998-1.000)	0.999 (0.997-1.000)	0.998 (0.995-0.999)
Left rotation	0.998 (0.995-0.999)	0.999 (0.998-1.000)	0.987 (0.971-0.996)	1.000 (0.999-1.000)
Extension	0.999 (0.999-1.000)	0.999 (0.999-1.000)	0.998 (0.996-0.999)	1.000 (0.999-1.000)

Table 7 Inter-rater reliability of JPET: Vertical

	Vertical			
	ICC (95% CI)			
Range	Average	Trial 1	Trial 2	Trial 3
Right rotation	0.978 (0.951-0.993)	0.992 (0.982-0.997)	0.994 (0.986-0.998)	0.911 (0.814-0.969)
Left rotation	0.964 (0.920-0.988)	0.687 (0.461-0.876)	0.984 (0.965-0.995)	0.999 (0.998-1.000)
Extension	0.998 (0.996-0.999)	0.999 (0.998-1.000)	0.992 (0.983-0.997)	0.998 (0.996-0.999)

Table 8 Inter-rater reliability of JPET: Gross

	Gross			
	ICC (95% CI)			
Range	Average	Trial 1	Trial 2	Trial 3
Right rotation	0.999 (0.998-1.000)	0.998 (0.995-0.999)	0.999 (0.998-1.000)	0.998 (0.996-0.999)
Left rotation	0.979 (0.954-0.993)	0.998 (0.995-0.999)	0.888 (0.772-0.961)	1.000 (1.000-1.000)
Extension	0.986 (0.969-0.995)	0.904 (0.801-0.967)	0.998 (0.996-0.999)	0.999 (0.998-1.000)

Standard Error of Measurement

The Standard Error of Measurement was used to provide a range around the observed value for each individual. The interval between plus and minus 1 SEM provides a probability of 68% of containing the true value.

Minimal Detectable Change

The Minimal Detectable Change individual ranged from 0.05-1.26 and the MDC group 0.05-0.32 **(**table 9). The MDC provides a probability of 99% of containing the true value.

Table 9 Standard error of measurement and Minimal detectable change

	Horizontal		
Range	**SEM**	**MDC individual**	**MDC group**
Right rotation	0.09	0.26	0.07
Left rotation	0.12	0.35	0.09
Extension	0.07	0.20	0.05

	Vertical		
Range	**SEM**	**MDC individual**	**MDC group**
Right rotation	0.45	1.26	0.32
Left rotation	0.43	1.19	0.31
Extension	0.11	0.29	0.08

	Gross		
Range	**SEM**	**MDC individual**	**MDC group**
Right rotation	0.12	0.33	0.09
Left rotation	0.41	1.14	0.29
Extension	0.41	1.12	0.29

Discussion

My results demonstrate that the overall agreement for assessing the reliability of recording JPET results across five raters was moderate to excellent across all ranges, demonstrating that the results of a future study investigating cervical proprioception as a risk factor to concussion using this tool can be considered as reliable. These results, although differing in methods, are consistent with the findings of Pinsault(129) and Juul(158) who found the reliability of the CJPET to be moderate to excellent. The clinical significance of these results is important. In clinical settings time and equipment are limited. The results of the current study and those of previously published research(129, 158) provide strong evidence that the CJPET is reliable when conducted by multiple raters and can therefore be used as a comparator of cervical proprioception between multiple time points.

Within the current study the MDC individual ranged from 0.2-1.26 cm and the MDC group 0.05-0.32 cm, suggesting a low probability that my results are due to chance and are again consistent with the findings of Juul who demonstrated an MDC group of between 0.55 cm and 0.75 cm. Juul did not include SEM for inter-rater reliability, however Pinsault found an SEM of 0.5-0.9° which, when translated to centimetres, is consistent with my findings.

As discussed, a lack of homogeneity in methods exists when using the CJPET in a research setting and it is often assumed that using specialist equipment offers greater reliability of results. The findings of this study and those of Pinsault and Juul prove this assumption to be false. When using a 3D ultrasound-based motion analysis device, Strimpakos found poor to moderate ICC's across all ranges(169). This trend continues with Swait who assessed cervical joint repositioning error with an electromagnetic-tracking system and found ICC's between moderate and good(168). These findings add additional credence to the methods employed within the current study. Inter-rater reliability represents the comparison of same day results and therefore does not take into account different physical states of the rater or participant. It does however provide an indication that when using consistent methods, good reproducibility should exist when conducting the CJPET.

Conclusion

This study investigated the reliability of five raters in measuring the CJPET. The methods employed were time and cost effective and my results demonstrate that the findings of the CJPET, undertaken in this format may be relied upon when being undertaken by multiple raters as inter-rater reliability ranged from moderate to almost perfect agreement. Furthermore, the MDC and SEM demonstrate continued confidence in establishing a true finding when using the CJPET.

Reliability Study Three - Reliability testing for Vestibular-Oculomotor Screening- intra-rater reliability

Introduction

The vestibular and oculomotor systems are key components, together with the proprioceptive system, in providing the body's sense of balance, as well as head and neck position, used to perform simple tasks of ambulation as well as more complex tasks executed in a sporting context(77). Different assessment techniques for the vestibular and oculomotor systems have been described throughout the scientific literature. Methods employ a range of different techniques(170-172) each with their own advantages and limitations(173), including the degrees of sensitivity and specificity, inter and intra-rater reliability and the need for specialist equipment and training(174-176).

Vestibular evoked myogenic potentials (VEMPs), is considered 'State-of-the-art' in vestibular and oculomotor assessment and are used in clinical settings to examine the integrity of the vestibular system(176). Myogenic potentials are divided into two different categories, a cervical VEMP (cVEMP) and an ocular VEMP (oVEMP). cVEMP and oVEMP are measured via electromyogenic response at the sternocleidomastoid muscle, measuring function of the saccule and inferior vestibular nerve and inferior oblique muscle measuring function of the utricule and superior vestibular nerve respectively. Behtani(176) studied 22 individuals (13 males, 18 and 60 years) for test-retest reliability and observed an excellent test-retest for both cVEMP and oVEMP with an ICC value of 0.90 and 0.97 respectively. It is acknowledged that this testing method is susceptible to subtle changes in experimental procedure that can affect the reliability of VEMP potentials. Methods also require specialist equipment and training, limiting the reproducibility of this assessment method across different settings. Further, methods of vestibular assessment include commercially available wearable inertial sensors that allow for functional assessments. Sankarpandi(171) assessed 27 individuals diagnosed either with unilateral or bilateral vestibular loss during instrumented Timed Up and Go (iTUG) and Postural Sway (iSway), administered three times over a single session. The iTUG

test parameters showed good intra-session reliability, with mean ICC values of 0.81. For the iSway test, the ICC was rated as good with an ICC 0.76.

The presence of vestibular and oculomotor dysfunction is a common finding following a mechanism of injury that leads to concussion(70, 177), which has led to the development of the Vestibular-Oculomotor Screening (VOMS) tool(76). VOMS is a method of vestibular and oculomotor assessment specifically designed to assess function in these two systems following a sports-related concussion. The test battery, originally described by Mucha and colleagues was described using a cohort of concussed and non-concussed adolescent participants (range 9–18 years) and found a significant difference in subjective symptoms scores in the concussed group upon completion of the five-domain test battery. Mucha and colleagues observed high internal consistency of the VOMS total symptom score and Near Point Convergence (NPC) distance however no assessment of test-retest reliability was conducted despite the study using multiple raters, potentially leading to reduced confidence when interpreting results. Worts(178) assessed the test-retest reliability of the VOMS tool under three conditions; rest, pre-training and 5 minutes post-cessation of training and observed an absolute agreement of symptom provocation ranging from 48.9% (vertical VOR) to 88.9% (smooth pursuit) across the three conditions. Both of these studies have studied the efficacy and reliability of VOMS adolescent participants which are consistent throughout the literature(76, 110, 111, 178, 179).

The aim of this study was to investigate the intra-rater reliability of a group of asymptomatic mixed sex and activity level 18–35-year-old participants when performing the VOMS assessment. The author hypothesises that there will be excellent inter-class coefficient in this group.

Methods

Participants

A sample of 24 asymptomatic mixed sex and activity level 18–35-year-old participants were recruited. Participants were emailed through a global UCL student email list and those that responded were invited to attend for reliability testing.

Participants were eligible for the trial if they were healthy, non-injured individuals between the ages of 18 and 35. Participants were excluded if they had a current

concussion, neck or shoulder pain, or any other medical condition that precluded them from undertaking rapid eye and head movements.

Procedure

Upon arrival at the test site, participants were asked to read and sign the participant consent form if they had not brought the completed form with them to testing. Participants were taken through a data collection form to record age and activity level (active or sedentary). They were also asked to complete the health screening form to ensure that there was no known medical reason that they were unable to undertake testing.

Participants were seated on a straight back chair positioned 90 cm in front of the examiner. Participants were then taken through the VOMS testing procedure as described in study 3 by one examiner. Following the completion of the VOMS testing, the participant was asked to rest in a seated position for ten minutes before the second set of tests was completed by the same examiner in an identical test environment.

Subjective symptom scores were recorded by a separate research assistant. Test scores were not shown to the examiner between a participants initial and repeat VOMS test.

Statistical methods

Demographic variables were summarised using mean (SD) for continuous data and percentage (N) for categorical data. Differences in demographics between the main and reliability studies were tested using unpaired t-test (continuous) and chi-squared test (categorical).

Reliability data were recorded as a numerical rating for symptom aggravation. Four symptoms were recorded over seven tests and the numerical agreement between VOMS test 1 and VOMS test 2 was compared. Percentage agreement, Cohen's Kappa Coefficient and Gwet's AC2 was used to establish agreement between domains.

Repeated measurements were made, with one rater rating the same participant on two occasions. As data were ordinal (ranging from 0-6), agreement between the two measurements was assessed using a weighted kappa and Gwet's AC2.
Scores are weighted so that results which are further apart are given more weight than results which disagree but are closer together. Kappa has been found to give misleading results where there is imbalance in the categories with low Kappa values occurring, despite a high percentage agreement between measures and therefore interpretation was based on Gwet's AC2.

In addition, I calculated the standard error of measurement (SEM) and minimal detectable change (MDC). SEM is a reliability measure that assesses response stability and is the amount of error that you can consider to be measurement error. It is calculated using the standard deviation and the reliability coefficient (ICC).

SEM = Standard Deviation from the 1st test x (square root of (1-ICC))

The MDC is the minimum amount of change in a patient's score that ensures it is not the result of measurement error and in the formula used it is based on a 95% confidence interval.

Table 10 Interpretation of Gwet's AC2

Range
<0.00 Poor
0.00-0.20 Slight
0.21-0.40 Fair
0.41-0.60 Moderate
0.61-0.80 Substantial
0.81-1.00 Almost Perfect

Results

Participant characteristics

When comparing the participant demographics between the study 3 and reliability study (n=99) a difference existed in age with the reliability group being significantly older (p=0.001). There were no other statistically significant differences, including sex (p=0.55), or activity levels (p=0.11).

Within the reliability dataset, participants were 28.5 ± 4 years of age, 50 % (n=12) female, 50 % (n=12) male. 70.8% (n=17) of the group were defined by the UK government activity guidelines as active and 29.2% (n=7) were defined as sedentary.

Table 11 VOMS reliability demographics

		Reliability	Study three	P value
Age, years	mean (SD)	28.5 (4.0)	22.5 (3.7)	[1]<0.001
Sex, % (N)	Male Female	50% (12) 50% (12)	56.9% (41) 43.1% (31)	[2].55
Activity level, % (N)	Active Sedentary	70.8% (17) 29.2% (7)	51.6% (32) 48.4% (30)	[2]0.11

1Unpaired t-test, 2Chi-squared test

Intra-rater reliability

The overall agreement was substantial to almost perfect for all VOMS domains between the two tests. The level of agreement between VOMS trial 1 and VOMS trial 2 ranged between 0.80-1.00, with the largest degree of variability existing in horizontal VOR for dizziness (0.80, range 0.59-1.00, 95% CI), smooth pursuits dizziness (0.91, range 0.77-1.00), VOR vertical dizziness (0.95, range 0.85-1.00), VMS (0.95, range 0.85-1.00), vertical saccades (0.95, range 0.86-1.00), VOR vertical nausea (0.95, range 0.86-1.00), smooth pursuits nausea (0.95, range 0.86-1.00) and horizontal saccades (0.95, range 0.86-1.00). An agreement of 1.00 was reported for all other test items and symptom domains. Results for individual domains are presented in table 12.

Table 12 Intra-class correlation coefficient (95% CI) for intra-rater reliability of VOMS

		Percent agreement	Weighted Kappa (95% CI)	Gwet's AC2 (95% CI)
Headache (all values are zero)	Smooth pursuits	100%	1.00	1.00
	Vertical saccades	100%	1.00	1.00
	Horizontal saccades	100%	1.00	1.00
	Convergence	100%	1.00	1.00
	VOR horizontal	100%	1.00	1.00
	VOR vertical	100%	1.00	1.00
	VMS	100%	1.00	1.00
Dizziness	Smooth pursuits	91.3%	0.30 (0.0-0.34)	0.91 (0.77-1.00)
	Vertical saccades	95.7%	0.74 (0.35-1.00)	0.95 (0.86-1.00)
	Horizontal saccades	100%	1.00	1.00
	Convergence	100%	1.00	1.00
	VOR horizontal	82.6%	0.71 (0.46-0.96)	0.80 (0.59-1.00)
	VOR vertical	95.7%	0.88 (0.66-1.00)	0.95 (0.85-1.00)
	VMS	95.7%	0.84 (0.51-1.00)	0.95 (0.85-1.00)
Nausea	Smooth pursuits	95.7%	0.65 (0.0-1.00)	0.95 (0.86-1.00)
	Vertical saccades	100%	1.00	1.00
	Horizontal saccades	95.7%	0.49 (0.47-0.51)	0.95 (0.86-1.00)
	Convergence	100%	1.00	1.00
	VOR horizontal	95.7%	0.0 (0.0-0.0)	0.95 (0.86-1.00)
	VOR vertical	100%	1.00	1.00
	VMS	100%	1.00	1.00
Fogginess	Smooth pursuits	100%	1.00	1.00
	Vertical saccades	100%	1.00	1.00
	Horizontal saccades	100%	1.00	1.00
	Convergence	100%	1.00	1.00
	VOR horizontal	100%	1.00	1.00
	VOR vertical	100%	1.00	1.00
	VMS	100%	1.00	1.00

Standard Error of Measurement

The SEM was used to provide a range around the observed value for each individual. The interval between plus and minus 1 SEM provides a probability of 68% of containing the true value.

Minimal Detectable Change

MDC provides a value for the minimum change that needs to be observed in order to be confident that the observed change is not a product of measurement error. The MDC individual ranged from 0-1.63 and the MDC group 0-0.42 (tables 13-16). These results suggest that a change of two points or more for symptom severity is a significant change.

Table 13 Standard error of measurement and Minimal detectable change: Headache

	Headache		
Range	**SEM**	**MDC individual**	**MDC group**
Smooth pursuits	0	0	0
Vertical saccades	0	0	0
Horizontal saccades	0	0	0
Convergence	0	0	0
VOR horizontal	0	0	0
VOR vertical	0	0	0
VMS	0	0	0

Table 14 Standard error of measurement and Minimal detectable change: Dizziness

	Dizziness		
Range	**SEM**	**MDC individual**	**MDC group**
Smooth pursuits	0.20	0.56	0.15
Vertical saccades	0.15	0.40	0.10
Horizontal saccades	0	0	0
Convergence	0	0	0
VOR horizontal	0.36	1.01	0.26
VOR vertical	0.15	0.40	0.10
VMS	0.15	0.40	0.10

Table 15 Standard error of measurement and Minimal detectable change: Nausea

	Nausea		
Range	**SEM**	**MDC individual**	**MDC group**
Smooth pursuits	0.59	1.63	0.42
Vertical saccades	0	0	0
Horizontal saccades	0	0	0
Convergence	0	0	0
VOR horizontals	0.15	0.41	0.11
VOR vertical	0	0	0
VMS	0	0	0

Table 16 Standard error of measurement and Minimal detectable change: Fogginess

	Fogginess		
Range	**SEM**	**MDC individual**	**MDC group**
Smooth pursuits	0	0	0
Vertical saccades	0	0	0
Horizontal saccades	0	0	0
Convergence	0	0	0
VOR horizontal	0	0	0
VOR vertical	0	0	0
VMS	0	0	0

Discussion

The author accepts the hypothesis that the VOMS tool has an overall excellent reproducibility when comparing the results of one rater. To the author's knowledge there is no published evidence that has previously investigated the intra-rater reliability of the VOMS tool and therefore the intra-rater reliability of the test was previously unknown.

Several papers have undertaken to investigate the long-term consistency of the VOMS tool(110, 178, 180) amongst adolescent and adult non-injured athletes and military personnel. These studies have found that when repeating the VOMS test between one day and six months apart, VOMS symptom items demonstrated moderate to excellent test–retest reliability between the initial assessment and long-term follow-up. These studies did not account for possible confounding factors that may have impacted vestibular and oculomotor function between the tests and therefore cannot be used to scrutinise the consistency of raters. One other significant difference to the current

study is that these papers used multiple raters and therefore were are not assessing intra-rater reliability.

Vestibular and oculomotor function and VOMS have been recognised as an important component in a rounded test battery following SRC(27, 76) and reliable inter-test consistency is an important factor in the continued monitoring of an athlete's progression from injury. The results of the current study provide confidence that the results of multiple tests can be reliably compared. When compared to the reliability of other tests assessing the somatosensory system, the VOMS test compares well to the King-Devick(178, 181) and out performs the mBESS(107, 180), again reinforcing the test's utility.

The current study was designed to assess the reliability of one rater across two tests and therefore no conclusions can be drawn pertaining to the between tester reliability of the VOMS test within the same test session. This considered, previously published research(178) has demonstrated the inter-rater reliability to be good when observing a 24-hour gap between tests.

Conclusion

The VOMS tool has excellent intra-rater reliability and can be reliably used to assess vestibular and oculomotor function across multiple tests in a mixed population of sexes and activity levels. This is of particular benefit when assessing the impact and recovery from head injury.

Chapter Four- Main studies

The three studies presented in this chapter represent the main body of work in this thesis. They look to answer three distinct research questions aimed at progressing our understanding of concussion and its management.

Study One- The relationship between neck strength and concussion

Introduction

Concussion is a micro-structural and functional injury of the brain resulting from external biomechanical forces, usually an opposition player or as a result of technique error(182, 183). Symptoms are usually rapid in onset and can last from minutes to months(184), with no current ability to accurately predict length or severity of presentation(185).

In professional rugby and within contact sports at large, SRC is increasingly becoming one of the highest burden injuries when considering frequency and time missed from competition(5, 186). Long-term implications of the injury continue to be a topic of discussion across sport, with no reliable data available on the long-term health cost of multiple concussive events(187).

Significant attention is now given to this topic within the sporting and scientific communities, however much of the research to date has focused on identification and diagnosis of concussive injuries (188-190) without attention given to effective management and prevention strategies. This is in spite of the most recent Concussion in Sport Group consensus statement stipulating that a clear understanding of the potentially modifiable risk factors required to design, implement and evaluate appropriate injury risk reduction strategies is needed(27).

The mechanism of injury that precedes a concussive event is variable depending on sport and often position played(19), however research demonstrates that concussions are most commonly sustained during forces causing linear or rotational movements of

the head and neck(191). Within Rugby Union 58-64% of all match concussions in professional male players occur within the tackle(192, 193); the most common concussive event, followed by the ruck, kicking contests and mauls(194). When engaging in a contact event during rugby, acceleration of the head has been found to occur within the sagittal plane in 50% of concussive events(195), suggesting a link with the flexor and extensor mechanism of the head and neck.

Laboratory and field-based studies provide indications as to the mechanism and potential mitigating factors of a concussive injury (90, 93, 96), with some studies demonstrating that muscle function may be a significant factor in reducing an external force and therefore the head accelerations thought to lead to a concussive injury(27). Evidence around muscle function in identifying concussion risk is varied. While muscle function contributes approximately 80% of the minimally required mechanical stability of the cervical spine(91), research comparing individual player characteristics, including isometric muscle strength, muscle size and response to cervical perturbations against head impact biomechanics has found no mitigating impact of increased neck strength, and in some cases observed an increase in impact severity(90, 93). These results are supported by a recent paper by Eckersley(196) who found that increased cervical muscle force does not influence short-term head kinematics when modelling head impacts in a laboratory setting. In contrast, earlier work has demonstrated that greater neck strength and anticipatory cervical muscle activation can reduce the magnitude of the head's kinematic response(96). This is supported by the sole field-based study investigating the association between neck strength and concussion incidence. Collins(92) observed neck strength in a group of 6,704 mixed sport and sex high school athletes and concluded that neck strength, when averaged across four ranges, was a significant risk factor to concussion. There were however no Rugby Union players in this cohort and no published evidence currently exists considering this sporting population and the impact of neck strength on concussion incidence.

The theory that neck strength plays a protective role against head injuries is further supported by Hendricks(195) who observed that the majority of rugby related concussions occur when a player is not aware of the impending contact and concluded that it is therefore likely that a player is able to sustain greater forces without injury if

the tackle is anticipated and the cervical muscles are activated(195). It is possible that activation of the neck and posterior shoulder muscles may reduce the risk of concussion by stabilising the head and neck during impact, thereby decreasing the resultant head acceleration(197).

Within Rugby Union, the largest isometric neck forces generated by professional male players exist in the extension range, approximately 90% higher than the peak lateral flexion values(118). Forwards generate significantly larger neck strength forces than backs(114, 118, 160, 198) across test parameters, which may be explained by their greater neck girth and length(118) . When comparing concussion incidence between playing positions, the evidence for neck strength helping to mitigate the risk of concussion is again contradictory and demonstrates consistently higher rates of concussion in backs(192, 199). Neck strength is, however, only one variable in this analysis and differences in the physical requirements of different rugby positions must be considered.

Methods for assessing neck strength in clinical and research settings vary. Versteegh(120) investigated the intra and inter-session reliability of a technique utilising self-resisted, isometric handheld dynamometry. Results suggested good to high levels of reliability for intra and inter-session reliability. Using the methods described by Versteegh and colleagues, this study aims to establish whether neck strength across six ranges; forward flexion, extension, left and right rotation and left and right-side flexion, is associated with increased risk for concussion in a group of professional male Rugby Union players.

The author hypothesises that reduced neck strength will be positively associated with an increased concussion incidence in male professional Rugby Union players.

Methods

Participants

Participants for this prospective cohort study were recruited from 10 professional rugby teams competing in the Georgian ‘Big 10’ league, the highest level of competition in Georgia. The 225 participants were between the ages of 18 and 35 consented to undertake testing following a communique sent by their National Governing Body. Written informed consent was provided by each participant on the date of testing following an explanation of study methods and the commitment involved

in participating in the study. A study information sheet was also sent out to each participant one week prior to testing.

Any athletes outside the age range of 18-35 or with current concussion, neck or shoulder injury were excluded from the study.

Anthropometry

Data collection was undertaken at the Georgian National Rugby Base in a dedicated testing environment, with height and weight recorded as described in chapter one, General methods. Age, position and medical history, including self-reported concussion history, were recorded for each participant.

Equipment

A Lafayette Manual Muscle Testing System Model-01165 (Lafayette Instrument Company, Lafayette IN, USA), was used to assess participant neck strength.

Diagnosis of concussion

The diagnosis of concussion was made by each club's doctor who was experienced in the diagnosis and management of concussion. All club doctors had completed the World Rugby concussion education modules and a pre-season concussion identification workshop run by the Georgian Rugby Union. Diagnosis was based on clinical judgement and comparison of pre-season neuropsychological tests including the SCAT 5 and Cogstate. Neuropsychological assessment has been described by the Concussion in Sport Group (CISG) as a 'cornerstone' of SRC management. The CISG state that 'the recognition of suspected SRC is best approached using multidimensional testing guided via expert consensus'(27). This includes the assessment of the SCAT 5, video assessment review (where available), clinical symptoms, physical signs, cognitive impairment, sleep/wake disturbance and neurobehavioral features. For the purpose of the diagnosis of concussion in this study, these are the parameters that were used. While it is important to acknowledge that this is not a full-proof method of concussion assessment, it is the method used under the current World Rugby structure and is therefore representative of diagnosis in the game as it stands.

Gathering match exposure data

Number of games played and match minutes were used to calculate players' match exposure. Exposure data were collected from the Georgian RFU via their league recording programme.

Gathering concussion data

Following the diagnosis of concussion, the club physiotherapist notified the research team via email or phone call and provided the name of the concussed player and date of injury.

The research team followed up with the club physiotherapist on four occasions during the course of the season to ensure that no concussions were missed for reporting.

Testing protocol

Participants were invited to sit on a treatment bed with their feet firmly planted on the floor, in front of a floor to ceiling mirror. Participants were then screened for neck dysfunction by one of two clinicians. A physiotherapist and an osteopath, both with over 10 years of clinical experience conducted a cervical range of movement assessment. The participant was asked to actively move through bilateral side flexion and rotation, forward flexion and extension. Over pressure was applied in the case that full range of movement was not achieved to investigate the presence of pain. Participants that had no evidence of pain through their cervical range of movement and no exclusion criteria were accepted to the study.

A standardised, calibrated Lafayette® digital hand-held dynamometer (HHD) was used to evaluate maximum force generated in kilogram-force (kgf). The HHD was programmed to beep once when initial force was detected and once when the applied force started to reduce, indicating that the user has reached their peak isometric force generation.

Participants stayed seated on the treatment bed facing the mirror with their feet firmly grounded. No back or arm support was offered in order to prevent bracing. One of the two clinicians then guided the participant through the testing procedure.

Testing started with the Horizontal Adduction (HADD) test in order to ensure that upper limb strength was adequate to overcome the force generated by the neck musculature (figure 3a). The test is undertaken by raising both shoulders to 90° flexion and flexing the elbows to approximately 90°. The HHD was then held in front of the body with both hands and an isometric force applied through the HHD by pushing the palms of the hands together in the direction of horizontal adduction. Participants were asked to push maximally until they heard the HHD beep, indicating that maximum force had been generated.

Prior to assessment of maximal contraction, a round of sub-maximal warm up efforts was undertaken using the methods described below. Each participant was instructed to apply 50% of their maximal pressure in a 5-second isometric contraction across each range.

Following a three-minute rest, isometric neck strength was then tested using methods validated by Versteeg(120). Six ranges of neck strength were assessed in the order of; forward flexion (with resistance applied with two hands to the forehead), extension (with resistance applied with two hands to the occiput) right and left side flexion (with resistance applied with the ipsilateral hand above the ear) and right and left rotation (with resistance applied along the mid jaw with the ipsilateral hand), see figure 3b-f. For rotation and side flexion ranges the shoulder was abducted to 90° and the participant was instructed to keep the elbow high using their reflection in the mirror as a reference.

When the participant was in the correct test position, they were instructed to build up to their maximum cervical muscle force over 3 seconds, maintaining the static neck position. Participants were instructed to stop the trial when they heard the HHD beep or could stop at any point during the assessment if they experienced pain. The peak force produced for each trial was recorded.

Each range was assessed consecutively without rest in the order described above. Following the completion of each round a one-minute rest was given and the next

round was commenced in the same order. Three rounds of assessment were recorded, and the participant’s mean score was used for analysis.

Figure 3 Test positions for neck strength: HADD test (A), forward flexion (B), extension (C), side flexion (D), rotation (E) handheld dynamometer (F)

Inter-rater reliability testing

Using the methods described above, 15 participants were assessed by both raters. Following the initial assessment by rater 1, participants were given a ten-minute rest and then asked to return to the assessment area to be assessed by rater 2. The same assessment order was followed by each rater; forward flexion, extension, right side flexion, left side flexion, right rotation, and left rotation. Rater 2 was blinded to rater 1 results and the order in which each rater assessed participants was chosen at random.

Statistical analysis

Data were analysed using Stata Version 14 (StataCorp,Texas). The study was powered to detect an effect size of 0.80 for a 10% increase in neck strength with 80% power at the 5% significance level (retrospectively calculated using GPower 3.1).

Normality was assessed using histograms and quantile-quantile plots.

Since distributions of the strength variables were skewed, log transformation was used to meet the model assumptions. Geometric means and geometric SDs were obtained by exponentiating the means and SDs on the log scale. Changes in strength over time were modelled using a linear mixed model.

A random intercept was fitted for player ID, and time was fitted as a fixed effect using two dummy variables to allow mid and post-season to be compared to pre-season as the reference category. Percent differences and 95% confidence intervals are presented. The model was then reparameterised to allow comparison of the mid and pre-season values. The variance partition coefficient (VPC) was calculated to illustrate how much of the total variation in neck strength was accounted for by variation between subjects. The significance level for the pairwise comparisons was adjusted for multiple comparisons using the Bonferroni correction.

Demographic variables are presented by concussion status as mean (SD) for normally distributed data, median [inter quartile range] for non-normal and % (N) for categorical data and compared using two-sample t-tests, Mann-Whitney u test and chi-squared tests respectively.

The associations of strength with concussion incidence were analysed by fitting a Poisson regression model with number of hours played as the exposure variable. A priori covariates included were age, club, and BMI. Associations with injury rate are

presented as incidence rate ratios with 95% confidence intervals. As neck strength was log-transformed in the analysis, I present the incidence rate ratios (IRR) for a 10% increase in each variable, calculated by multiplying the coefficients and confidence limits obtained from the model by ln (1.1) before exponentiating to obtain IRRs and confidence intervals. The optimal cut point to predict concussion was estimated using the Youden Index. The Youden J provides a single statistic that informs the performance of a dichotomous diagnostic test (Youden = sensitivity +_specificity -1). True and false positive rates were calculated as the percentage below this cut off in those with and without concussion. Figure 4 shows median (middle line), interquartile range (box) and values within 1.5 IQRs of the box (whiskers) for neck strength extension by concussion. Model assumptions including normality of residuals for the mixed models were conducted using residual plots. Evidence for non-linearity was assessed by comparing models with restricted cubic splines to the linear model. The mean (0.13) and variance (0.12) for the Poisson model were similar, with no evidence of dispersion. This was formally tested by fitting a negative binomial model and testing whether the overdispersion parameter differed from zero (p=0.32).

Results

Demographics

Of the players recruited to the study, 225 undertook testing at pre-season (24.08.18-27.08.18). Of these players 179 were tested at mid-season (26.01.19-29.01.19) and 74 at the end of season (08.04.19-11.04.19). Twenty two players did not attend mid-season testing because they had a current concussion, cervical or shoulder injury and 24 players did not report for testing at their scheduled time. At the end of season time point, 15 players did not report for testing due to a current concussion, cervical or shoulder injury and 136 players were absent from testing due to participation in an international rugby competition.

The median participant age was 22 years (18-35 years), mean height 182cm (165-197cm) and weight 98.5kg (63-135kg). Mean years as a professional was 4.7 years (1-20 years), and the mean number of self-reported career concussions was 1.6 (0-25 concussions). A mixed playing level existed within the study group. There were 23 current or previous senior international rugby players, 61 players that had played at under-20 international level and four players whose international career had not progressed beyond under-18 level. One hundred and thirty-seven participants had

played only domestic professional rugby. A full table of participant characteristics is presented in table 19.

Changes in neck strength over time

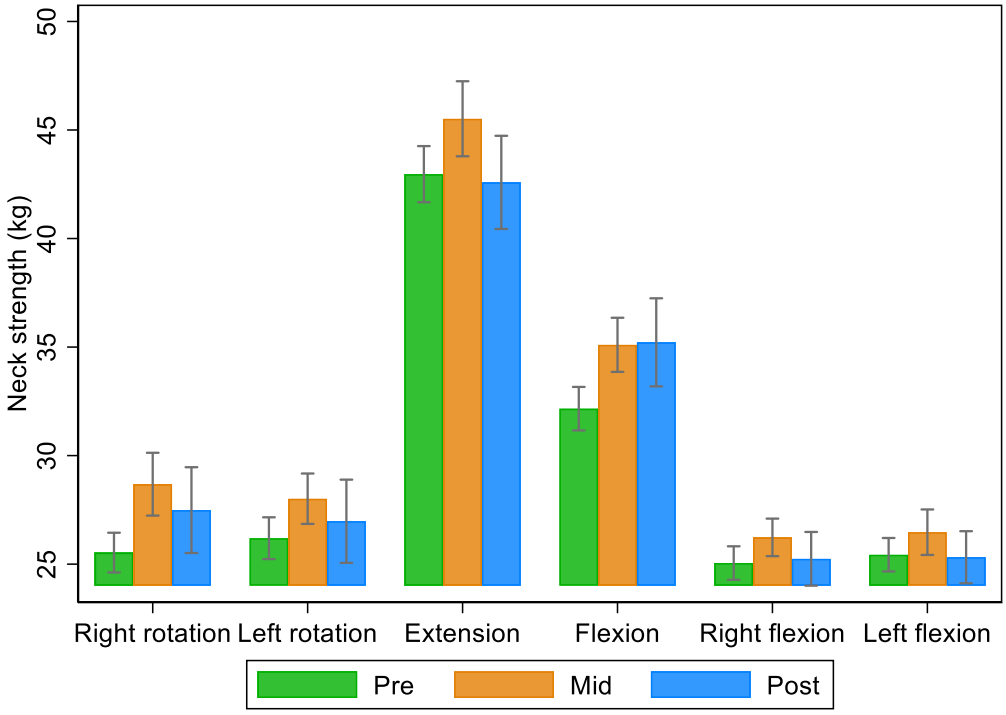
When analysing changes in strength over time, all ranges demonstrated a statistically significant increase in neck strength from pre-season to mid-season time points ($p<0.001$). There was no significant difference between mid-season and end of season for any range ($p=0.88$). Participants with post-season measures (n=72) tended to have lower neck strength values at mid-season than those that did not complete post-season testing (n=177). This may explain the disparity between the reported means between mid-season and end of season and the p-value.

Table 17 Geometric mean neck strength (approx. SD) by range and time-point

					Percentage difference (95% CI)**			VPC***
Range	**Pre**	**Mid**	**Post**	**P value***	**Mid vs. pre**	**Post vs mid**	**Post vs pre**	
Right rotation	24.6 (1.3)	27.4 (1.4)	26.3 (1.4)	p<0.001	10.3% (6.8, 13.9) p<0.001	-0.6% (-5.2, 4.2) p=0.802	9.6% (4.6, 14.8) p<0.001	0.706
Left rotation	25.2 (1.3)	27.0 (1.3)	25.8 (1.3)	p<0.001	6.0% (2.8, 9.4) p<0.001	-0.8% (-5.3, 4.2) p=0.714	5.1% (0.5, 9.9) p=0.029	0.718
Extension	41.9 (1.3)	44.2 (1.3)	41.7 (1.2)	p<0.001	4.9% (2.3, 7.2) p<0.001	-1.2% (-4.7, 2.4) p=0.500	3.6% (0.0, 7.3) p=0.049	0.747
Flexion	31.3 (1.3)	34.1 (1.3)	34.2 (1.3)	p<0.001	8.5% (5.7, 11.3) p<0.001	3.2% (-0.6, 7.3) p=0.100	12.0% (7.9, 16.3) p<0.001	0.845
Right flexion	24.4 (1.3)	25.6 (1.3)	24.7 (1.2)	p<0.001	4.3% (1.6, 7.0) p<0.001	1.1% (-2.6, 5.0) p=0.561	5.5% (1.6, 9.4) p=0.005	0.717
Left flexion	24.8 (1.3)	25.7 (1.3)	24.8 (1.2)	p<0.001	3.4% (0.5, 6.5) p=0.022	0.0% (-4.1, 4.3) p=0.996	3.5% (-0.8, 7.8) p=0.109	0.619
Total	173.5 (1.2)	185.6 (1.3)	178.7 (1.3)	p<0.001	6.4% (4.1 to 8.8) p<0.001	0.2% (-3.0 to 3.6) P=0.883	6.7% (3.3% to 10.2) p<0.001	0.761
Flexion:Extension	0.75 (1.3)	0.77 (1.2)	0.82 (1.3)	p<0.001	2.7% (0.8, 4.8) p=0.009	3.8% (0.9, 6.8%) p=0.01	6.7% (3.8, 9.7) p<0.001	0.598

*p value from mixed effects regression model to take account of repeated measures data. Neck strength is log-transformed in the analysis.
**significance level taken as p<0.017 for pairwise comparisons
***Variance Partition Coefficient showing the proportion of variance between participants

Figure 4 Mean neck strength (95% CI) by range and timepoint.



Change from baseline to mid-season by concussion.

Players with concussion recorded significantly bigger differences between pre- and mid-season neck strength than those without concussion for left rotation (0.02), extension (0.003), flexion (0.03) and right flexion (0.03).

Table 18 Change from baseline to mid-season by concussion.

	Percentage change (95% CI)		
Range	**No concussion N=196**	**Concussion N=29**	**P value***
Right rotation	9.1% (5.3, 12.9)	17.5% (8.0, 27.8)	0.11
Left rotation	4.4% (1.0, 7.9)	15.8% (6.9, 25.6)	0.02
Extension	3.3% (0.7,6.1)	14.3% (7.4, 21.7)	0.003
Flexion	7.1% (4.4, 10.2)	16.3% (8.7, 24.5)	0.03
Right flexion	3.1% (0.3, 6.0)	11.5% (4.3, 19.1)	0.03
Left flexion	2.7% (-0.5, 5.8%)	8.1% (0.3, 16.6)	0.22

*Tested by fitting a concussion x time interaction in the mixed model.

Incidence of concussion

There were 30 concussions in 29 players recorded over the study period, giving an overall rate of 13.7 concussions per 1000 hours played. Nineteen concussions occurred between pre-season and mid-season and 11 between mid and end of season time points (p=0.04). All concussions were recorded in match play.

Relationship between anthropometry, playing level and concussion incidence

No significant association was found between any anthropometric or playing marker and concussion incidence (table 19).

Table 19 Participant demographics by concussion

Variable	Players without concussion (n=196)	Players with concussion (n=29)	Overall (n=225)	P value
Age (years), mean (SD)	23.0 (4.0)	21.8 (4.0)	22.8 (4.0)	0.12[1]
Height (cm), mean (SD)	182.2 (6.13)	184.1 (6.68)	182.5 (6.2)	0.13[1]
Weight (kg), mean (SD)	96.7 (15.3)	96.8 (12.0)	96.7 (14.9)	0.96[1]
BMI (kg/m^2), mean (SD)	29.1 (4.1)	28.6 (3.2)	29.0 (4.0)	0.53[1]
Years pro, median [IQR]	4 [2-7]	3 [2-4]	4 [2-7]	0.11[2]
% with Previous concussion (N)	52.1% (99)	65.5% (19)	53.9% (118)	0.18[3]
No of concussions	1 [0-2]	1 [0-3]	1 [0-2]	0.31[2]
% international	40.5% (77)	58.6% (17)	42.9% (94)	0.07[3]

1 two-sample t-test, [2] Mann-Whitney U test, [3] chi-squared test

Relationship between neck strength and concussion

Results are expressed as incidence rate ratios for a 10% increase in neck strength which have been estimated using Poisson regression. There was a significant association between reduced neck extension strength and the rate of concussion (p=0.044 unadjusted, p=0.019 covariate adjusted). A 10% increase for extension is associated with a 13% decrease in concussion rate (p=0.019). A paired t-test also demonstrates a significant difference between concussed and non-concussed players for neck extension strength (p=0.023) (Table 21). There were no significant

associations between concussion incidence and any other unique range or composite score, including the neck flexion:extension strength ratio.

I tested for non-linearity and found no evidence after Bonferroni correction (Table 22).

Table 20 Geometric Mean baseline neck strength (kg) by concussion.

Range	No concussion N=196	Concussion N=29	IRR* (95% CI)-univariate	IRR**(95% CI)-adjusted
Right rotation	24.6 (6.7)	24.7 (7.1)	1.00 (0.87-1.14) P=0.997	1.02 (0.87-1.20) P=0.77
Left rotation	25.2 (7.2)	25.0 (7.0)	1.01 (0.89-1.15) P=0.89	1.03 (0.94-1.12) P=0.55
Extension	42.5 (9.7)	38.2 (8.4)	0.87 (0.75-1.00) P=0.044	0.87 (0.78-0.98) P=0.019
Flexion	31.5 (7.5)	29.6 (7.3)	0.92 (0.79-1.06) P=0.23	0.94 (0.77-1.14) P=0.53
Right flexion	24.6 (5.9)	23.0 (4.9)	0.90 (0.78-1.04) P=0.14	0.91 (0.79-1.05) P=0.22
Left flexion	25.0 (5.8)	23.5 (4.7)	0.90 (0.78-1.04) P=0.16	0.92 (0.77-1.10) P=0.37
Total	174.7 (38.1)	166.0 (35.6)	0.92 (0.79-1.08) P=0.32	0.94 (0.80-1.12) P=0.50
Flexion:Extension	0.74 (0.14)	0.78 (0.14)	1.13 (0.93-1.38) P=0.23	1.13 (0.97-1.33) P=0.13

*incidence rate ratio for a 10% increase in each variable.
**adjusted for age, BMI, clustered on club.

Table 21 Geometric Mean baseline neck strength (kg) by concussion.

	Geom. Mean (Geom SD)		
Range	**No concussion N=196**	**Concussion N=29**	**P value (t-test)**
Right rotation	24.6 (1.3)	24.7 (1.3)	0.98
Left rotation	25.2 (1.3)	25.0 (1.3)	0.86
Extension	42.5 (1.3)	38.2 (1.2)	0.023
Flexion	31.5 (1.3)	29.6 (1.3)	0.17
Right flexion	24.6 (1.3)	23.0 (1.2)	0.15
Left flexion	25.0 (1.3)	23.5 (1.2)	0.18
Total	174.7 (1.2)	166.0 (1.2)	0.25
Flexion:Extension	0.74 (1.2)	0.78 (1.2)	0.17

Paired t-test

Table 22 Test for non-linearity

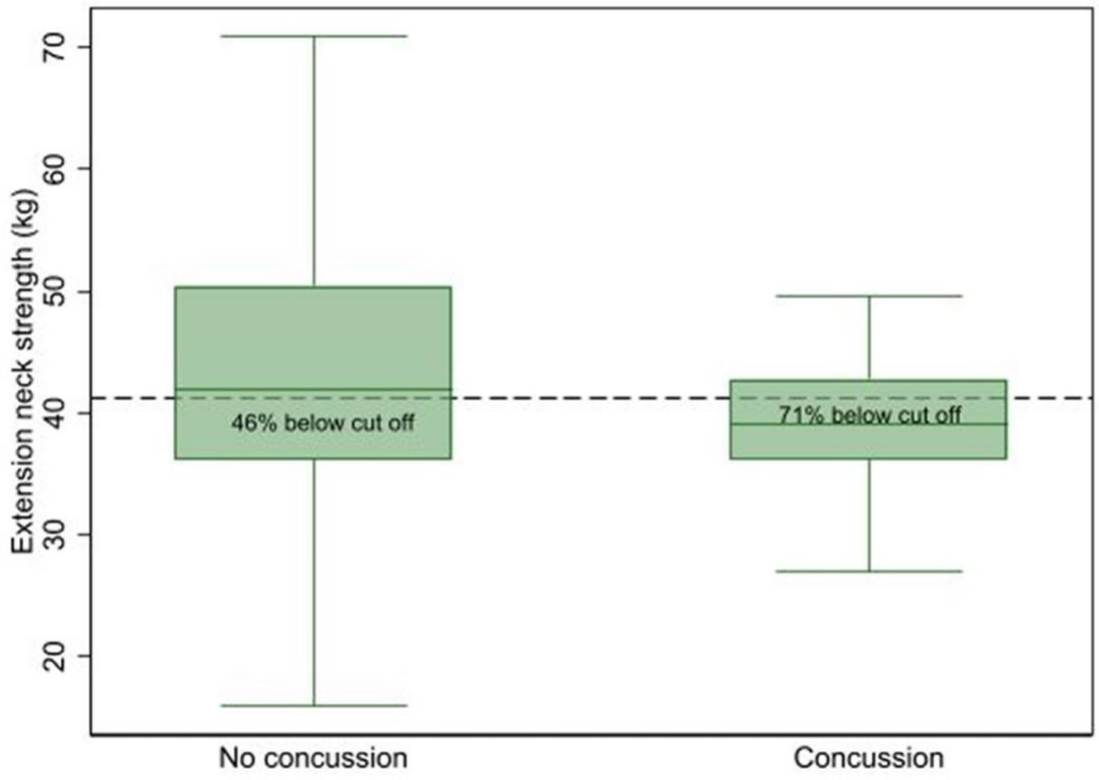
Range	Restricted cubic spline vs. linear model
Right rotation	P=0.68
Left rotation	P=0.04
Extension	P=0.23
Flexion	P=0.94
Right flexion	P=0.07
Left flexion	P=0.34

Significance level p<0.008 (Bonferroni correction for 6 comparisons).

Identification of high-risk players according to neck extension strength

A neck extension strength score of 41.2kg or below indicates players most at risk of sustaining a concussion with a true positive rate of 71.4% and a false positive rate of 46.1% (figure 5). 47% of players lay below this threshold at baseline. Increasing neck strength from below to above the threshold would decrease the expected rate per 1000 player hours from 17.6 to 6.8 in these players (absolute rate difference= -10.8 (95% CI: -20.4 to -1.2).

Figure 5 Discrimination for neck strength - extension



Inter-rater reliability

Inter-rater reliability was measured using the intraclass correlation coefficient (ICC) comparing the variability of ratings of the same individual to the total variation of ratings for all individuals. Measurements were averaged over the three trials. The overall agreement was fair to excellent for all ranges of neck strength measures between two raters (0.706-0.985)

Discussion

The author accepts the hypothesis that a significant association between neck muscle strength and concussion incidence would exist in male professional rugby players. The importance of this question is highlighted by the high incidence and reinjury rate of concussion in rugby(200) as well as the increased risk of musculoskeletal injury following return to play(7). These considerations demonstrate the importance of identifying modifiable factors that predispose athletes to concussion, paving the way for interventions to mitigate such risk, much like rule change in some sports has done to reduce the frequency of concussive events occurring(201).

This study is the first to identify a specific neck strength range associated with increased concussion rate in an athletic population and the first to identify that reduced neck strength is a risk factor for concussion in male professional rugby players. I observed a rate of 13.7 concussions per 1000 player-match-hours which is consistent with concussion rates in professional male Rugby Union(5-7). When adjusted for player match exposure, my results demonstrate that for every 10% increase in extension strength there is a 13% decrease in concussion rate. Further, I have identified what might be described as a minimally acceptable neck extension strength of 41.2kg. By highlighting those athletes with neck extension strength below this range, we are able to identify 71.4% of players that will sustain a concussion over the course of a professional rugby season. While it is important to acknowledge that a false positive rate of 46.1% exists in this analysis, it may provide rugby performance departments a target neck strength to work towards, providing further objectivity and rationale to strength training interventions. The limitations of the Youden index in the context of these results are important to highlight. The Youden index has been shown to display a greater risk of bias for skewed data with small sample sizes(202), although it is suited to determining optimal cut-off limits of a diagnostic variable(203). When interpreting the box plots presented in figure 4, overlap between the concussed and non-concussed groups can be seen within the whiskers that indicate variability outside the upper and lower quartiles. A total of 25% difference in neck extension strength is observed between the concussed and non- concussed groups.

These results build on earlier work by Collins(92) who found that a lower composite neck strength score was a risk to concussion in a mixed group of high school athletes. While some studies have found no significant association with neck muscle function and head movement velocity during simulated impacts(90, 204, 205), many of the lab-based studies have simulated impacts using a sudden backward pull of a participants head(204-209), promoting a reaction from the flexor muscle group of the neck. My results suggest that the extensor muscles may have a larger role to play than previously thought in attenuating forces of impact. The cervical extensors are consistently reported to be the muscle group that generate the highest isometric neck force(114, 210, 211). It may be possible therefore that this strength range represents the greatest defensive mechanism at reducing the force of impacts during sagittal plane impact, previously identified as the most common direction of concussive impacts in male professional rugby players(195).

I found no significant association with concussion and any anthropometric or playing measure which is consistent with previous literature(92, 212). There was a trend towards a greater risk of concussion with playing rugby at senior or junior international level ($p=0.07$) but it is only possible to speculate as to the reasons for this trend. It may be that international players find themselves in contact situations more regularly or that they have a higher propensity for risk taking behaviour, both of which may make them better players and therefore more likely to represent at international level.

It is my belief that this study is also the first to track professional rugby players' neck strength over the course of a professional season using three equally spaced time points. A significantly lower neck strength existed amongst the study population at pre-season compared to mid and end of season time points ($P<0.0001$) correlating with the concussion incidence in this study. Nineteen of the 30 concussions occurred between pre-season and mid-season, when average player neck strength was lower, and 11 concussions were sustained between the mid and end of season time points. This suggests that sporting organisations may benefit from a strength and conditioning focus on neck strength interventions at pre-season to mitigate the risk of concussions in the first half of the season. Research has shown that it is possible to make significant improvements in extensor neck strength through targeted interventions(213). Mansell(205) observed a 22.5% increase in neck extensor strength following an 8-

week programme of twice weekly extensor complex strengthening at 55% to 70% of the athlete's 10-repetition max. Equally, Becker and colleagues observed a significant increase in neck extensor strength following twice weekly resistance band training over a six-week period(214).

These insights provide important new information, particularly to rugby playing populations and their support teams who are able to direct targeted intervention to minimise the risk of a significant health and socio-economic problem. Rugby has one of the highest incidence rates of concussion across all sports(215, 216). Injury data shows no sign of this incidence reducing(186) and although this is due to a multitude of different factors such as better identification and reporting, similar trends are seen in a number of contact sports(217, 218). Significant financial(219, 220) and future health concerns have also been linked to head impacts(221, 222), although it must be emphasised that the link between concussion and future health concerns remains unproven.

The evidence presented in this investigation highlights the importance of further research in this field including evaluating the presence of other modifiable risk factors, and interventional studies investigating the efficacy of neck strength training in reducing concussion incidence, across different groups including, age, gender and playing level. Other physical qualities of neck function such as joint proprioception, muscle stiffness, range of movement and even vestibular and oculomotor function have been shown to be factors in other common injuries(223, 224) and should be considered as part of future research in concussion risk reduction.

I feel that the methods employed in this study were robust. The method of strength assessment used(120) has been shown to have good to high inter-session and between session reliability and my reliability study investigating the reliability between testers also demonstrated high kappa coefficients. The inclusion of player match exposure was an important factor in determining the true concussion risk, as those players who had low playing time over the course of the season were accounted for in the final statistical analysis. I was also fortunate to conduct this study on a well-controlled sample whose primary focus was their participation in a single sport. All clinicians responsible for diagnosis and reporting concussions during the study period

were blinded to the neck strength results of this study and were therefore less likely to be open to bias when making clinical decisions on player diagnosis.

Although the concussion rates in this study are consistent with the rates observed in previously published literature(5-7), for the purpose of statistical power, a relatively low number of concussions were recorded (29 concussions in 30 players). This may have impacted the strength of conclusions that can be drawn from the results presented.

Although all concussions occurred in match play, I did not take into consideration the type of training that each team was undertaking and therefore could not assess any additional risk that this would pose. Furthermore, this study had a significant drop out rate at end of season testing due to an international rugby competition. This made my end of season strength measures appear artificially low when compared to mid-season, however this was accounted for when analysing the difference in neck strength between time points. The difference in mean strength observed occurred because players that completed post-season testing had lower mid-season scores than the average and therefore were over represented in the end of season mean.

In order to causally test the effects of neck strength on concussion risk I looked for correlation in the regression model. From this evidence, assumptions on causality have been made, strengthened by accounting for random (individual player) and fixed effects, including age, BMI and clustered by club. Of course, it is not possible to account for all variables both internal and external, but the most reliable way of making these assumptions is through the execution of a controlled experiment.

One previous study has looked at the relationship between neck strength and concussion rate. Collins and colleagues performed a regression analysis, consistent with the current study, but made no discussion on causality within their analysis.

As no statistical technique exists that tests for causality(225) it is for the author and the reader to make assumptions on causality based on the methodological rigour of the study and the size of the effect, for which there is no threshold within statistical science or precedent within the field of concussion risk factors. I believe that an IRR for neck extension strength of 0.87 ($p=0.019$) allows for assumptions on causality to be made, especially considering the relatively small confidence interval compared to ranges with a p-value >0.05.

Conclusion

The findings of this study demonstrate that low isometric neck extension strength is a risk factor for concussion in male professional rugby players. I have gone further than previous studies in this subject by identifying a ‘minimally acceptable’ neck extension range that may help to guide sports medicine departments in formulating pre-season conditioning programmes.

Furthermore, this study is to my knowledge the first to track the next strength of male rugby players over the course of a professional season. I have observed that neck strength improves between pre-season and mid and end of season, suggesting that rugby players may be at greater risk of concussion during the early season. My data demonstrates that strength and conditioning may benefit from a focus on neck strengthening interventions during the early season.

Study Two- The relationship between cervical proprioception and concussion

Introduction

The prevalence and health impact of concussion is of growing concern at all levels of Rugby Union(200), including the professional game which has the highest incidence rate of concussion across all levels of the men's game(186, 226). Concussion rates in Rugby Union range from 8.9 to 21.5 concussions per 1000 player-match-hours at the elite level(5-7), with players more likely than not to suffer a concussion after 25 games(6). Concussion is now the most frequently occurring injury in professional rugby and has a mean time loss from competition of 19 days(186).

Up to 457 contact events occur per game in professional Rugby Union, 200 or which are tackles(227). The tackle has been reported to account for 58-64% of all match concussions in senior male players(192, 193), the most strongly linked match activity, followed by the ruck, kicking contests and mauls(194). Player position has been shown to have a significant impact on the number of contact events during a rugby match with forwards involved in up to 66% of tackles in a match(228) and backs carrying the ball into contact more times(229). When comparing concussion rates by position the evidence contradicts this and demonstrates consistently higher rates of concussion in backs(192, 199), with one study observing 22.5% more concussions in backs than in forwards over the course of two professional rugby seasons(230).

During a tackle, 1997 Newtons of force (equivalent to 204kg) is known to be transmitted to an opponent(231) , however there is currently no known minimal force threshold leading to concussion. Amongst the factors considered, contact technique has been identified, with head position proposed as a key variable(195, 232). Hendricks(195) graded tackling proficiency in a group of male rugby players and found that technical scores for head placement were lower during concussive tackle events, suggesting that head and neck position may be key in protecting against this injury. Simulated laboratory impacts have shown that an athlete is able to increase effective mass and momentum transfer by 67% by aligning the head, neck, and torso(142). One

conclusion that could be drawn from this is that there may be optimal joint positions of the cervical spine that help to mitigate the risk of a concussive event by spreading impact force to the torso rather than the head and neck. The ability to harness this protective mechanism could rely, in part, on effective cervical proprioception.

Joint and muscle proprioception is one physical ability known to have an interaction with MSK injury risk(233-235). In the neck, proprioceptors provide the central nervous system with information about position and movement of the cervical spine and initiate spinal reflexes that serve to provide stability and potentially limit head movement(121). Cervical proprioception is commonly measured via a method of joint reposition testing as first described by Revel(124). Cervical joint repositioning has been found to be significantly worse in rugby players versus non rugby playing athletes(121, 123) with neck extension the most significant source of error and no significant difference between forwards and backs(123).

There is minimal evidence of individual injury-prevention strategies designed to support the individual in addressing intrinsic risk factors for concussion in sport(27). To date, evidence of only one modifiable intrinsic risk factor has been demonstrated. In a study of 6704 mixed sport and sex high school athletes Collins(92) found that concussed athletes had a smaller mean overall neck strength than uninjured athletes, although no individual neck strength range was found to be more significant than another. One interventional study investigating 3188 school boy rugby players demonstrated that a global movement control programme conducted three times a week or more, comprising balance training, whole-body resistance training, plyometric training, and controlled rehearsal of landing and cutting manoeuvres, reduced contact injuries by 72% and concussion incidence by 59%(236). The mechanism behind this benefit is not fully understood, however it was hypothesised that results could be in part due to improved neck function as a result of increased neuro muscular function. No physical measures were taken pre or post intervention in this study, so it is not possible to verify this. Both of these studies have investigated amateur youth athletes which makes extrapolation to professional athletes difficult.

Despite the strong association between proprioception and neck injury(237-239), the link between cervical proprioception and concussion incidence is unknown.

Considering this and the implications of neuromuscular activation, neck muscle function, optimal joint position and tackle technique on force absorption and concussion risk, there is reason to hypothesise that this link exists. The aim of this study, therefore, was to establish whether a relationship exists between cervical proprioception and concussion incidence in a group of male professional rugby players. The author hypothesised that cervical proprioception would be positively correlated to concussion risk and therefore act as a risk factor to concussion. The null hypothesis is that there would be no significant association with cervical proprioception and concussion incidence across any cervical range.

Methods

Participants

Thirteen professional rugby teams were approached to participate in the study (four teams from the English Championship, one team in the Pro 14, and eight teams from the Georgian Didi 10).

A letter was sent to the Director of Rugby and CMO of each team outlining the study objectives, benefits and commitment required. Of the 13 teams approached, 11 agreed to be included with 165 players from those 11 teams willing and able to participate. A study information form and participant consent form were disseminated to each player through their medical team. Players were given two weeks to sign and return the consent form.

Anthropometry

Data collection was undertaken at each club's respective training base in a dedicated testing environment. Prior to testing, participants were consented to participate in the study and recorded for height and weight, as described in chapter one, General methods. Age, position, and medical history, including self-reported concussion history were recorded for each participant.

Equipment

A Senhang head mounted laser (figure 6e) was used to act as at reference point for the participants midline. The point of the laser was projected on to a laminated target 39cm in diameter (figure 6f).

Diagnosis of concussion

The diagnosis of concussion was made by team doctors who were experienced in the diagnosis and management of concussion and had all completed the World Rugby concussion education modules. Diagnosis was based on clinical judgement and comparison of pre-season neuropsychological tests, including the SCAT 5 and Cogstate. Neuropsychological assessment has been described by the Concussion in Sport Group (CISG) as a 'cornerstone' of SRC management. Following the diagnosis of concussion, the club physiotherapist notified the research team via email or phone call. Information given included the player's name and injury date.

Gathering match exposure data

Number of games played and match minutes were used to calculate players' match exposure. Exposure data were collected from three different sources due to the differing governing bodies responsible for overseeing the five study populations. Four teams' exposure data were collected from the National Rugby Football Union (RFU) that the teams played under, and the fifth team's exposure data were collected directly by the team sampled via their sports science and medicine department.

Gathering concussion data

Following the diagnosis of concussion, the club physiotherapist notified the research team via email or phone call and provided the following information: the name of the concussed player and date of injury. The research team followed up with the club physiotherapist a further four times during the course of the season to ensure that no concussions were missed for reporting.

Testing protocol

Participants were screened in a seated position for neck dysfunction by one of five clinicians, three physiotherapists, an osteopath and a sports therapist, all with over four years of clinical experience. Assessment included a cervical range of movement assessment assessing left and right-side flexion and rotation as well as flexion and extension. Over pressure was applied in the case that full range of movement was not achieved to investigate the presence of pain. Participants that had no evidence of pain through their cervical range of movement and no exclusion criteria were accepted to the study.

Participants were asked to sit upright in a straight back chair 90cm from a blank white wall. Hips and knees were positioned at 90 degrees with hands rested by their side. A lightweight Senhang® head-mounted laser was fitted to the participant's head with the light facing forwards. When comfortable placement of the head laser was achieved (figure 6e) the participant was asked not to touch the head laser for the duration of the test.

The head-mounted laser was then turned on and the participant was asked to rest in their perceived neutral neck position. Using the light from the head laser, the examiner placed the laminated target on the wall (figure 6e), ensuring that the centre of the target was in line with the point of the laser. The participant was at this stage instructed to memorise this head and neck position as their 'neutral' posture. Participants were familiarised with the task by performing one practice movement in each test direction (extension, left rotation, and right rotation) with their eyes open, returning to the centre of the target following completion of each range.

For the experimental procedure, participants were instructed to position the laser at the centre of the target and close their eyes. They were asked to perform right cervical rotation to the end of their available cervical range, taking two seconds to complete the outward movement and two seconds to return to their 'neutral' posture. When the participant felt that they had returned to their cervical neutral, they advised the examiner and the resting position was recorded on the target with a whiteboard marker. Two subsequent trials were performed to right cervical rotation. This was followed by three trials to left cervical rotation and then to cervical extension, providing exactly the same instructions. The point on which the laser beam stopped indicated the global error related to the centre of the target. Following the completion of each test, direction measurements (cm) were taken from each of the three recorded points, measuring the error from the x-axis (horizontal), y-axis (vertical) and the global error (figure 6f). Before each subsequent trial in a given direction, the participant was permitted to open their eyes and reposition to the centre of the target.

Figure 6 Test Positions Cervical Joint Position Error Test: Neutral cervical spine (A), right rotation (B), left rotation (C), extension (D), alignment of participant to target(E) laminated target 39cm diameter (F)

Re-test pre RTP

Following a diagnosis of concussion, the player was taken through a course of treatment deemed appropriate by the individual medical team and subsequently taken through the Graduated Return to Play protocol (appendix D2). At stage five of the protocol (full contact training) the player was reassessed for their Joint Position Error Score.

Assessment was completed by the club physiotherapist who was previously trained by the research team in the execution of the test. The test results were then sent to the research team via email using the participants study identification code.

Inter-rater reliability testing

Five raters, four physiotherapists and one osteopath, all with over five years of clinical experience were assessed for between tester consistency in measuring the JPET. Raters were asked to measure 12 identical targets randomly populated with three points to represent right cervical rotation, three points to represent left cervical rotation and three points to represent cervical extension. Raters measured the horizontal, vertical, and gross error for each point to the nearest 0.5cm and data were collated electronically by the primary researcher.

Statistical analysis

Data were analysed using Stata Version 14 (StataCorp, Texas). The study was powered to detect an effect size of 1.10 for a 10% increase in gross proprioception with 80% power at the 5% significance level using a base rate of 0.019 and mean exposure of 15.5 hours (retrospectively calculated using GPower 3.1). Normality of distributions was assessed using histograms and quantile-quantile plots. Because distributions of the proprioception variables were skewed, log transformation of the proprioception variables was used to meet the model assumptions. Geometric means and geometric SDs were obtained by exponentiating the means and SDs on the log scale. Changes in proprioception over time were modelled using a linear mixed model. A random intercept was fitted for player ID, and time was fitted as a fixed effect using two dummy variables to allow mid and post-season to be compared to pre-season as the reference category. The model was then reparameterised to allow comparison of the mid and pre-season values. Percent differences and 95% confidence intervals are presented. The variance partition coefficient (VPC) was calculated to illustrate how much

of the total variation in proprioception was accounted for by variation between subjects. The significance level for the pairwise comparisons was adjusted for multiple comparisons using the Bonferroni correction.

Associations of proprioception with concussion incidence were analysed by fitting a Poisson regression model with number of hours played as the exposure variable.
As exposure variables were log-transformed in the analysis, I present the incidence rate ratios (IRR) for concussion associated with a 10% increase in each proprioception variable. This was calculated by multiplying the coefficients and confidence limits obtained from the model by ln(1.1) before exponentiating to obtain IRRs and confidence intervals(240). A cluster option was used in the model to account for differences between teams. A priori covariates included in the adjusted model were age and BMI. Evidence for non-linearity was assessed by comparing models with restricted cubic splines to the linear model. Overdispersion was assessed by fitting a negative binomial model and testing whether the overdispersion parameter differed from zero (p=0.50).
Continuous variables are presented as mean (SD) and were compared between those with and without concussion using two-sample t-tests (height, age, weight, BMI). Comparisons of return to play measures with most recent measures were made using a paired t-test.

Results

Demographics

Of the players recruited to the study, 165 undertook testing at pre-season (between 14.08.18-22.08.18). Of these players 144 were tested at mid-season (08.01.19-21.01.2019) and 136 at the end of season (02.04.19-11.04.2019). Eleven players did not attend mid-season testing because they had been sent on loan to other clubs, four did not attend because they had a current concussion or cervical injury, and six players did not report for testing at their scheduled time. At the end of season time point, 11 players were on loan, six did not report for testing due to a current concussion or cervical injury, one did not report due to a medical issue and 11 players were absent from testing.

The median participant age was 23 years (18-35 years), mean height 184cm (165-201cm), and weight 98kg (73-128kg).

Table 23 Participant characteristics

Variable	Whole group (N=165)
Age, mean (SD)	23.9 (4.3)
Height, mean (SD)	184.2 (6.9)
Weight, mean (SD)	100.5 (13.6)
BMI, mean (SD)	29.6 (3.5)

Change in proprioception over time

When analysing changes in proprioception over time, gross left rotation values demonstrated a significant reduction in error between pre-season and mid-season(P=0.029), mid-season and end of season (P=0.058), and pre-season and end of season (P=0.0001). There was also a significant decrease in gross error between pre-season and mid-season (P=0.013) and pre-season and end of season (P=0.0003) but not between mid-season and end of season (P=0.248) for extension error. For right rotation there were no significant changes in gross error between each of the three testing points (P=0.195).

Table 24 Geometric mean Gross (Geom. SD) by range and time-point

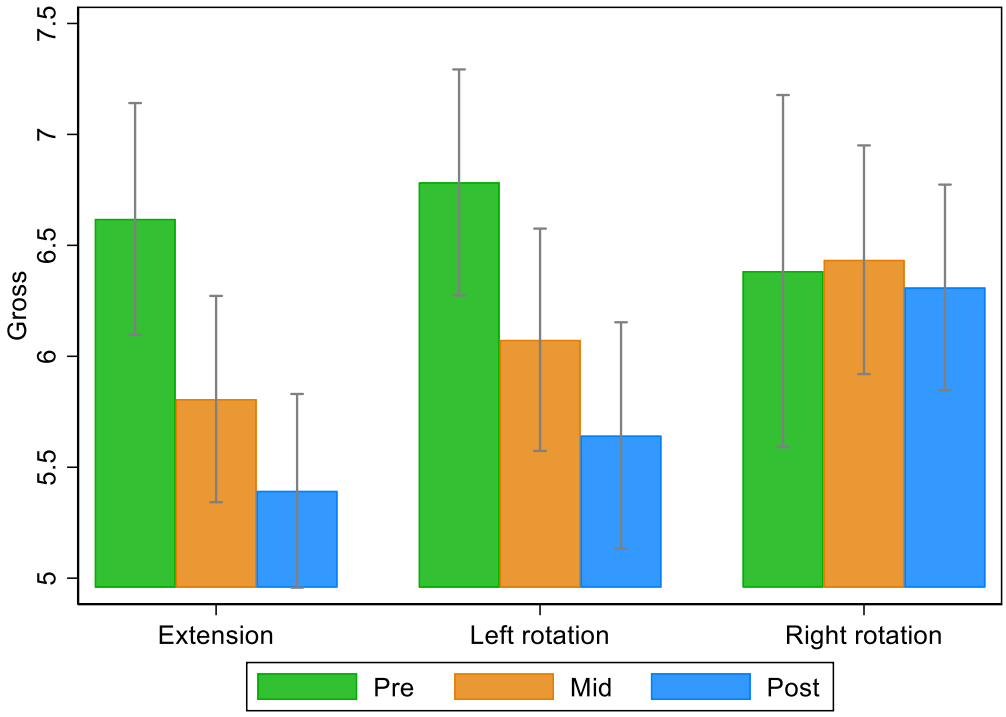
					Percentage difference (95% CI)**			**VPC*****
Range	**Pre N=162**	**Mid N=148**	**Post N=136**	**P value***	**Mid vs. pre**	**Post vs. mid**	**Post vs pre**	
Right rotation	5.52 (1.60)	5.92 (1.55)	5.86 (1.53)	0.195	7.6% (-1.0, 17.1) p=0.089	-1.2% (-9.5, 7.8) p=0.749	6.3% (-2.4, 15.8) p=0.181	0.303
Left rotation	6.17 (1.61)	5.59 (1.55)	5.08 (1.67)	0.0002	-9.4% (-17.3, -0.6) p=0.029	-9.5% (-17.8, 0.3) p=0.058	-18.0% (-25.3, -9.9) p<0.0001	0.261
Extension	5.97 (1.66)	5.24 (1.63)	4.92 (1.65)	0.001	-10.9% (-19.5, -1.2) p=0.013	-7.7% (-17.1, 2.7) p=0.248	-17.7% (-25.9, -8.7) p=0.0003	0.158

*p value from mixed effects regression model to take account of repeated measures data. Gross error is log-transformed in the analysis.

**significance level taken as p<0.017 for pairwise comparisons

***Variance partition coefficient indicating the proportion of variance attributable to variability between participants.

Figure 7 Mean Gross proprioception (95% CI) by range and time-point



Incidence of concussion

A total of 45 concussions incurred by 44 players were recorded over the study period (19.7/1000 player-match hours). Twenty-six concussions occurred between pre-season and mid-season and 19 between mid and end of season time points. All concussions were recorded in match play.

Relationship between anthropometry and concussion incidence

A significant association existed between concussion incidence and weight (p=0.008) and concussion incidence and BMI (p=0.035) in this study however there was no association between age or height and concussed incidence.

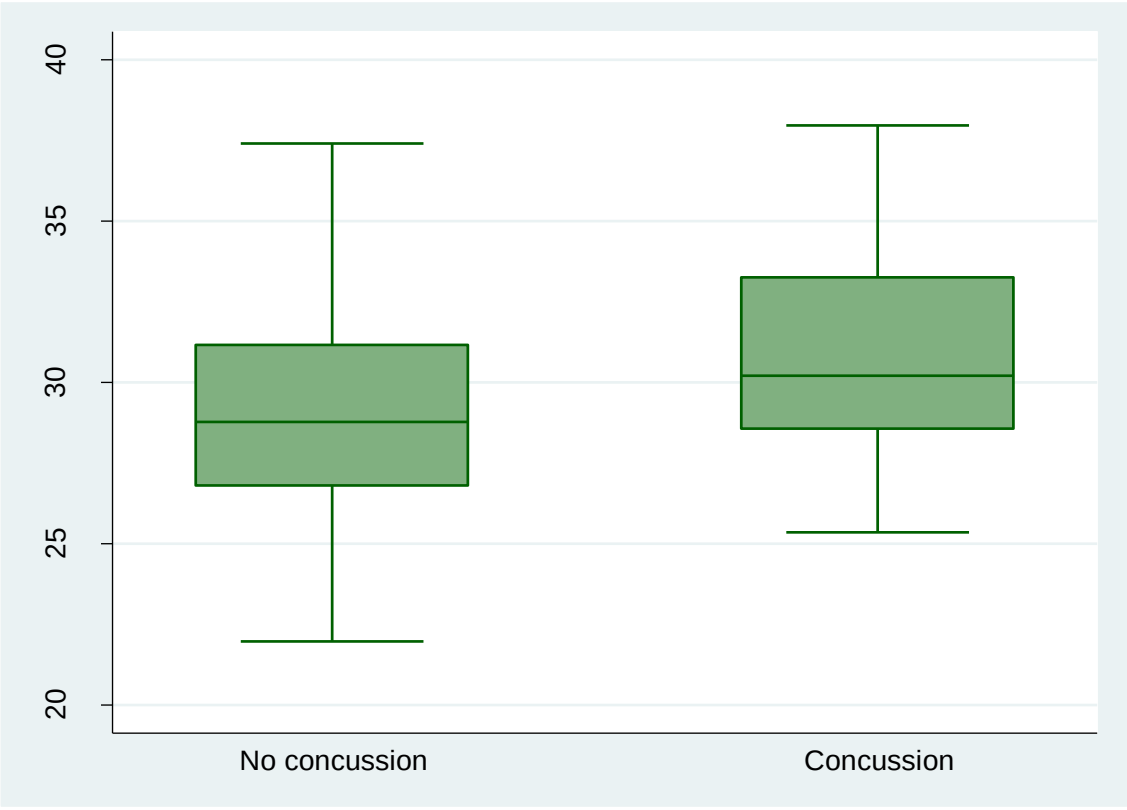
Table 25 Demographics by concussion

Variable	No concussion N=121	Concussion N=42	Overall N=163	P value[1]
Age, mean (SD)	23.7 (4.2)	24.5 (4.6)	23.9 (4.3)	0.27
Height, mean (SD)	183.7 (6.6)	185.8 (7.7)	184.2 (6.9)	0.11
Weight, mean (SD)	98.9 (14.0)	105.6 (11.0)	100.5 (13.6)	0.008
BMI, mean (SD)	29.3 (3.6)	30.6 (3.2)	29.6 (3.5)	0.035

[1] two-sample t-test

Figure 8 Mean weight by concussion incidence

Figure 9 Mean BMI by concussion incidence



Relationship between playing position and concussion incidence

Analysis of concussion rates versus playing position revealed that forwards in this study had double the risk of sustaining a concussion compared to backs (IRR=2.1 p=0.02). After adjustment for age and BMI the IRR was 1.97 (p=0.13). Props sustained the highest concussion incidence with a rate of 30.7 per 1000 player-match hours, followed by hookers (27.4), second row (24.2) and flankers (21.9). The back row position with the highest concussion incidence were centres, with a concussion incidence of 20.3 concussions per 1000 player-match hours. Rates for all positions are presented in table 26.

Table 26 Concussion rates by playing position (IRR, 95% CI)

Range	N	Number of concussions	Rate per 1000 hours	IRR (95% CI)*	IRR (95% CI)**
Back	71	14	12.08	1.00	1.00
Forward	90	27	24.84	2.06 (1.12-3.77)	1.97 (0.82-4.74)
P value				P=0.020	P=0.13
Full back	11	2	13.11		
Wing	14	3	11.93		
Centre	21	8	20.13		
Fly half	9	0	0		
Scrum half	16	1	5.22		
Prop	25	9	30.70		
Hooker	14	4	27.41		
2nd row	22	6	24.24		
Flanker	27	8	21.98		
Number eight	2	0	0		

*incidence rate ratio for a 10% increase in each variable.
**adjusted for age, club, BMI.

Relationship between cervical proprioception and concussion

Horizontal and gross error values were significantly higher for right rotation in those players who suffered a concussion. There is a 5% increase in concussion rate for each 10% increase in gross right rotation error (P=0.021) and a 6% increase in concussion rate for each 10% increase in right rotation along the horizontal plane (P=0.0001). There was no significant association in right rotation vertical error (P=0.57) or in left rotation or extension error in any plane of motion. After adjustment for age and BMI these effects remained significant.

Table 27 Geometric Mean proprioception values (approximate SD) by concussion

	Range	No concussion N=119	Concussion N=42	IRR* (95% CI)- univariate	IRR** (95% CI)- adjusted
Horizontal	Right rotation	3.39 (1.91)	4.38 (1.66)	1.06 (1.03-1.09) P<0.0001	(1.04-1.09) P<0.0001
	Left rotation	4.14 (1.91)	3.92 (1.79)	0.997 (0.97-1.02) P=0.82	0.99 (0.95-1.03) P=0.67
	Extension	2.10 (1.98)	2.12 (2.00)	1.01 (0.95-1.08) P=0.65	(0.96-1.05) p=0.76
Vertical	Right rotation	4.05 (1.52)	4.26 (1.66)	1.02 (0.96-1.09) P=0.57	(0.92-1.11) P=0.83
	Left rotation	4.43 (1.70)	4.12 (1.55)	0.97 (0.93-1.01) P=0.11	0.96 (0.92-1.00) P=0.03
	Extension	5.79 (1.62)	5.72 (1.67)	0.995 (0.96-1.04) P=0.82	0.98 (0.94-1.02) P=0.30
Gross	Right rotation	6.35 (1.46)	7.05 (1.55)	1.05 (1.01-1.10) P=0.021	1.05 (1.00-1.10) P=0.04
	Left rotation	7.28 (1.52)	7.01 (1.42)	0.98 (0.92-1.04) P=0.49	0.96 (0.90-1.02) P=0.20
	Extension	7.01 (1.53)	6.88 (1.53)	0.996 (0.95-1.05) P=0.86	0.98 (0.93-1.02) P=0.33

*incidence rate ratio for a 10% increase in each variable.
**adjusted for age, club, BMI.

Figure 10 Horizontal right rotation error for concussed and non-concussed

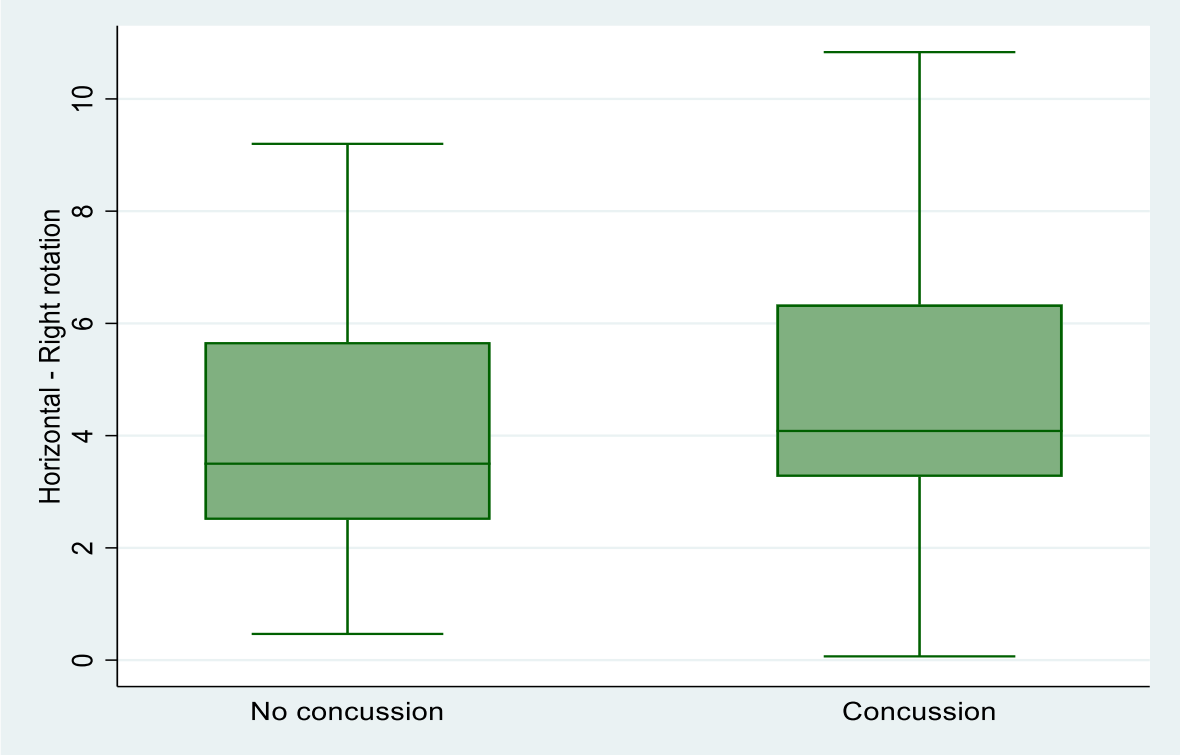
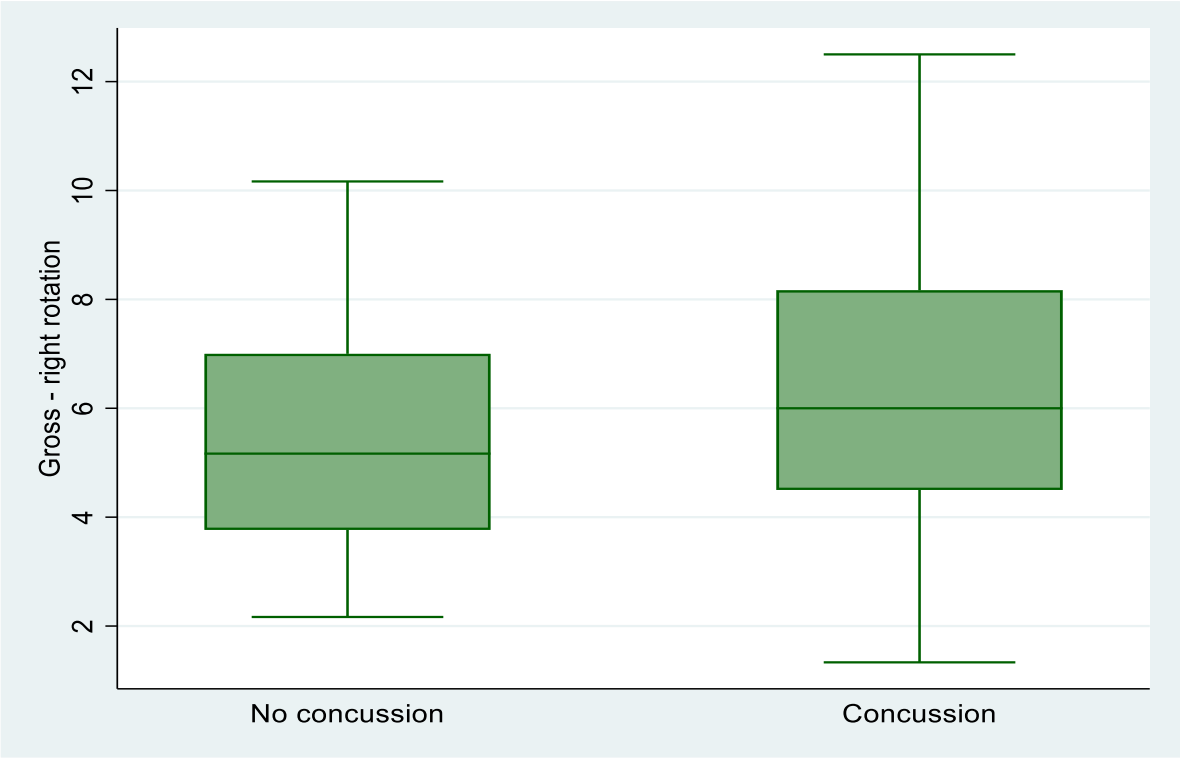


Figure 11 Gross right rotation error for concussed and non-concussed



Of the players who sustained a concussion during the study period, 12 were tested for cervical proprioception the day before or on the day of full contact training. Following a concussion, no significant change in cervical proprioception was observed at the point of return to full contact training for gross right rotation (P= 0.40), left rotation (P=0.36), or extension (P=0.45). The same theme was observed for horizontal right rotation (P=0.79), left rotation (P=0.48), or extension (P=0.75) and for vertical right rotation (P=0.18), left rotation (P=0.59), or extension (P=0.33).

Table 28 Return to play gross error vs. most recent measure

	Gross			
Range	**Most recent**	**Return to play**	**% Difference (95% CI)**	**P value**
Right rotation	5.33 (3.17)	6.23 (4.16)	16.9% (-21.5, 74.2)	0.40
Left rotation	6.18 (2.71)	5.11 (2.03)	-17.2% (-46.8, 29.0)	0.36
Extension	4.80 (3.45)	5.70 (2.72)	18.7% (-27.2, 93.6)	0.45

*paired t-test

Table 29 Return to play horizontal error vs. most recent measure

	Horizontal			
Range	**Most recent**	**Return to play**	**% Difference (95% CI)**	**P value**
Right rotation	3.01 (2.89)	3.23 (4.63)	7.2% (-39.6, 90.1)	0.79
Left rotation	3.44 (2.15)	2.79 (1.80)	-18.8% (-56.8, 52.3)	0.48
Extension	2.23 (1.59)	2.42 (1.47)	8.7% (-37.8, 90.0)	0.75

*paired t-test

Table 30 Return to play vertical error vs. most recent measure

	Vertical			
Range	**Most recent**	**Return to play**	**% Difference (95% CI)**	**P value**
Right rotation	2.25 (2.22)	3.47 (2.53)	54.2% (-21.7, 203.6)	0.18
Left rotation	3.69 (2.10)	3.21 (2.11)	-13.1% (-50.5, 52.6)	0.59
Extension	3.09 (3.00)	4.51 (2.54)	45.9% (-35.5, 230.2)	0.33

*paired t-test

Inter-rater reliability

Inter-rater reliability was measured using the intraclass correlation coefficient (ICC), comparing the variability of ratings of the same individual to the total variation of ratings for all individuals. Across five raters measuring the results of 12 charts the overall agreement was moderate to excellent across all ranges (right rotation, left rotation and extension) for horizontal, vertical and gross measures (0.687-1.000).

Discussion

The author accepts the hypothesis that there is a significant association between poor cervical proprioception and concussion incidence in male professional rugby players. This question was deemed important due to the severity, frequency and time loss from competition associated with concussion across all levels of rugby(200), and the dearth of evidence around modifiable intrinsic risk factors to this injury(27, 241). I have demonstrated that low cervical proprioception is a risk factor to concussion in male professional rugby players, with horizontal error and gross error values significantly

higher for right rotation in those who suffered concussion. The concussion incidence in this study (19.7 concussions per 1000 player-match hours) is consistent with incidence rates previously presented within the literature(5-7).

To the author's knowledge this is the first time that cervical proprioception has been shown to be a risk factor to concussion and only the second modifiable intrinsic risk factor to be associated with concussion following the work by Collins(92), who found a significant association with poor composite neck strength and concussion in a group of high school athletes.

The literature concerning modifiable risk factors to concussion is limited, however existing lab-based studies provide some insight into the possible mechanisms behind my results. Muscle strength and anticipatory muscle contraction are thought to reduce the velocity of head shake during an impact, which in turn reduces the risk of brain injury(242). A body of evidence exists that demonstrates that it is the speed of neck muscle contraction or stiffness, rather than muscle strength that attenuates the force of an impact(90, 96, 243, 244).

It is of course true that the two physical qualities of neck muscle strength and stiffness may be strongly linked but it is likely that the regional proprioceptors, the golgi tendon organs and muscle spindles, form much of this stiffness response(245, 246).

The other important role of the proprioceptors is that of aligning the head and neck with the torso. Evidence suggests that the optimal head, neck and torso alignment may lead to greater efficiency when absorbing the force of an impact(142), with the most likely mechanism of optimal positioning being that of regional proprioception(247, 248).

Regarding the unilateral nature of my findings (right rotation error showing significant association with concussion incidence), I can only hypothesise as to the reason for this. Although to my knowledge no published evidence exists concerning tackle side, it is commonly accepted within rugby that players are more likely to tackle with their dominant shoulder, in most cases the right, making the right side of the neck the contact side. This may expose those athletes who have a deficit in right sided proprioception to injury as a result of sub-optimal cervical positioning and poor muscle stiffness. It is also true that in this study right rotation repositioning error was the only

direction that did not improve over the course of the season, possibly due to repeated trauma from tackling. Further research is required to investigate the inclination of rugby players to tackle with their dominant shoulder and neck. Furthermore, the difference in tackle technique and head position during concussive and non-concussive tackle events should be investigated. It is of course important to acknowledge that, although it is the most common concussion inducing incident in rugby(230, 249), not all concussions occur in the tackle, and this study has not recorded the mechanism of injury. I am therefore not able to definitively make this correlation.

This study is, to the author's knowledge, the first paper that has tracked cervical proprioception in players over the course of a professional rugby season. A statistically significant reduction in cervical repositioning error was found in left rotation and extension over the course of the season. This trend points towards cervical proprioception improving with number of matches played and correlates with the concussion incidences in this study, which observed the majority of concussions occurring between pre-season and mid-season testing. There was no improvement in gross right rotation repositioning error between pre-season and mid-season and mid-season and end of season time points. This may be a reflection of what is likely to be an increase in contact events to the right side as mentioned above. Lark and McCarthy (2007) postulated that muscular damage to the neck and shoulder region may have affected mechanoreceptors leading to proprioception being compromised(123). This have may have led to the reduction rather than an improvement in cervical proprioception seen in this study during right rotation.

With regard to deficits in cervical proprioception at return to play following a concussion, no significant deficit was found to exist between return to play scores and the most recent pre-injury screening score, indicating that cervical proprioception is unchanged as a result of a concussive injury. This may be a symptom of low numbers in this arm of the study and greater numbers may tell a different story, especially given the trends observed in many of the return to play JPET scores in this study.
While the diagnosis of concussion is concerned with the brain injury only, the similar and overlapping symptoms originating from other local structures following an impact cannot be overlooked. Symptoms arising from cervical spine injury are consistent with

those of concussion(70) and may confuse the clinical picture when making a diagnosis or establishing readiness to return to play. Poor cervical proprioception is strongly associated with neck pain(250) and symptoms arising from the neck are thought to occur due to damage of the proprioceptors involved in head and neck position sense(47, 83, 251).

The results found in this study highlight that early identification of poor cervical proprioception may help medical teams to put strategies in place to enhance cervical proprioception and reduce concussion risk. Recent research has demonstrated that cervical joint position sense can be improved through specific proprioceptive training(250) although the long-term benefit of this training was not recorded. Future research will need to apply these methods to an interventional study as well as looking at other athletic groups.

Methods used in this study were designed to be reflective of the equipment available to most sporting medical teams and although other tools for measuring cervical proprioception exist that may be deemed more reliable(157, 252), they often come with a high monetary and time cost. My methods take in the region of 10 minutes to complete per athlete and equipment can be purchased at a low cost.

This study was performed on healthy professional male rugby players. Results presented here may be transferable to other sporting and non-sporting populations, however further research is required to investigate this. I did not blindfold players when conducting the JPET as it was not felt practical in the sporting setting to blindfold players and may have led to movement of the head laser. The reliability study shows fair to good correlation coefficients and I am satisfied that this action did not unduly affect my results.

Conclusion

Using the JPET for cervical proprioception, it is possible to highlight rugby players who are at greater risk of concussion. The CJPET is a fast and cheap test to set up and does not require specialist equipment. The results of this study also show that cervical proprioception improves over the course of a rugby season, indicating that players may be at greater risk of sustaining a sports-related concussion in the first half of the season.

Study Three- The impact of high intensity exercise on vestibular-oculomotor function

Introduction

The vestibular-oculomotor system is a complex sensorimotor system responsible for detection of motion, stabilisation of gaze, regulation of head position and associated motor responses(75). Injury can occur to both central and peripheral vestibular-oculomotor structures, with dysfunction commonly associated with head trauma(75). Vestibular and oculomotor dysfunction following a concussive injury is a well-documented comorbidity (70, 253) and is associated with an increase in symptom severity and prolonged recovery from SRC(73, 253). Following SRC 85-90% of patients will recover to their neurological baseline within 1–2 weeks however the remaining 10-15% will suffer persistent symptoms (254). Patients complaining of persistent symptoms such as headache, dizziness, balance disturbances and visual disturbances such as screen intolerance and photosensitivity have traditionally been categorised as suffering from 'post-concussive syndrome' (PCS)(72, 253), however it is now clear that there may be contributing pathologies to these persistent symptoms.

The presence of vestibular, oculomotor and cervical dysfunction following SRC has been observed in 58-81% of patients(70, 73). In a retrospective review of 247 patients Corwin(73) found patients with vestibular signs on initial examination took significantly longer to be cleared to return to full activity (median 106 days vs 29 days, p=0.001) compared to age-matched patients with no vestibular findings. The lasting impact of vestibular and oculomotor dysfunction has also been observed by Elbin and colleagues who found a significant deficit in pre-injury vestibular and oculomotor performance up to 14 days post injury(179). Although the literature associated with this topic displays mixed methodology and is largely based on adolescent athletes, it highlights a significant link between SRC and vestibular-oculomotor dysfunction. The identification of vestibular-oculomotor dysfunction as a comorbidity to concussion has led to greater interest in its identification in a sporting setting where specialist equipment is often unavailable(76, 110). A number of concussion testing batteries now include elements of vestibular-oculomotor assessment (255) as well as stand-alone

tests designed to identify the presence of concurrent vestibular-oculomotor dysfunction(111, 174). The reliability of these tests in diagnosing concussion(76, 256) and identifying vestibular-oculomotor dysfunction(174) have been shown to be favourable and are commonly being used for side line concussion evaluation in sports settings which may have an impact on test-retest reliability.

The impact of exertion on concussion assessment tools has been shown to have a detrimental effect on performance when considering the Modified Balance Error Score (mBESS)(102) and the Sport Concussion Assessment Tool (SCAT)(257), however an improvement in test scores has been observed following moderate intensity exercise prior to conducting the King-Devick test(258).

The Vestibular/Oculomotor Screening (VOMS) tool is a test battery developed to assess vestibular and oculomotor function following a mechanism of injury consistent with a concussion(76). It has recently been proposed as an aid to concussion diagnosis, demonstrating high test-retest reliability and diagnostic accuracy(76, 111). Due to its proposed use as a side-line concussion evaluation tool, Moran(259) assessed the impact of high intensity exercise on VOMS in a population of 17 (nine male, eight female) healthy, recreationally active, college-aged participants (20.7 ± 2.3 years). Using heart rate and the Borg scale to monitor the intensity of a treadmill run, participants ran at a mean heart rate of 192.2 ± 9.3 bpm, and mean RPE of 17.8 ± 1.5. When post-run VOMS scores were compared against baseline, no significant difference was noted on any VOMS component. These findings are consistent with those of Worts(178) who observed agreement of between 57.8-91.1% in VOMS scores between baseline and post practice, indicating minimal impact of exertion. Contrary to these findings Ratka(260), investigated the impact of a fatigue protocol of running and body weight exercise on baseline VOMS scores in a group of 15 healthy adults (22.20 ± 1.424 years) using RPE and heart rate to assess exercise intensity. In this study a statistically significant interaction effects for NPC (p=0.008) and total VOMS scores (p=0.005) was observed between pre and post exertion.
While all of these studies assessed VOMS post-exercise the time between exercise cessation and initiation of testing was unspecified and study participants exercised at different exercise intensities, making comparisons difficult. Little is currently known about the immediate impact of high intensity exercise, consistent with the demands of

sporting performance, on VOMS findings or variability especially when considering age, sex and physical activity status. These factors may have implications when interpreting VOMS and govern decisions as to the timing of test administration following a suspected concussion.

The aim of this study was primarily to investigate the immediate impact of high intensity exercise on VOMS performance. Secondary aims were to investigate the difference across different populations, including activity levels, sport and sex.

The author hypothesises that there will be a significant difference in VOMS scores following high intensity exercise and further variation will be observed between different groups, including activity level, sport and sex.

Methods

Participants

UCL's Sports Development Manager, responsible for the coordination of UCL sporting societies was approached to offer support and contacts to UCL sports teams. This was agreed following a face-to-face meeting between the post holder and the primary researcher. Following the meeting, emails were sent to the club presidents of men and women's rugby and women and men's hockey inviting them to participate in the study. Upon agreement an email was disseminated to the first and second team of each squad and participants were invited to make contact with the research team if they wished to participate.

Student athletes were provided with study information and a participant consent form two weeks prior to data collection. Upon reporting to data collection, the participants were asked to hand in their consent form. If they had not brought it, they were provided with a form to sign prior to testing.

Anthropometry

Equipment

Tape measure (cm), Metronome, Tongue depressor with letter 'E' 12-point font printed at end. Treadmill h/p/cosmos locomotion® 150/50 DE med.

Testing protocol

Participants were invited to a private lab setting and seated in a straight-backed chair. The participant was positioned opposite the examiner, 90cm from the test target. The participant was asked to provide a symptom score on a 0-10 numerical rating (0- no symptoms, 10- very high severity) for headache, dizziness, fogginess and nausea prior to commencing testing. If they did not understand any of the symptoms, an explanation was given to ensure that they understood the correct way in which to report. Corrective lenses were worn if required by the participant to view the examiner and target with visual clarity.

Following the recording of baseline symptoms testing was commenced. Participants completed the full vestibular/ocular-motor testing battery, seven tests including smooth pursuits, horizontal saccades, vertical saccades, convergence, horizontal vestibular-ocular reflex (VOR), vertical VOR and visual motion sensitivity (VMS). Following each test participants were asked to rate their symptoms (headache, dizziness, fogginess, and nausea) out of 10. When the symptoms had returned to baseline the next test was then started.

Smooth pursuits

The examiner holds the tongue depressor at eye level and moves it 45cm to the left and 45cm to the right of the participant's midline. One repetition is complete when the target has moved to the left and the right and returned to the start position. The target is moved at a rate requiring two seconds to move from midline to left and back and two seconds to move to the right and back to midline. Two repetitions of the test are completed and the participant asked to provide subjective scores for the presence of each of the four symptoms.

Horizontal saccades

The examiner holds two points 45cm to the left and 45cm to the right of midline so the participant's gaze is taken 30 degrees in each direction. The participant is then instructed to look from left to right as quickly as possible while keeping their head still. One repetition is counted when the participant has moved their eyes in both directions and returned to the midline. Ten repetitions are completed.

Vertical saccades

The examiner holds two points 45cm above and 45cm below the participant's midline so the participants gaze is taken 30 degrees in each direction. The participant is then instructed to look from up and down as quickly as possible while keeping their head still. One repetition is counted when the participant has moved their eyes in both directions and returned to the midline. Ten repetitions are completed.

Convergence

A tongue depressor with a letter 'E' in Arial font size 12 was held by the examiner at arm's length. The participant was instructed to focus on the 'E' while the examiner slowly moved it towards their nose. The participant was asked to inform the examiner when they experienced double vision (two distinct images) and the examiner looked for an outwardly deviating eye, both signifying the end of the test. Blurred vision was ignored.

The distance was recorded at the point that the test was terminated to the tip of the nose. Three trials were conducted and each one recorded in centimetres using a ruler.

Horizonal vestibular-ocular reflex

The participant fixed their gaze on the target and moved their head horizontally 20 degrees to the left and 20 degrees to the right. A speed of 180 beats per minute was followed using a metronome (one beat in each direction). One repetition was complete when the head moved to the left and right and 10 repetitions were performed.

Vertical vestibular-ocular reflex

The participant fixed their gaze on the target and moved their head vertically 20 degrees up and 20 degrees down. A speed of 180 beats per minute was followed using a metronome (one beat in each direction). One repetition was complete when the head moved up and down and 10 repetitions were performed.

Visual motion sensitivity

The participant stood with feet shoulder width apart facing the examiner. The participant held their arm out straight in front of them with their thumb up. While focusing on the thumb the participant rotated their trunk 80 degrees to the left and 80 degrees to the right, keeping their outstretched arm rigid. The test was performed at a

speed of 50 beats per minute (one beat in each direction). One repetition is complete when the participant rotates from left to right. Five repetitions were completed.

Figure 12 VOMS tests: Smooth pursuits (A), Saccades (B), Convergence (C), Vestibular-ocular reflex (D), Visual motion sensitivity (E) Tongue depressors (F)

Interpretation of symptoms provocation at baseline

A positive test (symptom exacerbation) was recorded as a symptom score >2. For convergence, if the score was >5cm then it is positive. The number of positive tests for each player is the sum of the positive tests over the four symptoms and seven domains.

Interpretation of symptom provocation post run

A positive test (symptom exacerbation) was recorded as a symptom score post-exercise greater than two points above pre-exercise. For convergence, if the score was below 5cm pre-exercise and above 5cm post-exercise then it is positive. If it was above 5cm pre-exercise, then an increase of >2cm was considered positive.

The number of positive tests for each participant is the sum of the positive tests over the four symptoms and seven domains (range 0-28).

Static bike warm up

Following completion of baseline testing, participants were invited to undertake a 3-minute static bike warm up. They were instructed to maintain a 40 watt output which could be monitored on a screen in front of them. Resistance levels and cadence to achieve this wattage were self-selected.

Treadmill run

Following the completion of the warmup, participants were invited to complete a 5-minute treadmill run at a Rate of Perceived Exertion of 17/20 on the Borg scale. Borg's rating of perceived exertion (RPE) is a widely used psychophysical tool used to assess subjective perception of effort during exercise due to its strong correlation with physiological markers of exercise intensity including heart rate and blood lactate (261).

Participants were familiarised with the Borg scale using a visual representation of the scale (see appendix D1) and asked to step on to the sides of the treadmill, avoiding the central belt. The treadmill was then started at a speed of 7mph and the participant was asked to lower themselves onto the moving belt and start running. As this point the treadmill speed was increased until the participant indicated that they had reached an RPE of 17/20. The time taken to reach this RPE was recorded for all participants.

RPE was monitored throughout the run and the treadmill speed was reduced when the participant indicated that their perceived exertion had exceeded 17/20. This was repeated for the duration of the run. Following completion of the run participants were asked to move immediately to their seat and post exercise VOMS testing was started.

Post run VOMS testing

Post-run VOMS testing utilised an identical testing procedure to that employed at baseline testing. Following the initial post-run VOMS test (Post run 1) participants were given a 30 second rest before commencing Post run test 2. A third post-run VOMS test was only initiated if the participant displayed symptoms on Post run 2. If there were no symptoms on Post run 2 testing was terminated.

Intra-rater reliability testing

24 asymptomatic mixed gender (12 male) and activity level 18–35-year-old participants were assessed by a single rater for intra-rater reliability. A single VOMS test was administered under identical test conditions. Following a 10-minute break a second test was administered and consistency between the two tests were compared.

Statistical analysis

Data were analysed using Stata Version 16 (StataCorp,Texas). The number of positive tests for each participant was calculated as the sum of the positive tests over the four symptoms and seven domains. Results are presented as the median number of positive tests with interquartile range and the number and percentage of participants with at least one positive test. The proportions with a positive test were compared between different groups using Fisher's exact test. In addition, an exact logistic regression model was used to allow adjustment for baseline characteristics. Within-participant differences in positivity between time-points, symptoms and domains were tested using Cochran's Q test. Post-hoc pairwise comparisons were made with the significance level Bonferroni corrected to allow for the number of comparisons made. Symptom scores were summed over the four symptoms and seven domains to get an overall score for each person at baseline and at each follow-up. The baseline score was subtracted from each follow-up score to give the change in score. Normality of data were assessed using histograms. Changes were compared between groups using Kruskal-Wallis test and within groups using Wilcoxon signed-rank test.

Results

Participant demographics

Seventy-five participants took part in data collection. Forty-five collegiate athletes [18 male rugby players, 14 female rugby players, 3 male hockey players and 10 female hockey players] were included for analysis, alongside 30 sedentary participants [13 male and 17 female] (table 31). Sedentary was defined as failing to meet the U.K governments exercise guidelines of at least 150 minutes of moderate intensity activity a week or 75 minutes of vigorous intensity activity a week(262).

Participant demographics are presented in table 28. There was a significant difference between groups for age (p=0.029), weight (p=<0.0001) and height (p=<0.0001).

Table 31: Participant demographics

	MR N=18	FR N=14	FH N=10	MSED N=13	FSED M=17	Total N=72	P value
Age median [IQR]	22 [21-23]	20 [19-22]	20.5 [19-21]	22 [22-26]	21 [21-29]	21 [20-23]	0.029[1]
Range	19-24	19-26	19-23	19-35	19-32	19-35	
Mean (SD)	21.6 (1.6)	21 (2.3)	20.5 (1.4)	24.5 (5.0)	24.5 (4.7)	22.5 (3.7)	0.003[2]
Sex							
Male	18 (100%)	0 (0%)	0 (0%)	13 (100%)	0 (0%)	41 (56.9%)	
Female	0 (0%)	14 (100%)	10 (100%)	0 (0%)	17 (100%)	31 (43.1%)	-
Weight, mean (SD)	88.4 (13.4)	62.7 (7.8)	63.8 (6.8)	76.2 (9.0)	60.3 (10.7)	71.1 (15.2)	<0.0001[2]
Height, mean (SD)	179.4 (6.3)	164.7 (6.4)	166.6 (4.8)	175.8 (7.5)	163.9 (7.7)	170.5 (9.3)	<0.0001[2]

[1]Kruskal-Wallis test, [2] unpaired t-test.
MR= Male rugby, FR= Female rugby, FH= Female hockey, MSED= Male sedentary, FSED= Female sedentary

Mean time to 17/20 Rate of Perceived Exertion (RPE)

In order to ensure standardisation of exercise intensity across groups, the time to reach an RPE of 17/20 was recorded for each individual (table 32). All groups mean time to 17/20 RPE was within the target time frame of 30 seconds.

Table 32: Mean time to 17/20 RPE

Group	Average time (seconds) to 17/20 RPE
Female Rugby	23.4
Male Rugby	18.5
Female Hockey	22.7
Male Hockey	19.1
Female Sedentary	28.6
Male Sedentary	28

Pre-High Intensity Exercise

Symptoms provocation at baseline by group

At baseline, across all participants the median number (IQR) of positive tests per participant was 0 (0-1) while the percentage of participants with at least one positive test was 25.3%. Female sedentary participants had the highest proportion of positive baseline tests (47.1%), followed by male sedentary participants (23.1%). Of the sporting population, male rugby players demonstrated the highest proportion of baseline symptoms (22.2%) followed by female rugby players (21.4%). The group with the lowest proportion of positive baseline tests was the hockey group, with female hockey players demonstrating a positive test rate of 10% and male hockey players displaying no positive tests (n=3).

Table 33: Participants with one or more positive domains by group

Group	Male Rugby N=18	Female Rugby N=14	Male Hockey N=3	Female Hockey N=10	Male sedentary N=13	Female sedentary M=17	Total
% with symptoms (N)	22.2% (4)	21.4% (3)	0% (0)	10.0% (1)	23.1% (3)	47.1% (8)	25.3% (19)

When comparing baseline results between groups there were no significant differences between females and males (p=0.71), collegiate athletes and sedentary individuals (p=0.16), female rugby players and male rugby players (p=1.00) or female hockey players and female rugby players (p=0.87).

Table 34: Comparison of baseline symptoms between groups

Group	Females vs. Males	Sporting vs. sedentary	Female Rugby vs. Malae Rugby	Female Hockey v. Female Rugby
OR (95% CI) P value	1.43 (0.43-5.10) P=0.71	0.41 (0.12-1.35) P=0.16	0.96 (0.12-7.03) P=1.00	0.42 (0.01-6.36) P=0.87

Symptoms provocation at baseline by domain

A significant difference in baseline test existed between domains (<0.0001). VOR was the most provocative test at baseline with VOR horizontal accounting for 20.8% of all positive tests and VOR vertical accounting for 13.9%. Visual Motion Sensitivity accounted for 12.9% of positive baseline tests, followed by 4.2% and 2.8% for vertical and horizontal saccades respectively. No baseline symptom provocation was observed for convergence or smooth pursuits.

For pairwise comparisons the significance level is taken as p<0.002 to allow for multiple comparisons. Symptom rate for VOR horizontal is significantly higher than for convergence, saccades horizontal, saccades vertical and smooth pursuits (all p<0.002). For VOR vertical the symptom rate is significantly higher than for convergence and smooth pursuits (p<0.002).

Table 35: Percentage (N) with positive baseline tests by domain

Domain	Total
Convergence	0
Saccades – Horizontal	2.8% (2)
Saccades – Vertical	4.2% (3)
Smooth Pursuits	0
VOR – Horizontal	20.8% (15)
VOR – Vertical	13.9% (10)
Visual Motion	12.5% (9)
P value*	<0.0001

*Cochran's Q test
*Adjusted significance level of p<0.002

Symptom provocation at baseline by symptoms

There were significant differences in the proportion of positive domains by symptom (Cochran's Q test p<0.0001). Symptom levels for dizziness (25%) were significantly higher than for headache (2.8%, p<0.0001), nausea (4.2%, p=0.0003) and fogginess (2.8%, p<0.0001). No other symptom groups demonstrated a significant difference.

Table 36 Percentage (N) with positive tests for each symptom (whole group)

Symptom	Total
Headache	2.8% (2)
Dizziness	25.0% (18)
Nausea	4.2% (3)
Fogginess	2.8% (2)
P value*	<0.0001

*Cochran's Q test

*Adjusted significance level of p<0.008

Post-High Intensity Exercise

Post-exercise symptom provocation whole group

The percentage of participants with at least one positive domain at the first post-run VOMS test (Post 1) was 62.5%. At the second post-run VOMS test (Post 2) 40.3% of participants had a positive domain and at the third post run test (Post 3) 38.2% of participants had at least one positive domain. A significant difference is observed for overall difference between the three time points (p=0.0006). Post 1 was significantly different to Post 2 (p=0.002), and Post 1 was significantly different when compared to Post 3 (p=0.0009), however there was no significant difference between Post 2 and Post 3 (p=0.08).

Post-exercise symptom provocation by subgroup

At Post 1, female sedentary participants were most likely to report one or more positive domains (82.4%) and male rugby players were least likely to report a positive domain (50.8%) but there was no statistically significant difference between any groups for Post 1 symptom provocation.

For Post 2 the female hockey group were more likely to report one or more symptoms (70%), representing an increase in symptom provocation compared with Post 1. At Post 2 the male rugby group again reported the lowest rate of symptom provocation. These two groups demonstrated a significant pairwise difference (p=0.011), as did the comparison between male rugby and the sedentary female group (p=0.015).

At Post 3, the female sedentary group reported the lowest rate of symptom provocation (17.7%) and the male sedentary reported the highest (66.7%), representing an increase in Post 1 and Post 2 symptom provocation for the male sedentary group. The difference between the female sedentary and male sedentary groups at this time point represents a significant pairwise difference (p=0.028)

For the whole group, the greatest change in symptom provocation existed in Post 2 (p=0.025). There was also a significant difference across groups in Post 3 (p=0.033) but no significant difference in symptom provocation existed between groups in Post 1 (p=0.361).

Table 37: Participants with one or more post run positive domains by group

	Male Rugby N=18	**Female Rugby N=14**	**Female Hockey N=10**	**Male Sedentary N=13**	**Female Sedentary M=17**	**Total**	**P value***
Post 1	50.0% (9)	57.1% (8)	60.0% (6)	61.5% (8)	82.4% (14)	62.5% (45)	p=0.361
Post 2	16.7% (3)	28.6% (4)	70.0% (7)	38.5% (5)	58.8% (10)	40.3% (29)	p=0.025
Post 3	55.6% (5)	18.2% (2)	55.6% (5)	66.7% (6)	17.7% (3)	38.2% (21)	p=0.033

*Fisher's exact test for statistical significance across groups.
*Adjusted significance level of p<0.017

When comparing sex and sport groups, females had significantly higher rates of symptom exacerbation than males at Post 2 (p=0.049), but lower rates by Post 3 (p=0.032). There was no statistically significant difference between the two groups at Post 1 (p=0.023). No significant difference existed between any other groups at any time point.

Table 38: Comparison of post-run symptoms between groups

Group		Females vs. Males	Sporting vs. sedentary	Female Rugby vs. Male Rugby	Female Hockey v. Female Rugby
Post 1	OR (95% CI) P value	1.82 (0.68-4.88) P=0.23	0.43 (0.16-1.20) P=0.11	1.32 (0.27-6.82) P=0.97	1.12 (0.16-8.10) P=1.00
Post 2	OR (95% CI) P value	3.04 (1.00-9.98) P=0.049	0.48 (0.16-1.44) P=0.22	1.96 (0.27-16.38) P=0.70	5.37 (0.75-50.8) P=0.11
Post 3	OR (95% CI) P value	0.24 (0.06-0.90) P=0.032	1.45 (0.40-5.52) P=0.73	0.20 (0.01-1.84) P=0.20	5.11 (0.54-76.45) P=0.20

Post-exercise symptom provocation by domain

There are significant differences in rates between domains at all three time points (Post 1 p=0.0001, Post 2 p=0.0001, Post 3 p= 0.002).

At Post 1, symptoms on convergence testing were the lowest (2.8%, n=2) compared to VOR-horizontal which had the highest rates of symptom provocation (43.1%, n=31). At Post 2 the lowest rates of symptom exacerbation were again observed in convergence (1.4%, n=1). Symptom exacerbation was highest for VOR vertical (25.0%, n= 18), followed by VOR-horizontal (23.6%, n=17.) At Post 3 Convergence was again the lowest rate of symptoms (1.9%, n=1). The increase of 0.5% from Post 2 despite remaining n=1 is accounted for by fewer participants undertaking Post 3 due to absence of symptoms on Post 2.

The highest rate of symptoms were observed in VOR horizontal (21.8%, n=12), surpassing VOR vertical and accounting 18.5% (n=10) of symptoms.

Significant differences existed between timepoints for horizontal saccades (p=0.005), vertical saccades (p=0.005), VOR horizontal (p=0.0004) and VOR-vertical (p=0.002). Significant pairwise differences (p<0.017) existed between Post 2 and Post 1, and Post 3 and Post 1 for VOR-horizontal.

When considering the progression of post-run symptom exacerbation, a mixed pattern existed between tests. Between Post 1 and Post 2 a significant decrease was seen in horizontal saccades (p=0.01), vertical saccades (p=0.04), VOR horizontal (p=0.001) and VOR vertical (p=0.003). No other significant differences were observed. At Post

3, a statistically significant decrease was seen compared to Post 1 at horizontal saccades (p=0.02), vertical saccades (p=0.007), VOR horizontal (p=0.002) and VOR vertical (p=0.004). No other significant change was observed. When comparing Post 2 with Post 3, no significant difference existed in any domain.

Table 39: Positive test by domain

Domain	Post 1	Post 2	Post 3	P value*	Post 2 vs post 1*	Post 3 vs. post 1*	Post 2 vs. post 3*
Convergence	2.8% (2)	1.4% (1)	1.9% (1)	P=0.37	P=1.00	P=1.00	-
Saccades Horizontal	19.4% (4)	6.9% (5)	9.1% (5)	P=0.005	P=0.01	P=0.02	1.00
Saccades Vertical	25.0% (18)	12.5% (9)	10.9% (6)	P=0.005	P=0.04	P=0.007	0.45
Smooth Pursuits	6.9% (5)	6.9% (5)	9.1% (5)	P=1.00	P=1.00	P=1.00	1.00
VOR Horizontal	43.1% (31)	23.6% (17)	21.8% (12)	P=0.0004	P=0.001	P=0.002	0.27
VOR Vertical	40.3% (29)	25.0% (18)	18.5% (10)	P=0.002	P=0.003	P=0.004	0.12
Visual Motion	26.4% (19)	18.3% (13)	18.2% (10)	P=0.08	P=0.24	P=0.10	0.25
P value	<0.0001	<0.0001	0.002				

*Cochran's Q test

**significance level taken as p<0.017 for pairwise comparisons

There are significant differences in rates between symptoms at all three time points. Significance level used for pairwise tests is p<0.008 to allow for multiple comparisons. Test used is Cochran q test. At Post 1 Dizziness has the highest rates and is significantly different to all other symptoms (p<0.0001). Dizziness also has the highest rates and is significantly different to all other symptoms (p=<0.0001) at Post 2.

At post 3 Dizziness again has the highest rates and is significantly higher than fogginess (p=0.0002).

Table 40 Percentage (N) with positive tests for each symptom post run (whole group)

Symptom	Post1 N=75	Post2 N=75	Post3 N=57
Headache	8.3% (6)	6.9% (5)	10.9% (6)
Dizziness	55.6% (40)	31.9% (23)	29.1% (16)
Nausea	16.7% (12)	6.9% (5)	10.9% (6)
Fogginess	15.3% (11)	6.9% 5)	3.6% (2)
P values	P<0.0001[1]	P<0.0001[1]	P=0.0002[1]

1Cochran's Q test

Baseline v Post-High Intensity Exercise

Total symptom scores for whole group and individual groups are presented as IQR, mean and standard deviation and significance values.

Pre v post-exercise symptom provocation whole group

When considering the whole group, a significant difference existed between baseline and post run scores at Post 1 (p<0.0001) and Post 2 (p=0.001) but not Post 3 (p=0.075).

Table 41:Comparison of post-pre symptoms whole group

Time point	Metric	Overall
Pre	Mean (SD) Median [IQR]	1.9 (3.8) 0 [0-2]
Post 1	Mean (SD) Median [IQR] P value vs. pre *	11.3 (26.2) 5 [0-13] P<0.0001
Post 2	Mean (SD) Median [IQR] P value vs. pre *	7.5 (25.1) 1 [0-6] P=0.001
Post 3	Mean (SD) Median [IQR] P value vs. pre*	5.9 (18.9) 2 [0-4] P=0.075

*Wilcoxon signed-rank test

Pre v post-exercise symptom provocation by group

When analysing groups based on sex and activity levels, significant differences exist within the two groups of male v female and sporting v sedentary.

Male vs female

Females demonstrated significant differences in symptoms exacerbation at Post 1 (11.4 (18.9), 6 [0-15], p<0.0001) and post 2 (5.7 (9.6), 3 [0-7], p=0.013) when compared to baseline but not Post 3 (2.0 3.3, 1 [0-3], p=0.830.) A different pattern is seen in males who also demonstrated a significant increase in symptoms between baseline and Post 1 (11.2, (34.0), 2 [0-8], p<0.0001) and Post 2 9.8 (36.6, 0 [0-6], p=0.041) but unlike the females demonstrated a continued symptom exacerbation at Post 3, above the levels seen at Post 1 and Post 2 (13.4 (31.3), 4 [0-8], p=0.002). At baseline (p=0.23) and Post 1 (p=0.08) no significant difference in symptom exacerbation existed between groups, however at Post 2 (p=0.05) and Post 3 (P=0.02) the males demonstrated a significant increase in symptom exacerbation when compared to females.

Table 42: Comparison of post-pre symptoms male vs female

Time point	**Metric**	**Female N=41**	**Male N=31**	**P value M vs. F****
Pre	Mean (SD) Median [IQR]	2.7 (4.7) 0 [0-3.5]	0.9 (1.8) 0 [0-1]	P=0.23
Post 1	Mean (SD) Median [IQR] P value vs. pre	11.4 (18.9) 6 [0-15] P<0.0001	11.2 (34.0) 2 [0-8] P<0.0001	P=0.08
Post 2	Mean (SD) Median [IQR] P value vs. pre	5.7 (9.6) 3 [0-7] P=0.013	9.8 (36.6) 0 [0-6] P=0.041	P=0.05
Post 3	Mean (SD) Median [IQR] P value vs. pre*	2.0 (3.3) 1 [0-3] P=0.830	13.4 (31.3) 4 [0-8] P=0.002	P=0.02

*Wilcoxon signed-rank test, **Mann-Whitney U test

Sporting vs sedentary

When considering activity levels, both the sporting and sedentary groups demonstrated significantly increased symptom exacerbation at Post 1 (5.1 (6.3), 4 [0-7], p<0.0001), (20.1 (38.7), 12 [2-20], p<0.0001). At Post 2 both groups continued to demonstrate significantly increased levels of symptom exacerbation although this level in both the sporting (3.6 (6.1), 0.5 [0-4], p=0.009) and sedentary groups (13.1 (38.3), [0-8], p=0.045) was reduced compared to Post 1. At Post 3 both groups observed a reduction in symptom exacerbation compared to Post 2, however only the sporting group remained significantly increased when compared to baseline (3.3 (4.3), 2 [0-5.5], p=0.021).

There was no significant difference in symptom exacerbation between the sporting and sedentary groups at baseline (p=0.11), however at Post 1 the sedentary group had significantly higher symptom exacerbation (p=0.009) when compared to the sporting group. This trend did not continue at Post 2 (p=0.20) or Post 3 (p=0.68) where no significant difference existed.

Table 43: Comparison of post-pre symptoms sporting vs sedentary

		Sporting N=42	**Sedentary N=30**	**P value sedentary vs. sporting****
Pre	Mean (SD) Median [IQR]	1.3 (3.1) 0 [0-0]	2.7 (4.6) 0 [0-4]	P=0.11
Post 1	Mean (SD) Median [IQR] P value vs. pre*	5.1 (6.3) 4 [0-7] P<0.0001	20.1 (38.7) 12 [2-20] P<0.0001	P=0.009
Post 2	Mean (SD) Median [IQR] P value vs. pre	3.6 (6.1) 0.5 [0-4] P=0.009	13.1 (38.3) 3 [0-8] P=0.045	P=0.20
Post 3	Mean (SD) Median [IQR] P value vs. pre*	3.3 (4.3) 2 [0-5.5] P=0.021	8.8 (27.1) 1 [0-3] P=0.892	P=0.68

*Wilcoxon signed-rank test, **Mann-Whitney U test

Male rugby vs female rugby

Although both the male and female rugby groups demonstrated a significant increase in symptom provocation at Post 1 (3.5 (3.9), 2 [0-5], p=0.003) and (5.0 (5.5) , 4.5 [0-10], p=0.03) and the male rugby group at Post 3 (4.6 (4.4), 4 [1-7], p=0.047), no significant difference was observed between male and female rugby groups at any time point. This indicates that no one group had a greater impact from the high intensity run.

Table 44 Comparison of post-pre symptoms male rugby v female rugby

		Male rugby N=18	**Female rugby N=14**	**P value MR vs FR****
Pre	Mean (SD) Median [IQR]	0.9 (2.0) 0 [0-1]	1.7 (3.8) 0 [0-1]	P=0.85
Post 1	Mean (SD) Median [IQR] P value vs. pre *	3.5 (3.9) 2 [0-5] P=0.003	5.0 (5.5) 4.5 [0-10] P=0.031	P=0.51
Post 2	Mean (SD) Median [IQR] P value vs. pre*	2.0 (4.7) 0 [0-1] P=0.672	2.9 (6.0) 0 [0-3] P=0.23	P=0.56
Post 3	Mean (SD) Median [IQR] P value vs. pre*	4.6 (4.4) 4 [1-7] P=0.047	2.0 (4.8) 0 [0-2] P=0.81	P=0.06

*Wilcoxon signed-rank test, **Mann-Whitney U test
MR= Male rugby, FR= Female rugby

Female rugby vs female hockey

When considering the impact of different sports, a significant between-group difference in symptom provocation was observed at Post 2 (p=0.014). This is a reflection of the hockey group demonstrating a symptom exacerbation increase compared to baseline, where the rugby group did not (2.9 (6.0), 0 [0-3], p=0.23), (7.6 (7.0), 5 [3-11], p=0.012). At no other time point was the between-group difference statistically significant.

Table 45 Comparison of post-pre symptoms female rugby vs female hockey

		Female rugby N=14	Female hockey N=10	P value FH vs FR**
Pre	Mean (SD) Median [IQR]	1.7 (3.8) 0 [0-1]	1.3 (4.0) 0 [0-0]	P=0.38
Post 1	Mean (SD) Median [IQR] P value vs. pre *	5.0 (5.5) 4.5 [0-10] P=0.031	8.1 (9.6) 5.5 [0-11] P=0.031	P=0.55
Post 2	Mean (SD) Median [IQR] P value vs. pre*	2.9 (6.0) 0 [0-3] P=0.23	7.6 (7.0) 5 [3-11] P=0.012	P=0.014
Post 3	Mean (SD) Median [IQR] P value vs. pre *	2.0 (4.8) 0 [0-2] P=0.81	3.6 (3.4) 2.5 [1-6.5] P=0.28	P=0.088

*Wilcoxon signed-rank test, **Mann-Whitney U test
FR= Female rugby, FH= Female hockey

Pre v post-exercise symptom provocation by time point

Analysis of pre v post high intensity run reveals that all groups demonstrated a significant change in baseline scores at Post 1 with the largest difference observed in the female sedentary group (18.7, (26.8), 15 [9-20], p=0.0001). The next largest increase in baseline scores at Post 1 was the male sedentary group (21.9 (51.5), 3.0 [0-17], p=0.004), followed by the female hockey (8.1 (9.6), 5.5 [0-11] p=0.03) and female rugby groups (5.0 (5.5), 4.5 [0-10] p=0.03). The group with the smallest change between baseline and Post 1 was the male rugby group, although this was also significantly different when compared to baseline (3.5 (3.9), 2 [0-5], p=0.003).

At Post 2, the group with the largest symptom increase from baseline was the female hockey group (7.6 (7.0), 5 [3-11], p=0.01), although symptom exacerbation levels in this group still represented a reduction compared to Post 1. The only other group that remained significantly different to baseline at Post 2 was the male sedentary group (20.6, (55.7), 0 [0-9], p=0.03). There was no significant difference between baseline scores in the male rugby (2.0 (4.7), 0 [0-1], p=0.672), female rugby 2.9 (6.0) 0 [0-3], p=0.234) or female sedentary groups (6.9 (13.0), 3.5 [1-7], p=0.59).

At Post 3 the only subgroup with a significant symptom exacerbation compared to baseline was the male rugby group (4.6 (4.4), 4 [1-7], p=0.05), representing a 31.4% increase from Post 1 and a 129.9% increase from Post 2 mean scores. No significant increase was observed between baseline and Post 3 for female sedentary (1.2 (1.4)0.5 [0-2.5], p=0.059), male sedentary (22.22 (43.4), 4 [0-21], p=0.063), female hockey (3.6 (3.4), 2.5 [1-6.5], p=0.281) or female rugby (2.0 (4.8), 0 [0-2], p=0.813).

Table 46: Difference in total score (pre-post) by group

		MR N=18	**FR N=14**	**FH N=10**	**MSED N=13**	**FSED M=17**	**Total**
Pre	Mean (SD) Median [IQR]	0.9 (2.0) 0 [0-1]	1.7 (3.8) 0 [0-1]	1.3 (4.0) 0 [0-0]	0.9 (1.6) 0 [0-0]	4.2 (5.5) 2 [0-7]	1.9 (3.8) 0 [0-2]
Post 1	Mean (SD) Median [IQR] P value vs. pre	3.5 (3.9) 2 [0-5] 0.003	5.0 (5.5) 4.5 [0-10] 0.03	8.1 (9.6) 5.5 [0-11] 0.03	21.9 (51.5) 3.0 [0-17] 0.004	18.7 (26.8) 15 [9-20] 0.0001	11.3 (26.2) 5 [0-13] <0.0001
Post 2	Mean (SD) Median [IQR] P value vs. pre	2.0 (4.7) 0 [0-1] P=0.672	2.9 (6.0) 0 [0-3] P=0.234	7.6 (7.0) 5 [3-11] P=0.01	20.6 (55.7) 0 [0-9] P=0.03	6.9 (13.0) 3.5 [1-7] P=0.59	7.5 (25.1) 1 [0-6] p=0.001
Post 3	Mean (SD) Median [IQR] P value vs. pre*	4.6 (4.4) 4 [1-7] p=0.05	2.0 (4.8) 0 [0-2] P=0.813	3.6 (3.4) 2.5 [1-6.5] P=0.281	22.22 (43.4) 4 [0-21] P=0.063	1.2 (1.4) 0.5 [0-2.5] P=0.059	5.9 (19.0) 2 [0-4] P=0.075

*P values are from Wilcoxon signed-rank test (exact test).
MR= Male rugby, FR= Female rugby, FH= Female hockey, MSED= Male sedentary, FSED= Female sedentary

Symptom provocation by domain

When comparing each domain against the baseline, significant differences existed at Post 1 in horizontal saccades (p=<0.0001), vertical saccades (p=<0.0001), VOR horizontal (p=<0.0001), VOR vertical (p=<0.0001) and visual motion sensitivity (p=<0.0005) only. All of these changes were an increase in symptom exacerbation. At Post 2 significant differences existed compared to baseline at vertical saccades (p=0.001), smooth pursuits (p=0.03), VOR horizontal (p=<0.002), VOR vertical (p=<0.01) and visual motion sensitivity (p=<0.05). At Post 3 significant increases were

seen compared to baseline in horizontal saccades (p=0.03), smooth pursuits (p=0.016), and visual motion sensitivity (p=0.05).

Table 47: Positive test by domain vs baseline

Domain	% Positive test by domain at baseline	Baseline score Mean (SD) Median [IQR]	Post 1 score vs baseline	Post 2 score vs baseline	Post 3 score vs baseline
Convergence	0	0 (0) 0 [0-0]	0.64 (3.7) 0 [0-0] P=0.125	0.42 (3.30) 0 [0-0] P=0.500	0.39 (2.86) 0 [0-0] P=1.00
Saccades - Horizontal	2.8% (2)	0.06 (0.33) 0 [0-0]	1.26 (3.96) 0 [0-0] P=0.0001	0.68 (3.74) 0 [0-0] P=0.094	0.69 (3.23) 0 [0-0] P=0.031
Saccades - Vertical	4.2% (3)	0.14 (0.59) 0 [0-0]	1.44 (3.91) 0 [0-1.5] P<0.0001	0.78 (3.42) 0 [0-0] P=0.018	0.65 (2.93) 0 [0-0] P=0.250
Smooth Pursuits	0	0 (0) 0 [0-0]	0.82 (3.68) 0 [0-0] P=0.063	0.71 (3.74) 0 [0-0] P=0.031	0.67 (3.19) 0 [0-0] P=0.016
VOR -Horizontal	20.8% (15)	0.74 (1.55) 0 [0-0]	2.82 (4.41) 1 [0-4] P<0.0001	1.86 (4.12) 0 [0-3] P=0.002	1.65 (3.67) 0 [0-2] P=0.481
VOR - Vertical	13.9% (10)	0.49 (1.23) 0 [0-0]	2.44 (4.48) 0.5 [0-3] P<0.0001	1.67 (4.19) 0 [0-2] P=0.012	1.0 (2.68) 0 [0-1] P=0.434
Visual Motion Sensitivity	12.5% (9)	0.44 (1.17) 0 [0-0]	1.92 (4.48) 0 [0-2] P=0.0005	1.38 (3.98) 0 [0-1] P=0.054	1.24 (2.75) 0 [0-1] P=0.057
P value	<0.0001	<0.0001	<0.0001	<0.0001	0.0006

1 Cochran's Q test, 2Wilcoxon signed rank test

Intra-rater reliability

Intra-rater reliability was measured using Gwet's AC2, comparing the variability of ratings of the same individual across two tests, ten minutes apart. The overall agreement was substantial to excellent for all VOMS items across all symptom domains (0.80-1.00, 95% CI).

Discussion

The author hypothesised that there would be a significant increase in participant baseline VOMS scores following a five-minute high intensity treadmill run and that a variation in symptom provocation would exist between different groups, categorised by activity level, sport participation and sex. The author accepts the above hypothesis.

The most important finding of this study is that high-intensity exercise has a deleterious effect of the vestibular and oculomotor systems. I am only able to hypothesise as to the mechanism responsible for this change. A reduction in the neural drive to the working muscle is a phenomenon termed central fatigue(263), and is one mechanism thought to play a role in negatively impacting oculomotor function(264). The mechanism for this is associated with a progressive exercise-induced reduction in voluntary muscular force production and physical performance through a down-regulation of central neurotransmission(263, 264). Hydration has also been suggested as a confounding factor in adverse vestibular and oculomotor function (178, 259) and has been shown to have an impact on the symptoms reported during VOMS and on visual memory(265). Although I did not measure hydration in this study it is possible that, following a five-minute high-intensity treadmill run, participants' hydration levels could have been affected, leading to the changes in the VOMS ability observed.

Symptom exacerbation following the high intensity treadmill run was significantly higher at all levels of analysis. When considering the whole group (n=75), across all tests, symptom exacerbation was present in 62.5% of participants during the first post-run test, 40.3% at the second post-run test and 38.2% of participants had at least one positive domain at test three, compared to a baseline symptom aggravation of 25.3%. This is significant as this study's immediate post-run VOMS results are consistent with the number of positive VOMS domains observed in a concussed group of collegiate athletes (61%)(76) and a group of mixed sex adolescents (63%)(266), indicating that high-intensity exercise has a comparable immediate impact on the vestibular and oculomotor systems as a concussive injury.

To the author's knowledge three other studies have examined pre to post exercise VOMS scores (178, 259, 260). Worts and colleagues, assessed VOMS function pre and post athletic training, however observed no standardised time period between

cessation of training and initiation of VOMS assessment. The study found no significant difference between the pre and post exercise time points although considering the difference in methods employed from those of the current study, a comparison of results is of limited value. Ratka(260) found a significant interaction between an interval fatigue protocol including a 5-minute run and total VOMS scores in a group of 15 physically active participants (mean age 22.2 years). These results are consistent with those of Moran(259) who observed a significant increase in symptom provocation in a group of 17 college students following a treadmill run. With a mean RPE of 17.8, comparable to the exercise intensity employed in this study, a significant increase between baseline and immediate post-exercise total symptom scores were observed. At the second and third post-run VOMS assessments, Moran observed a significant reduction in symptom provocation when compared to the immediate post-run assessment. In contrast to the current study Moran observed a between test rest period of 20 minutes leaving little room for comparison of secondary and tertiary test results.

When considering individual components of the VOMS test, I observed a significant increase in symptom provocation following testing for horizontal and vertical saccades, visual motion sensitivity and horizontal and vertical VOR at Post 1, with only convergence and smooth pursuits demonstrating no statistically significant difference when compared to baseline. Of these positive tests at Post 2, only horizontal saccades recovered sufficiently to demonstrate no significant difference when compared to baseline. All other domains remained statistically different to their baseline scores and, interestingly, smooth pursuits increased in symptom aggravation at Post 2, becoming statistically different to the baseline score. The change in significance at this stage is a reflection of a change in distribution. At Post 3 only smooth pursuits, horizontal saccades and visual motion sensitivity were significantly increased when compared to baseline. Conversely, Moran(259) found that no single domain was significantly higher post run than at baseline at any time point. These conflicting results may be a reflection of study numbers (17 in Moran's study verses 75 in this study).

The results of the current study suggest both vestibular and oculomotor function are likely to be impacted by high intensity aerobic exercise. VOR (horizontal and vertical) was associated with the highest percentage of participants reporting symptom

provocation which is consistent with the findings of Mucha(76) who reported the highest rates of symptom provocation in this domain amongst concussed participants, although observed no clinically significant change in any non-concussed participant for any individual VOMS item. Following a fatigue protocol Ratka(260) also reported VOR horizontal and vertical to be the domains most commonly provoking VOMS symptoms.

When considering provocation of each of the four symptoms investigated during VOMS, this study found dizziness to be the most prevalent symptom at Post 1 followed by nausea, fogginess and headache respectively. At Post 2 dizziness was again the most common symptom, with no difference between the remaining three symptoms. At Post 3 dizziness remained the most common symptom followed nausea and headache and finally fogginess. These findings are consistent with those of Ratka(260) who performed only one post-exercise VOMS test and found dizziness to be the most common symptom, however the remaining symptoms were ranked in a different order. To the author's knowledge no other studies looking at the VOMS test have reported results by symptom.

The current study went further than those of Moran and Ratka and considered different subgroups of activity level, sex and sport. My results show that increases in VOMS symptom provocation post high intensity run was significant across all groups. These observations are significant when considering the timing of VOMS administration and all but rule it, as well as other tests that rely on vestibular and oculomotor function, out, as a sideline assessment tool, given the presence of false positives in clinically normal individuals following exertion.

When considering the difference in symptom exacerbation between groups, both females and males demonstrated significant increases in symptom exacerbation in post-run scores. The male group, however, demonstrated a slower recovery than the female group. When directly comparing the two groups no difference existed at baseline or Post 1, however at Post 2 and Post 3 the male group demonstrate significantly increased symptom provocation compared to baseline. It is difficult to account for these differences in vestibular and oculomotor recovery. Evidence points towards comparable vestibular and oculomotor response between males and females when concerned with VOMS function(267), rehabilitation response(268), balance

performance and vestibular thresholds(269). The only difference of note is that post-head injury vestibular and oculomotor function has been shown to be more significant amongst female sufferers(270). When comparing a purely athletic group (rather than a mixed activity level group of males and females) a different pattern emerges. Amongst male and female rugby players no significant difference was observed at any time point. The homogeneity of this group allows for a reliable comparison of the impact of exertion on VOMS in these groups and suggests that sex does not impact baseline or post-exercise vestibular and oculomotor function when assessed with the VOMS tool.

When comparing activity levels, both the sedentary and sporting populations demonstrated significant post-exercise increases in symptom exacerbation. When comparing the two groups directly, symptom exacerbation was highest in the sedentary group during the first post-run VOMS assessment. These findings may be a result of an increase in physical fitness amongst the sporting group leading to a reduced impact of exertion on the vestibular and oculomotor systems, however there is currently no evidence directly investigating this variable. Differences may also be accounted for by the sporting groups' regular physical activity leading to a training effect and subsequent habituation of the vestibular and oculomotor systems. In studies investigating the impact of training programmes designed to stimulate the vestibular and oculomotor systems with head and body movements, significant improvements in overall sensory organisation and vestibular-oculomotor function have been observed (271, 272). Much of the available literature linking activity levels to vestibular function is grounded in ageing populations and demonstrates a shift towards greater vestibular and oculomotor function in active individuals(273). This theory however is not reflected in baseline scores where no significant difference was observed in pre-exercise vestibular-oculomotor function between the sporting and sedentary groups.

When comparing sport played, I analysed the difference between female rugby and hockey players. Both groups participate in multi-directional contact sports, however a significantly higher head injury incidence is reported in rugby throughout the literature(215, 274). When analysing VOMS results a significant increase in symptoms was observed in both groups immediately post exercise, with no significant difference between the two groups. A variable picture then existed in the following two VOMS assessments, represented by a slower recovery in the hockey group which remained

significantly increased in Post 2 but not Post 3. The differences in symptom exacerbation in these two groups is not easily explained. Both are team sports with similar physical demands(275) and no evidence exists within the current literature base that may explain my findings.

I feel that the current study has robust methods, allowing for confidence in the reliability of my results. A single assessor of VOMS was used for all pre and post exercise assessments and this assessor was observed to have excellent intra-rater reliability. Furthermore, all participants were assessed in the same lab, ensuring consistency of the test environment.

I did not take an objective measure of exercise intensity, opting to be guided by RPE. Significant correlations have been found between RPE and physiological parameters(276) and the ability of participants to reach 17/20 on the Borg scale within 30 seconds gives us further confidence that the relative exercise intensity across participants was standardised.
Given the short time between the administrations of the VOMS rounds, it is possible that the decrease in overall symptom provocation seen at Post 2 and Post 3 may be a reflection of the brain's ability to adapt to the task and minimise negative impact of vestibular and ocular movement. In essence a learning effect may have taken place and therefore I cannot fully equate this change to resolution of cardiovascular stress.

In order to facilitate clarity of results, severity of symptom aggravation was not analysed in this study. A binary yes or no was applied to each positive domain regardless of the severity score recorded for each VOMS symptom. While this provided the desired clarity and simplicity of interpretation, it is possible that additional information could have been gathered if I was able to establish the relative severity of symptoms rather than just the number of positive tests. Analysing test results in this way may be an avenue for future research. Future research may also repeat the same methods while using an objective measure of participant cardiovascular fitness as well as in an elite athlete population, providing further insights into the impact of fitness and athletic ability on VOMS function following high-intensity exercise.

Conclusion

The findings of this study demonstrate that vestibular and oculomotor function, when assessed using the VOMS test, is negatively impacted by a five-minute high-intensity treadmill run. This study is the first to compare different groups based on sex, activity levels and sport and show a more frequent impact of high intensity exercise in sedentary individuals when compared to an athletic population, but no difference between different sexes and sports. These results may help to guide sports medicine departments as to the appropriate timing of VOMS assessment following sports participation and suggest that a period of rest should be observed prior to commencement. The duration of rest cannot be defined by the current study as I did not record the time to symptom resolution. My results may also pave the way for investigating the degree to which vestibular and oculomotor function under stress could be seen as an athletic ability and trained to improve sporting performance.

Chapter Five- Discussion

General discussion

Our understanding of concussion; its causation, optimal assessment, effective treatment, and the factors that predispose individuals to this injury, is in its infancy. The collection of studies presented in this thesis aims to enhance our understanding of concussion and its associated systems and begins to lay a foundation for future research looking at other intrinsic risk factors, as well as interventional studies aimed at reducing injury rates.

Effectively reducing injury incidence for a given injury in a given sport is a multi-step process and benefits from using a model such at the Translating Research into Injury Prevention Practice (TRIPP) model(277). The model outlines six stages that help to enhance effectiveness and sustainability of planned interventions in the field. The first stage in this process is injury surveillance, involving identification of the type and size of the problem which, in the area of SRC has been well established across a range of sports(2, 4, 5, 17, 19, 23, 59, 65, 193, 199, 218, 274, 278). The next step is to establish the aetiology and mechanism of injury which is where two of the studies within this thesis have acted, namely the identification of how and why SRC occurs. Following this, stage 3 aims to develop preventative measures, followed by the scientific evaluation of interventional efficacy (stage 4). Stage 5 aims to describe the implementation context to inform implementation strategies and stage 6, aims to evaluate the effectiveness of the preventative measures in the implementation context(277).

To date, only one published research paper has identified a modifiable intrinsic risk factor to concussion**(92)**, leaving a number of physical athletic qualities to investigate. Following the research completed in this thesis we have a deeper understanding of two of these qualities, neck strength and cervical proprioception. The findings of the study investigating the association between neck strength and concussion rates build on the work by Collins(92) and demonstrates that neck extension is the key range in identifying rugby players at risk of concussion. The findings of this study show that for every 10% increase in neck extension strength, the rate of sustaining a concussion

reduces by 13% in male professional rugby players (p=0.019). Further, statistical analysis reveals that below this range, 71.4% of players that will sustain a concussion over the course of a professional rugby season are identifiable, acknowledging a false positive rate of 46.1%. These insights provide important reference points for sports medicine and performance departments as they guide not only the focus of conditioning and injury risk reduction strategies, but also provide a reference target for rugby playing athletes to achieve. Rugby authorities may choose to go further in their efforts to reduce concussion incidence in the sport and mandate a minimally acceptable neck extension strength for all players competing in match play.

The findings of study two demonstrate the association between poor cervical proprioception and concussion rates in professional rugby players, a novel finding not previously investigated in the published literature. Further analysis reveals a significant association between right rotation repositioning error and concussion rate. With every 10% increase in gross right rotation error a 5% increase in concussion rate is seen (p=0.021) and a 6% increase in concussion risk exists for each 10% increase in right rotation along the horizontal plane (p=0.0001). These findings are illuminated by a recent narrative synthesis of tackle research in Rugby Union(249) whose findings demonstrate that the tackle is the most common match event to lead to a concussion(17, 193, 230) and that good contact technique during the tackle, for both the ball carrier and tackler is a key determinant to injury risk. Further, this study finds that when studying the tackle in controlled settings that movement patterns and production of force are weaker on the non-dominant shoulder due to poorer position sense of the shoulder region while tackling. In addition, tackles on the non-dominant shoulder were characterised by less control of head movement, which had a more flexed and laterally bent position compared with tackles on the dominant shoulder. It may be that the findings of this thesis reflect the conclusions of Burger(249) in showing that poor proprioception leads to poor tackle technique and subsequent increase in concussion rates. This assumes that the right shoulder is the most commonly used side to enter a contact event in rugby for which there is no published evidence, but which is a commonly accepted assumption within the sport.

The findings of studies one and two also provide insight into how these two qualities, neck strength and cervical proprioception, evolve over the course of a rugby season

in male professional players. The results presented in chapter three demonstrate that a statistically significant increase in all neck strength ranges from pre-season to mid-season existed for all ranges ($p<0.001$) but no significant increase or decrease between mid-season and end of season is seen for any range ($p=0.88$). This time period was also the stage of the season that 19/30 concussions occurred, demonstrating a correlation with group concussion rates and the degree of neck strength. The reason for this increase in neck strength is unknown. It was beyond the scope of the study to record the type of conditioning that players were undertaking and therefore it is not possible to state that it was a result of a structured conditioning programme. It may be that the natural deconditioning that occurs during the off season was superseded by strength gains as a result of playing rugby.

When looking at cervical proprioception a similar evolving pattern can be seen over the course of the season for left rotation and extension repositioning error but not right rotation. A significant reduction in error between pre-season and mid-season($P=0.029$) and mid-season and end of season ($P=0.058$) is seen for gross left rotation. There was also a significant decrease in gross error between pre-season and mid-season ($P=0.013$) and pre-season and end of season ($P=0.0003$) for extension error. There were no significant changes in gross error at any time point for right rotation error. The lack of improvement in this range may provide some explanation as to why this was the range associated with an increased concussion rate. Consistent with the findings of chapter three, the majority of concussions (26/44) were sustained in the time period spanning pre-season to mid-season demonstrating that players were most at risk of concussion when their cervical proprioception was at its lowest.

The positive evolution of both physical athletic qualities points towards an increase in neck conditioning over the course of a rugby season either through structured conditioning or an incidental result of the physicality of the sport, demonstrating an ability to enhance these qualities. Considering this, and the findings of chapters three and four which demonstrate that poor function in neck strength and cervical proprioception predisposes professional rugby players to concussive injuries, a robust pre-season conditioning programme for the cervical spine should be considered.
Although our understanding of concussion risk factors is improving, the incidence of SRC shows no sign of abating. Injury rates in youth sport are estimated to be as high

as 0.23 injuries per 1000 AE's with the three sports with the highest incidence rates; rugby, hockey, and American football, demonstrating rates of 4.18, 1.20 and 0.53 per 1000 AE's respectively(215). A similar pattern can be seen in amateur adult sports that reveals a concussion rate of 1.35 per 1000 AE's in horse racing(279) and 5.6 and 5.5 concussions per athletic exposures for male and female amateur rugby respectively(280). There is a general trend for higher concussion rates in elite level sport with the concussion rate in American football 6.61 concussions per 1000 AE's (281) and professional rugby 15.8/1000 player-match-hours(6)

Despite the increased emphasis placed upon concussion recognition and its appropriate management, 30.5%-68.8% of athletes report having suffered undiagnosed SRC's(282, 283). This has been shown to have significant impact on future head injury outcomes with athletes reporting previously undiagnosed concussions having higher mean Post Concussion Symptom Scale scores and an increased likelihood of suffering loss of consciousness in subsequent concussions (31% v. 22%; $p = 0.038$)(283). A worrying 350-855% greater incidence of concussion related symptoms in later life has also been reported in American football players reporting undiagnosed concussions(282). The high number of undiagnosed concussions and the subsequent impact highlights the importance of effective and reliable diagnostic markers for SRC, as well as an understanding of the potential variables that may confuse the clinical picture. The most recent Consensus Statement on Concussion in Sport states that the examination of the vestibular and oculomotor systems is a key feature of SRC assessment(27). This has led to vestibular(76), oculomotor (284) and somatosensory function(285) to be incorporated in to a range of concussion test batteries with limited consideration for the effects of acute exertion consistent with sporting participation, on test results. Study three assessed the impact of high-intensity exercise on the Vestibular and Ocular Motor Screening tool (VOMS). The results of this investigation revealed a number of different insights that may be of value to clinicians and performance professionals from both medical and performance perspectives. Following the analysis of baseline testing across participants of different activity levels, sex and sporting backgrounds, results show that a significant number of non-injured individuals (25.3%) will have clinically significant resting VOMS scores. Of these participants, sedentary individuals were most symptomatic with female and male sedentary participants demonstrating a positive rate of 47.1% and 23.1%

respectively. Further points of interest show that participants whose primary sport was rugby (a contact sport) were more symptomatic than those whose primary sport was hockey (non-contact). These results point towards two possible insights. Firstly, that sedentary individuals appear to have poorer vestibular and oculomotor function than active individuals, possibly indicating a training effect of regular sporting participation. Clearly it was beyond the scope of this thesis to compare the type and degree of physical activity difference between groups. It may however provide insights to treating clinicians as to what might be considered as 'normal' in different patient groups and indicates that vestibular and oculomotor function may be considered an athletic ability to be trained in order to improve athletic performance. The second insight that these results offer is that individuals involved in contact sports such as rugby may suffer from poorer vestibular and oculomotor function. This finding is consistent with a study by Miyashita and Ullucci(286), who found a significant correlation between change in vestibular function and visual performance and total number of head impacts in a sporting population. The impact of these findings raises other questions. We know from published data that ongoing dysfunction of these systems leads to prolonged recovery following concussion(287, 288) but could it also predispose an individual to future concussions, acting as an identifiable risk factor?

All groups demonstrated a statistically significant increase in symptom provocation on post-exertion VOMS testing. Between-group comparison of pre v post-exertion testing reveals a mixed picture, with different groups displaying evidence of higher symptomology at different time periods (Post 1-Post 3). It is unclear why this pattern exists, however larger group sizes may make for a clearer picture. What these results do show is that high intensity exercise has a delirious effect on vestibular and oculomotor function with symptom provocation rates (62.5%) consistent with those seen in concussed patients (61-63%)(76, 266). This is important to acknowledge as it stresses the importance of an adequate rest period between cessation of exercise and the onset of VOMS testing. What is also clear from these results is that there is a general improvement of VOMS symptoms over time following cessation of high intensity exercise with significant group differences between Post 1 and Post 2 and Post 2 and Post 3.

When considering the individual VOMS domains and symptoms the results presented in study three are consistent with the published literature looking at VOMS at rest(76,

110, 267) and post-exercise(259, 260) with the highest symptom scores present on VOR ($p<0.0001$), VMS ($p=0.0005$) and saccades domains ($p<0.0001$) with dizziness the most common symptom ($p<0.0001$). This finding was consistent at rest and post-exercise and provides clinicians with useful insights on normative results, as well as potential targets to direct injury risk reduction, rehabilitation, and performance strategies.

Results presented in this thesis provide fertile ground for future research. Chapters three and four demonstrate the feasibility of field-based risk factor studies in controlled populations, including professional athletes, and provide a foundation for the next steps in the TRIPP process which should include interventional studies aimed at enhancing neck extension strength above 42.1 kg/f and improving cervical proprioception in athletes across a range of high-risk sports.

Further research should build on the findings of studies one and two and investigate other potential risk factors to concussion using comparable methods. The utilisation of a controlled professional athlete population combined with exposure data and methodological reliability studies provides additional confidence in study conclusions and increases utility in an elite athlete population. Two areas that have been shown to be deficient on post-concussion testing are vestibular and oculomotor(179, 266), and somatosensory function(289, 290). Studies addressing these systems post-concussion have made assumptions that deficiency in their function is a direct impact of a concussive injury without consideration of the individual's pre-injury state. Further research may reveal pre-concussion deficits in these systems and help to establish a contributing variable to concussive injuries. Baseline screening of these systems amongst specific populations will provide greater insight into the relevance of the pre-concussed condition and provide interventional targets aimed at reducing the incidence of concussion.

A drop in performance preceding concussion has been documented(60) indicating a change in athlete condition pre-injury. One potential change and one of the strongest determinants for a drop in athletic performance is fatigue(102, 291). Conversely, a reduction in concussion incidence following interventions designed to improve MSK function has been observed(236, 292). It may be possible to extrapolate therefore that a reduction in neuromuscular activity and subsequent force capacity leads to

reduced protection for the head and neck (62), or a reduction in technique and subsequent safe practice. Considering this, an investigation monitoring both physical and mental fatigue and subsequent concussion incidence would be of high value to sporting teams and organisations. There is no single marker which consistently identifies fatigue, making it difficult to measure, however research has demonstrated that subjective scales of fatigue(293), mood(294) and objective measures of muscle power(295) are sensitive to changes in exercise induced fatigue and therefore may be important markers to monitor in relation to concussion incidence. An awareness of the impact of fatigue on concussion risk would provide a rationale for athlete monitoring and proactive interventions including optimising physical readiness and the potential temporary removal of athletes from training and match play.

The impact of the menstrual cycle on female athlete health and MSK injury risk is becoming clearer(296, 297), with suggestions of higher injury rates seen during different phases of the menstrual cycle. To date no data is available concerning the direct link between menstrual cycle and concussion risk, however. With the rise in professionalism and subsequent athlete monitoring in women's sport this and other kinds of observational studies are now easier and even more important to establish. Repeating the studies covered in this thesis investigating neck strength and cervical proprioception and their interaction with concussion incidence should be considered as next steps, as should the investigation of the other potential risk factors discussed earlier in this chapter.

The identification and diagnosis of concussion and its comorbidities is one of the most challenging aspects of concussion management(26). Although a significant proportion of the concussion literature has been dedicated to the topic(27, 54, 108, 190), progress is incremental and there is currently no silver bullet providing a one stop diagnostic shop. Consequently, the need to assess each system in its constituent parts continues. The importance of vestibular and oculomotor dysfunction is now well established(70, 81) and chapter five of this thesis provides evidence of the need for a rest period between cessation of exercise and the initiation of testing. Future studies could go further by formally assessing the time to baseline on VOMS testing and may also consider monitoring the correlation between VOMS symptom severity and heart rate.

I assessed the impact of exertion on vestibular and oculomotor function in a controlled lab-based setting in a bid to provide insight to sporting populations. Future research should look to recreate ‘real life’ sporting scenarios where dynamic body movement and opposition contact may also contribute to the increased symptoms seen on VOMS testing. This may demonstrate a further increase in symptom severity and in doing so, enhance the need to treat the vestibular and oculomotor systems as performance targets and not just an area to manage when dysfunction is diagnosed.

The VOMS tool has been shown to be a reliable and consistent measure of vestibular and oculomotor function(180) . The findings presented in chapter five, however, show that it has a false positive rate of over 25%, necessitating the need for a baseline measure to be taken in order to be confident of any post impact changes. It is also recommended that the VOMS test should take up to 10 minutes, providing logistical challenges to sporting organisations needing to undertake mass baseline testing. As such, future research may look to establish normative data across different groups including, sport, sex, injury history and age. This would provide reference values that would allow for more accurate interpretation of one-off assessments and in doing so, provide value to athletes and clinicians alike.

Chapter Six- Conclusion

Summary

Concussion is an injury unlike any other. The sequalae of symptoms leads to a swathe of emotional, physical, and perceptual changes that place limitations on the lifestyle of sufferers beyond those seen in nearly any other sporting injury. The sensation of helplessness felt by many concussion sufferers is testimony to our lack of understanding, including the best methods of assessment, treatment, and techniques to protect against the injury, which serves only to reinforce and aggravate patient symptoms.

This thesis has attempted to answer questions related to risk factors and assessment of concussion in a real-world setting, and in doing so empower clinicians to take actionable steps to reduce concussion incidence and enhance the reliability and effectiveness of assessment.

The findings of this thesis create impact across converging areas of cervical, vestibular-oculomotor and concussion assessment. Reliability study one builds on the work by Versteegh (120) who examined the between session reliability of self-resisted neck strength assessment using a HHD. From the results of this study we can be confident that the inter-rater reliability of this measurement can also be relied upon. This has particular significance to performance departments and other clinicians undertaking large scale neck strength assessment. The utilisation of self-resisted assessment removes the issue of assessor fatigue and therefore declining levels of resistance offered by the examiner through the HHD. The results of study one demonstrates that this technique is consistent when instructed by different clinicians.

Reliability study two demonstrates moderate to excellent inter-rater reliability of JPET measurements. Due to the varied methods employed when describing this test in the published literature, this is to the authors knowledge, the first reliability study assessing examiner technique using the methods first described by Revel(124) and provides confidence across different assessors. This is important in performance, clinical and academic settings as it allows multiple clinicians to assess the same individual with confidence.

Reliability study three is, at the time of writing, the first study to assess the intra-rater reliability of the VOMS test and demonstrates substantial to excellent reliability across all VOMS domains. These results should improve confidence in the test-retest reliability of the VOMS tool, although it is also important to consider clinician experience in performing the test.

The experimental studies in chapter four of this thesis have answered three distinct questions. Study one looked to establish the correlation between neck strength and concussion incidence and in doing so has for the first time identified a unique neck strength range as a risk factor for concussion. Poor neck extension strength is directly associated with concussion risk, with a 13% reduction in concussion rate for every 10% increase in neck strength. Although the results of this study highlight that it is beneficial for all players to strengthen the neck extensor muscles, they also identify what could be described as a minimally acceptable neck extension strength value. A neck extension strength of 41.2kg/f will identify 71.4% of players that will go on to suffer a concussion in a male professional rugby season. This data provides rugby performance teams with a target strength for this population.

Study two continues to investigate neck function by exploring the relationship between cervical proprioception and concussion rates in a population of male professional rugby players. Cervical proprioception is a function that is frequently considered in the field of neck pain. Despite a body of evidence demonstrating the link between head and torso alignment and head impact attenuation and between poor tackle technique and higher concussion rates, there is currently no published literature investigating the link between cervical proprioception and concussion rates. Study two established the link between these two parameters, identifying a 5% increase in concussion rate for each 10% increase in gross right rotation error and a 6% increase in concussion rate for each 10% increase in right rotation along the horizontal plane. Interestingly, right rotation repositioning error was also the only range that did not improve over the course of the season. It is possible that this is due to repeated trauma from contact events, most likely to be on the players dominant side, in most cases the right.

Study three investigated the impact of high intensity exercise on vestibular and oculomotor function in a population of mixed activity level, sport and gender participants. Results demonstrate that high intensity exercise has a comparable delirious impact on vestibular and oculomotor function as concussion. This is an important finding that illustrates the importance of a rest period between cessation of sporting participation and initiation of VOMS testing. Furthermore, results demonstrate that this symptom aggravation is seen across all study groups, including sedentary and sporting populations, males, and females and those that play different sports.

The findings communicated in this thesis have the power to create change in the way we assess and manage the risk of concussion. As we grow our understanding of the injury, how best to identify it and its comorbid conditions, the factors that lead to increased risk of injury and then, importantly, how to prevent it, we may begin to see a reduction in concussion severity and even incidence. The importance of achieving this is pressing. The short, medium- and long-term effects of this injury are haunting world sporting governing bodies, national governing bodies, sports clubs, and athletes alike and it is the author's hope that this thesis provides a small brush of colour to this landscape.

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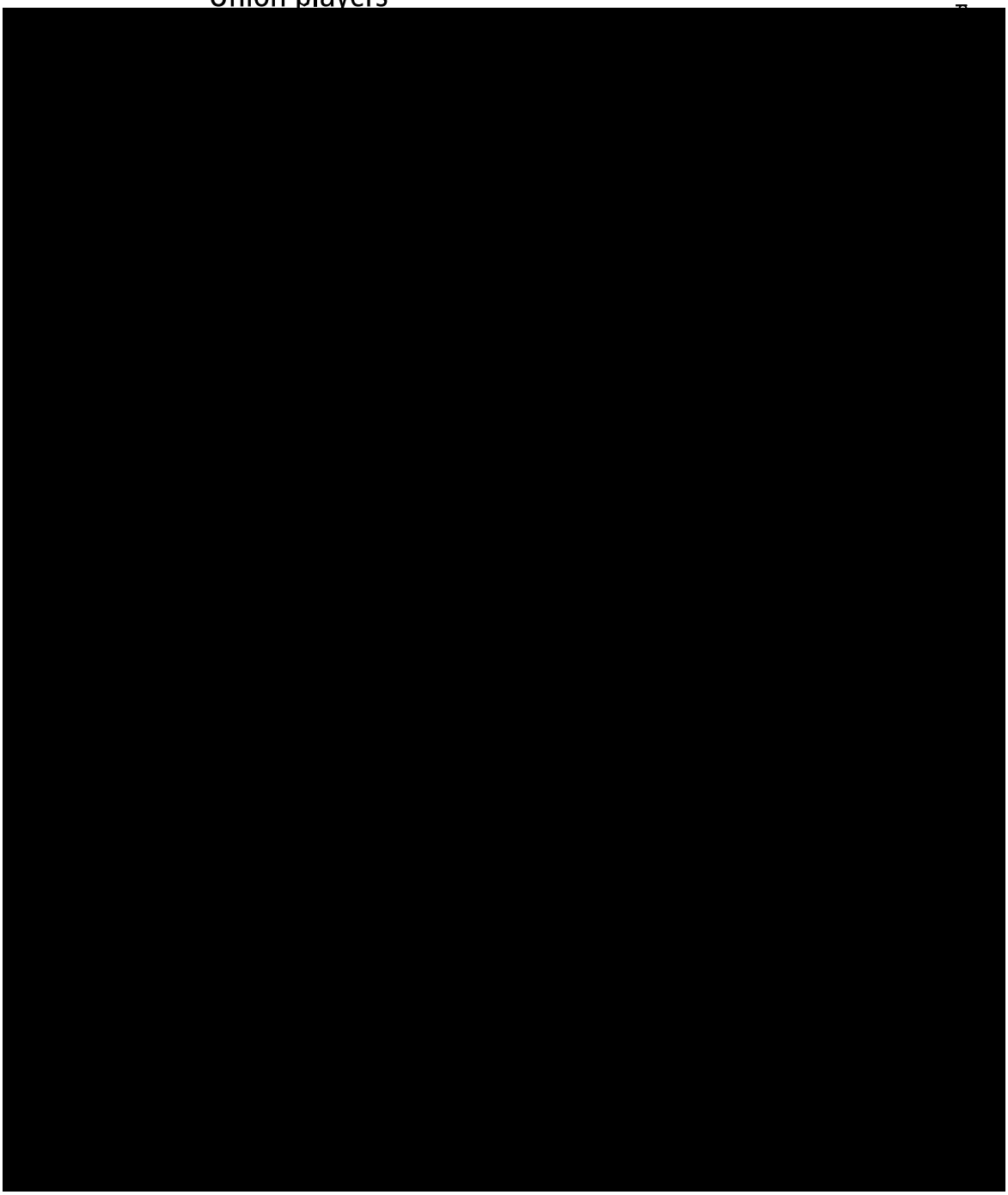
Appendix A: Evidence of impact

Original research

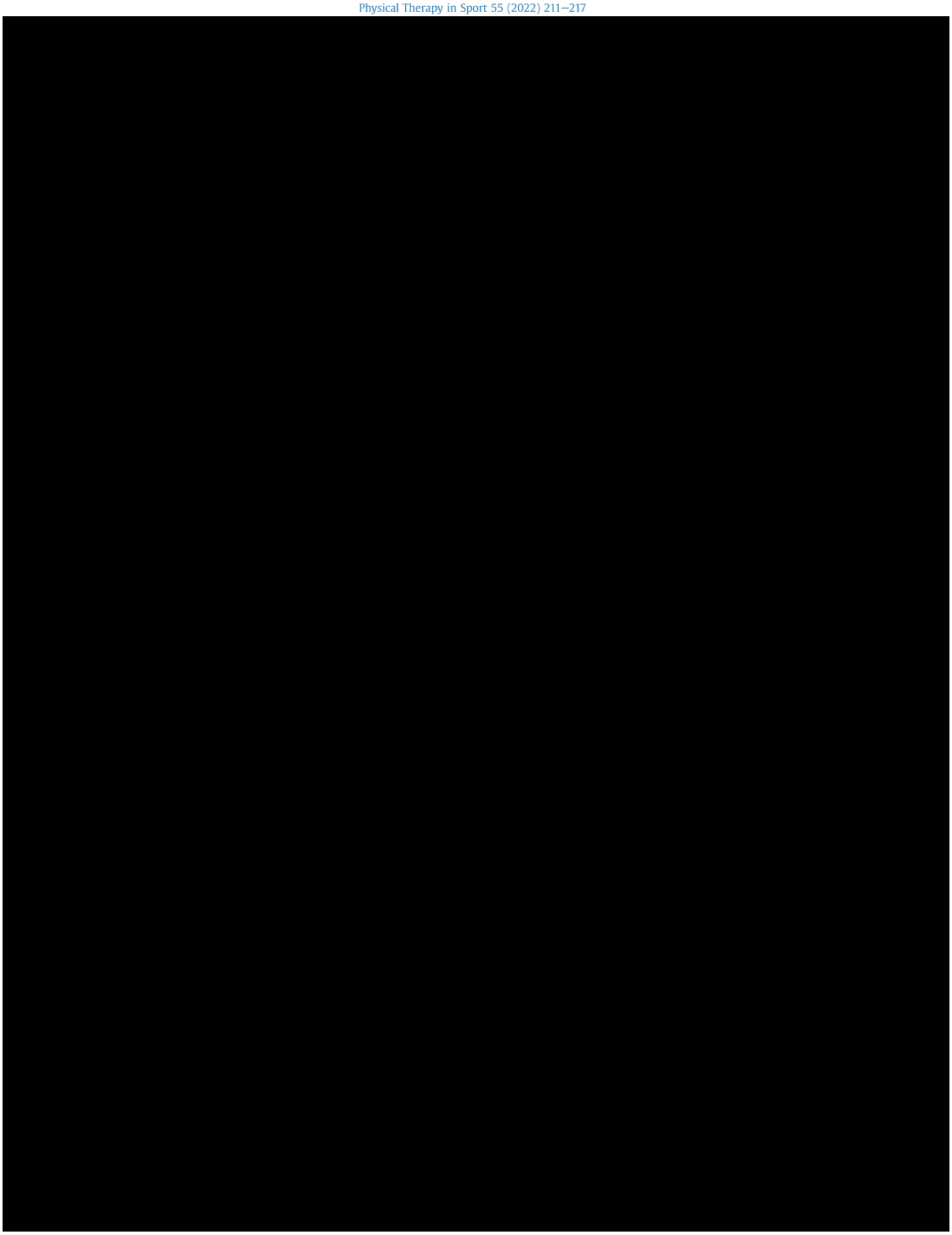
Poor isometric neck extension strength as a risk factor for concussion in male professional Rugby Union players

Br J Sports Med: first p



A2: Physical Therapy in Sport publication: Study 2

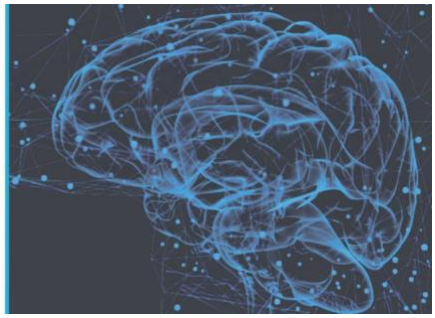
Physical Therapy in Sport 55 (2022) 211–217



A3: Drake foundation presentation: Studies 1 and 2

Drake Sports Head Impact Research Symposium

26 April 2022
Wembley Stadium



09:00–09:30	**Registration**
09:30–09:45	**Welcome** *Lauren Pulling (The Drake Foundation), Charlotte Cowie (The Football Association)*
Morning session 1	**Long-term risk** ***Chair:*** *Jonathan Schott (University College London)*
09:45–10:00	**The Concussion in Sport Forum – what does the UK need?** *James Calder (Consultant and Imperial College London)*
10:00–10:20	**FIELD study update** *Emma Russell (University of Glasgow)*
10:20–10:40	**BRAIN study update** *Neil Pearce (London School of Hygiene and Tropical Medicine), Giulia Seghezzo (Queen Mary University of London)*
10:40–10:50	**PREVENT study update** *Craig Ritchie (University of Edinburgh)*
10:50–11:00	**BrainHOPE** *Willie Stewart (University of Glasgow)*
11:00–11:10	**Advanced Brain Health Clinic (ISEH/ICL/UCL)** *David Sharp (Imperial College London), Richard Sylvester (National Hospital for Neurology and Neurosurgery)*
11:10–11:30	**Panel discussion: Long-term risk: opportunities, challenges and where we go now** *Jonathan Schott (Chair), Neil Pearce, Freja Petrie (Swansea University), Craig Ritchie, Emma Russell, David Sharp, Willie Stewart*
11:30–11:50	**Refreshment break**
Morning session 2 ***11.50***	**New technologies** ***Chair:*** *Dario Cazzola (University of Bath)*
11:55–12:10	**Sex differences in neck strength and head impact kinematics in university rugby union** *Freja Petrie (Swansea University)*
12:10–12:25	**Update from the RFL: challenges and opportunities in exposure measurement** *Ben Jones (Leeds Beckett University)*
12:25–12:40	**Discovery iMG data from elite rugby, how iMG data will influence contract training guidance and future plans** *Keith Stokes (University of Bath)*
12:40–12:55	**Computational prediction of traumatic brain injury in sporting collisions** *Mazdak Ghajari (Imperial College London)*
12:55–13:05	**Development of an advanced biofidelic headform for the physical re-creation of head impacts in cricket** *Rory England (Loughborough University)*
13:05–13:25	**Panel discussion: Opportunities and challenges in sensor research and data building** *Dario Cazzola (Chair), Mazdak Ghajari, Ben Jones, Simon Kemp, Paddy Riley (The Premier League), Keith Stokes*
13:25–14:25	**LUNCH [Speaker photo on stage: 13:25]**

#DrakeSHIRS

A4: IOC World Conference on Prevention of Injury & Illness in Sport 25-27, November 2021 Poster session: Study 1

International Olympic Committee

Medical and Scientific Department

Unclassified

Lausanne, 14 September 2021

ABSTRACT – 2nd Round - Poster Presentation

Dear Theo Farley,

With reference to the abstract entitled "The relationship between neck strength and concussion in male professional rugby players" – [1878] submitted for the upcoming "IOC World Conference on Prevention of Injury & Illness in Sport" to be held in Monaco from 25 to 27 November 2021, we are very pleased to inform you that your paper has been **accepted as a 2nd Round - Poster Presentation.**

Your abstract will also be also published electronically in the British Journal of Sports Medicine to coincide with the conference. In some cases, minor changes will be needed to comply with the abstract format required by the journal. If so, you will be contacted by email. Abstract publication requires timely response to any queries.

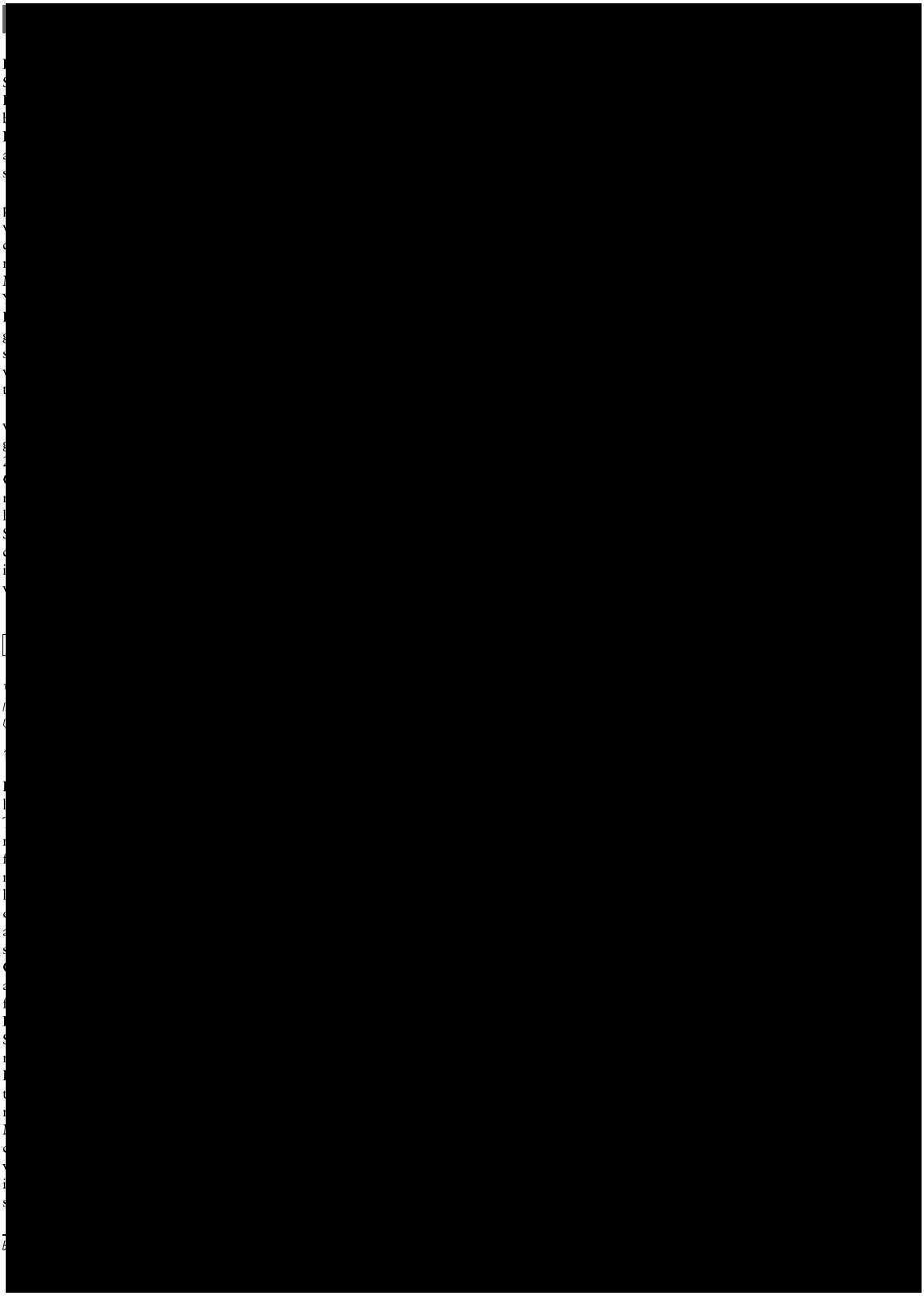
The allocated poster board space is a maximum size of 150cm high and 90cm wide, and lettering/figures should be large enough to be viewed at a distance of 2 metres.

The authors are responsible for the printing of their poster in advance. No on-site facilities for poster printing will be provided.

All posters will be displayed in the Grimaldi Forum. Further information will be given in due course.

Maison Olympique, 1007 Lausanne, Switzerland | Tel. +41 21 621 6111 | Fax +41 21 621 6216 | www.IOC.org

A5: **IOC World Conference on Prevention of Injury & Illness in Sport 25-27, November 2021 BJSM abstract publication: Study 1**



A6: **IOC World Conference on Prevention of Injury & Illness in Sport 25-27, November 2021 Poster session: Study 2**

International
Olympic
Committee

Medical and Scientific Department

Unclassified

Lausanne, 14 September 2021

ABSTRACT – 2nd Round - Poster Presentation

Dear Theo Farley,

With reference to the abstract entitled "The relationship between cervical proprioception and concussion in male professional rugby players" – [1877] submitted for the upcoming "IOC World Conference on Prevention of Injury & Illness in Sport" to be held in Monaco from 25 to 27 November 2021, we are very pleased to inform you that your paper has been **accepted as a 2nd Round - Poster Presentation.**

Your abstract will also be also published electronically in the British Journal of Sports Medicine to coincide with the conference. In some cases, minor changes will be needed to comply with the abstract format required by the journal. If so, you will be contacted by email. Abstract publication requires timely response to any queries.

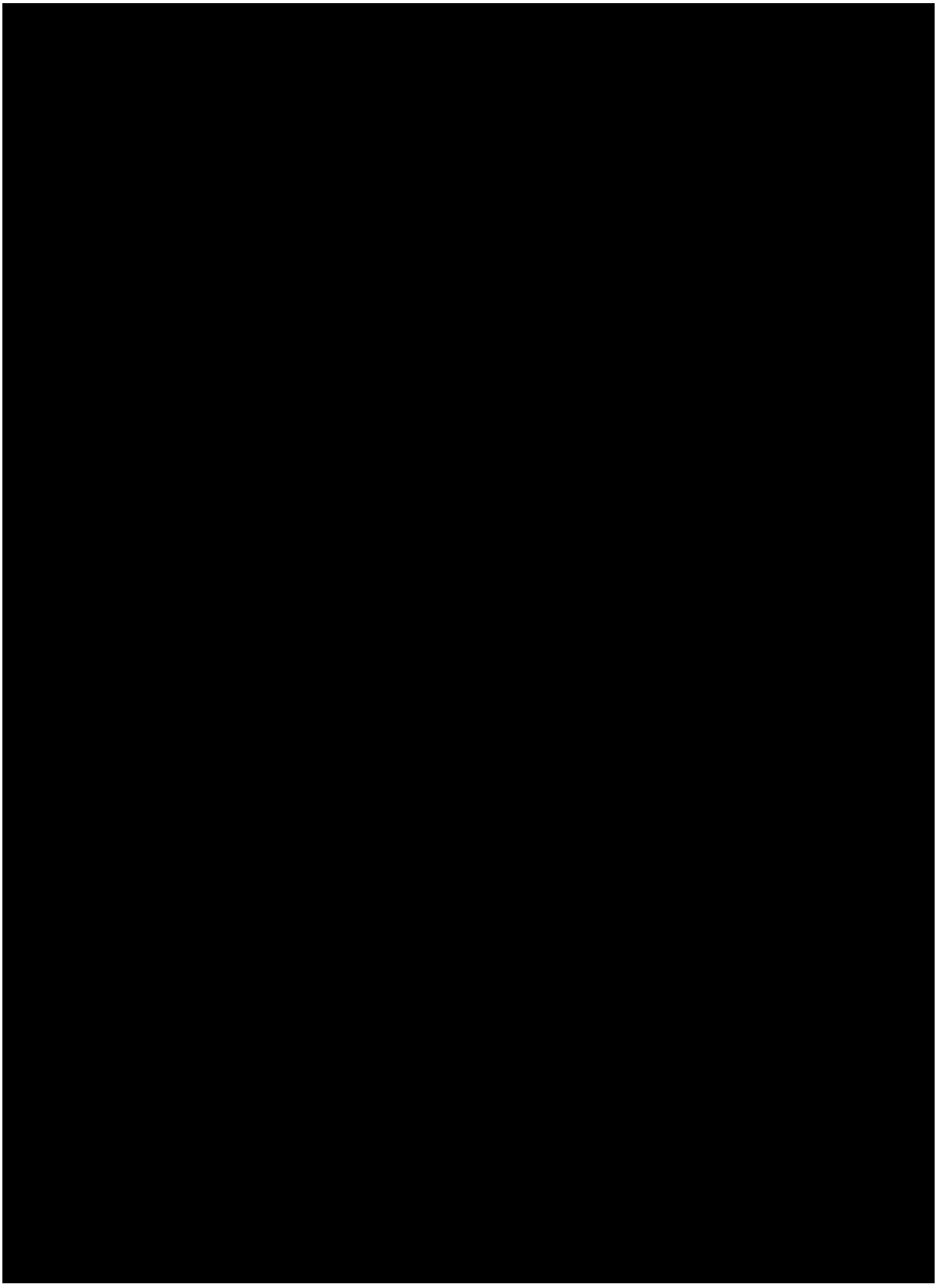
The allocated poster board space is a maximum size of 150cm high and 90cm wide, and lettering/figures should be large enough to be viewed at a distance of 2 metres.

The authors are responsible for the printing of their poster in advance. No on-site facilities for poster printing will be provided.

All posters will be displayed in the Grimaldi Forum. Further information will be given in due course.

Maison Olympique, 1007 Lausanne, Switzerland | Tel. +41 21 621 6111 | Fax +41 21 621 6216 | www.IOC.org

7: **IOC World Conference on Prevention of Injury & Illness in Sport 25-27, November 2021 BJSM abstract publication: Study 1**



A8: **QMUL 20th Annual Conference in Sport and Exercise Medicine Presentation of findings: Study 3**

SEP
14

QMUL 20th Annual Conference in Sports and Exercise Medicine (SEM)

£0 – £43.71

Sales Ended | Details

Description

The Centre for Sports and Exercise Medicine (CSEM) is based at the William Harvey Research Institute at Barts and The London School of Medicine and Dentistry. This year the team behind the Annual Sports and Exercise Medicine Conference has put together an exciting programme bringing together the very best of science and its application to clinical practice.

Building on the success of last years conference (pictures below), this years conference will follow a similar format, combining lectures with smaller parallel practical breakout workshops.

The aims of the Conference are to share the latest research developments in the field of Sports and Exercise Medicine (SEM), discuss the evidence and techniques relating to common sports injury management, and develop clinical skills in the assessment and management of common sporting injuries. Three, themed sessions, each include a Keynote, PhD or Post-Doctoral and post-graduate or undergraduate presentation. The themes include:

- Managing Plantar Heel Pain
  - Session Chairs - Mr Trevor Prior
  - Keynote - Dr Matt Cotchette
  - Prof Dylan Morrissey
  - Miss Halime Gruelle
- The Female Athlete
  - Session Chair - Dr Ritan Metha
  - Miss Kate Panter (Keynote)
  - Ms Alicia Tang
  - Dr Matt Towner
  - Dr Stephanie Murphy
- Concussion
  - Session Chair - Dr Ian Beasley
  - Keynote - Dr Richard Sylvester
  - Mr Theo Farley

Date and time

Fri, September 14, 2018
8:30 AM – 6:00 PM BST
Add to calendar

Location

Arts 2, Queen Mary University of London
Mile End Road
London
E1 4NS
View Map

Refund policy

Refunds up to **7 days** before event

Appendix B: Notification of Ethics Approval

B1: Notification of Ethics Approval: Study 1

UCL RESEARCH ETHICS COMMITTEE
OFFICE FOR THE VICE PROVOST RESEARCH

3rd August 2018

Theo Farley
Department of Surgery and Interventional Sciences
UCL

Dear Theo,

Notification of Ethics Approval
Project ID/Title: 11785/004: Is neck strength a risk factor to concussion in rugby union players

Further to your satisfactory responses to the Committee's comments, I am pleased to confirm in my capacity as Joint Chair of the UCL Research Ethics Committee (REC) that the UCL REC has ethically approved the overall study until **30th September 2021.**

Notification of Amendments to the Research
You must seek Chair's approval for proposed amendments (to include extensions to the duration of the project) to the research for which this approval has been given. Each research project is reviewed separately and if there are significant changes to the research protocol you should seek confirmation of continued ethical approval by completing an 'Amendment Approval Request Form'
http://ethics.grad.ucl.ac.uk/responsibilities.php

Adverse Event Reporting – Serious and Non-Serious
It is your responsibility to report to the Committee any unanticipated problems or adverse events involving risks to participants or others. The Ethics Committee should be notified of all serious adverse events via the Ethics Committee Administrator (ethics@ucl.ac.uk) immediately the incident occurs. Where the adverse incident is unexpected and serious, the Joint Chairs will decide whether the study should be terminated pending the opinion of an independent expert. For non-serious adverse events the Joint Chairs of the Ethics Committee should again be notified via the Ethics Committee Administrator within ten days of the incident occurring and provide a full written report that should include any amendments to the participant information sheet and study protocol. The Joint Chairs will confirm that the incident is non-serious and report to the Committee at the next meeting. The final view of the Committee will be communicated to you.

Final Report
At the end of the data collection element of your research we ask that you submit a very brief report (1-2 paragraphs will suffice) which includes in particular issues relating to the ethical implications of the research i.e. issues obtaining consent, participants withdrawing from the research, confidentiality, protection of participants from physical and mental harm etc.
In addition, please:

Office of the Vice Provost Research, 2 Taviton Street
University College London
Tel: +44 (0)20 7679 8717
Email: ethics@ucl.ac.uk
http://ethics.grad.ucl.ac.uk/

B2: Notification of Ethics Approval: Study 2

UCL RESEARCH ETHICS COMMITTEE
OFFICE FOR THE VICE PROVOST RESEARCH

3rd August 2018

Theo Farley
Department of Surgery and Interventional Sciences
UCL

Dear Theo,

Notification of Ethics Approval
Project ID/Title: 11785/007: Is neck proprioception a risk factor to concussion in rugby union players

Further to your satisfactory responses to the Committee's comments, I am pleased to confirm in my capacity as Joint Chair of the UCL Research Ethics Committee (REC) that the UCL REC has ethically approved the overall study until **30th September 2021.**

Notification of Amendments to the Research
You must seek Chair's approval for proposed amendments (to include extensions to the duration of the project) to the research for which this approval has been given. Each research project is reviewed separately and if there are significant changes to the research protocol you should seek confirmation of continued ethical approval by completing an 'Amendment Approval Request Form'
http://ethics.grad.ucl.ac.uk/responsibilities.php

Adverse Event Reporting – Serious and Non-Serious
It is your responsibility to report to the Committee any unanticipated problems or adverse events involving risks to participants or others. The Ethics Committee should be notified of all serious adverse events via the Ethics Committee Administrator (ethics@ucl.ac.uk) immediately the incident occurs. Where the adverse incident is unexpected and serious, the Joint Chairs will decide whether the study should be terminated pending the opinion of an independent expert. For non-serious adverse events the Joint Chairs of the Ethics Committee should again be notified via the Ethics Committee Administrator within ten days of the incident occurring and provide a full written report that should include any amendments to the participant information sheet and study protocol. The Joint Chairs will confirm that the incident is non-serious and report to the Committee at the next meeting. The final view of the Committee will be communicated to you.

Final Report
At the end of the data collection element of your research we ask that you submit a very brief report (1-2 paragraphs will suffice) which includes in particular issues relating to the ethical implications of the research i.e. issues obtaining consent, participants withdrawing from the research, confidentiality, protection of participants from physical and mental harm etc.
In addition, please:

Office of the Vice Provost Research, 2 Taviton Street
University College London
Tel: +44 (0)20 7679 8717
Email: ethics@ucl.ac.uk
http://ethics.grad.ucl.ac.uk/

B3: Notification of Ethics Approval: Study 3

UCL RESEARCH ETHICS COMMITTEE
OFFICE FOR THE VICE PROVOST RESEARCH

1st February 2018

Dr Theo Farley
Department of Surgery and Interventional Sciences
UCL

Dear Dr Farley

Notification of Ethics Approval with Provisos
Project ID/Title: 11785/001: The difference in Vestibular-Oculomotor Screening (VOMS) assessment pre-exercise and at three different time points post-exercise in elite and recreational athletes and sedentary individuals

I am pleased to confirm in my capacity as Joint Chair of the UCL Research Ethics Committee (REC) that I have ethically approved the data collection element of your study until **30th September 2020**.

Ethical approval is subject to the following conditions:

Notification of Amendments to the Research
You must seek Chair's approval for proposed amendments (to include extensions to the duration of the project) to the research for which this approval has been given. Ethical approval is specific to this project and must not be treated as applicable to research of a similar nature. Each research project is reviewed separately and if there are significant changes to the research protocol you should seek confirmation of continued ethical approval by completing an 'Amendment Approval Request Form'
http://ethics.grad.ucl.ac.uk/responsibilities.php

Adverse Event Reporting – Serious and Non-Serious
It is your responsibility to report to the Committee any unanticipated problems or adverse events involving risks to participants or others. The Ethics Committee should be notified of all serious adverse events via the Ethics Committee Administrator (ethics@ucl.ac.uk) immediately the incident occurs. Where the adverse incident is unexpected and serious, the Joint Chairs will decide whether the study should be terminated pending the opinion of an independent expert. For non-serious adverse events the Joint Chairs of the Ethics Committee should again be notified via the Ethics Committee Administrator within ten days of the incident occurring and provide a full written report that should include any amendments to the participant information sheet and study protocol. The Joint Chairs will confirm that the incident is non-serious and report to the Committee at the next meeting. The final view of the Committee will be communicated to you.

Final Report
At the end of the data collection element of your research we ask that you submit a very brief report (1-2 paragraphs will suffice) which includes in particular issues relating to the ethical implications of the research i.e. issues obtaining consent, participants withdrawing from the research, confidentiality, protection of participants from physical and mental harm etc.
In addition, please:

Appendix C: Participant information and consent forms

C1: Participant information form: Study 1

Participant Information Sheet- Didi 10 Rugby players
UCL Research Ethics Committee Approval ID Number: 11785/004

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study:
Is neck strength a risk factor to concussion in rugby union players

Department: Department of surgery and interventional sciences
Name and Contact Details of the Principal Researcher: Theo Farley. t.farley@ucl.ac.uk

1. **Invitation Paragraph**
   You are being invited to take part in a research project. Before you decided it is important for you to understand why the research is being done and what participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

   Thank you for reading this.

2. **What is the project's purpose?**
   We are investigating whether neck strength is a risk factor to concussion in rugby players.

3. **Why have I been chosen?**
   You have been asked to participate because you are part of the rugby team in the Didi 10. To be included in this study you must be a rugby player and have no medical condition that would exclude you from playing rugby or conducting a neck strength assessment.

4. **Do I have to take part?**
   It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and asked to sign a consent form). You can withdraw at any time without giving a reason and without it affecting any benefits that you are entitled to.

   If you decide to withdraw you will be asked what you wish to happen to the data you have provided up that point.

5. **What will happen to me if I take part?**
   Involvement in this study will include the researcher assessing your neck strength and taking a baseline score for the Cognetivity cognition test

   We will then monitor your injury rates and minutes played during the course of the season. Injuries include concussion and any other injuries that you sustain while playing rugby or prevents you from playing rugby.

   The observational period will last the whole season and we will re-assess your scores on the Cognetivity test in the event that you suffer a concussion.

6. **What are the possible disadvantages and risks of taking part?**

This study will involve the commitment of your time (10 minutes) to complete the initial assessment

7. **What are the possible benefits of taking part?**
   You will discover some of the potential mechanisms that leave you vulnerable to concussion.

8. **What if something goes wrong?**
   Should you wish to make a complaint about the conduct of the researcher or the research process you may contact Dr Courtney Kipps the head of department for the MSc in Sports Medicine, Exercise and Health.

   Should you wish to report a serious problem with anything to do with the research process, please also contact Dr Courtney Kipps.

   At c.kipps@ucl.ac.uk

   If you feel the need to escalate your concerns you may contact the Chair of the UCL Research Ethics Committee – ethics@ucl.ac.uk

9. **Will my taking part in this project be kept confidential?**
   All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any ensuing reports or publications. Furthermore all of your data and results will be anonymised upon data entry so will not be traceable at any time.

   At no point will your personal data be shared with any third party or outside organisation.

10. **Limits to confidentiality**
    - Please note that assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.
    - Please note that confidentiality will be maintained as far as it is possible, unless during our conversation I hear anything which makes me worried that someone might be in danger of harm, I might have to inform relevant agencies of this.
    - Confidentiality will be respected subject to legal constraints and professional guidelines.
    - Confidentiality will be respected unless there are compelling and legitimate reasons for this to be breached. If this was the case we would inform you of any decisions that might limit your confidentiality.
    - Confidentiality may be limited and conditional and the researcher has a duty of care to report to the relevant authorities possible harm/danger to the participant or others.

11. **What will happen to the results of the research project?**

The results of this research project will be collected for the purpose of publication in a peer reviewed journal. Should you wish to attain a copy of this published research you are encouraged to contact the principle researcher who will be happy to provide it to you. At present there is not fixed date for publication.

No individual will be mentioned within the reporting of this paper however your university will be credited with taking part.

12. Data Protection Privacy Notice

Notice:
The data controller for this project will be University College London (UCL). The UCL Data Protection Office provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk. UCL's Data Protection Officer is Lee Shailer and he can also be contacted at data-protection@ucl.ac.uk**.**

Your personal data will be processed for the purposes outlined in this notice. The legal basis that would be used to process your personal data will be [the provision of your consent.] You can provide your consent for the use of your personal data in this project by completing the consent form that has been provided to you.

Your personal data will be processed so long as it is required for the research project. We will anonymise the personal data you provide and will endeavour to minimise the processing of personal data wherever possible.

If you are concerned about how your personal data is being processed, please contact UCL in the first instance at data-protection@ucl.ac.uk. If you remain unsatisfied, you may wish to contact the Information Commissioner's Office (ICO). Contact details, and details of data subject rights, are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

16. Contact for further information

For further information please contact Theo Farley at t.farley@ucl.ac.uk, ISEH, 170N Tottenham Court Road, London, W1T 7HA.

Please feel free to take this information sheet home for review and discussion should you feel the need.

Thank you for reading this information sheet and for considering taking part in this research study.

C2: Participant information form: Study 1 (Georgian translation)

მონაწილის საინფორმაციო ფურცელი- მორაგბეები

UCL კვლევის ეთიკის კომიტეტის დამტკიცების ID ნომერი: _____

თქვენ გადმოგეცემათ ამ საინფორმაციო ფურცლის ასლი

კვლევის სათაური:
არის თუ არა მორაგბეებში კისრის სიძლიერე ტვინის შერყევის რისკ ფაქტორი
განყოფილება: ქირურგიისა და ინტერვენციული მეცნიერების განყოფილება
მთავარი მკვლევარის სახელი და საკონტაქტო ინფორმაცია: თეო ფარლი t.farley@ucl.ac.uk

1. მოწვევის ნაწილი
   თქვენ მოწვეული ხართ კვლევის პროექტში მონაწილეობის მისაღებად. გადაწყვეტილების მიღებამდე აუცილებელია გესმოდეთ, თუ რატომ ტარდება კვლევა და რას მოიცავს თქვენი მონაწილეობა. გთხოვთ წაიკითხოთ შემდეგი ინფორმაცია დაკვირვებით და სურვილის შემთხვევაში განიხილეთ საკითხი სხვებთან. მოგვმართეთ გაუგებრობის ან დამატებითი ინფორმაციის შემთხვევაში. დაფიქრდით და გადაწყვიტეთ გსურთ თუ არა მონაწილეობის მიღება.

   მადლობას მოგახსენებთ წაკითხვისთვის.

2. რა არის პროექტის მიზანი?
   ჩვენ ვიკვლევთ, არის თუ არა მორაგბეებისთვის კისრის სიძლიერე ტვინის შერყევის რისკ ფაქტორი.

3. რატომ ამირჩიეს მე?
   თქვენ აგირჩიეს, ვინაიდან ხართ რაგბის გუნდის ნაწილი. ჩვენი მიზანია მოვიწვიოთ 100 მორაგბე კვლევისთვის.
   იმისათვის, რომ ჩაერთოთ კვლევაში, საჭიროა იყოთ რეკრეაციული, რჩეული მორაგბე და არ გქონდეთ ისეთი სამედიცინო მდგომარეობა, რაც გამორიცხავს თქვენთვის რაგბის თამაშს ან კისრის ძალის შემოწმების ჩატარებას. მოგეთხოვებათ, წინასწარ გაიაროთ სამედიცინო შემოწმება, რათა დავრწმუნდეთ, რომ არ არსებობს მიზეზი, რაც ხელს შეუშლის თქვენს მონაწილეობას კვლევაში.

4. უნდა მივიღო თუ არა მონაწილეობა?
   თქვენზეა დამოკიდებული მიიღებთ თუ არა მონაწილეობას. თუ გადაწყვეტთ მონაწილეობის მიღებას, თქვენ გადმოგეცემათ ეს საინფორმაციო ფურცელი (და მოგეთხოვებათ ხელი მოაწეროთ თანხმობის ფორმას). შეგიძლიათ ახსნა-განმარტების გარეშე უარი თქვათ მონაწილეობაზე ნებისმიერ დროს.

   თუ გადაწყვეტთ გაუქმებას, თქვენი სურვილის მიხედვით მოხდება შენახვა ან გაუქმება იმ მონაცემებისა, რაც მანამდე შეგროვდა.

5. რა მოხდება თუკი მონაწილეობას მივიღებ?
   ამ კვლევაში ჩართულობა მოიცავს მკვლევარის მიერ თქვენი კისრის სიძლიერის განსაზღვრას.

კისრის სიძლიერის შეფასების პარალელურად, თქვენ უნდა დაუსახელოთ მკვლევარს ნებისმიერი გადატანილი ტრავმა, რათა ვაწარმოოთ ტრავმების შემთხვევების მონიტორინგი, რომელიც მოიცავს ტვინის შერყევას და სხვა ნებისმიერ დაზიანებას, რაც რაგბის თამაშის პერიოდში მოგსვლიათ.

დაკვირვების პერიოდი გაგრძელდება მთელი სეზონი, ხოლო კვლევის პროექტი - ორი სეზონი, რათა მკვლევარმა შეძლოს დასკვნისთვის საკმარისი რაოდენობის შეგროვება.

6. რა არის მონაწილეობის მიღების შესაძლო რისკები და უარყოფითი მხარე**?**
თქვენ მოგეთხოვებათ ამცნოთ მკვლევართა გუნდს გადატანილი ტრავმების შესახებ. ინფორმაცია იქნება კონფიდენციალური ორგანიზაციაში თუ მის გარეთ.

7. რა იქნება თუკი რამე არასწორად მოხდება**?**
მკვლევარის ან კვლევის პროცესის შესახებ საჩივრის დაწერის სურვილის შემთხვევაში, დაუკავშირდით დოქტორ კორტნი კიპსს (Dr Courtney Kipps) სპორტისა და ვარჯიშის მედიცინის განყოფილების უფროსს.

გთხოვთ ასევე მიმართოთ დოქტორ კორტნი კიპსს კვლევის პროცესისას რაიმე სერიოზული პრობლემის შემთხვევაში

c.kipps@ucl.ac.uk

თუ გრძნობთ, რომ საჭიროა თქვენი დამოკიდებულების მწვავედ გამომჟღავნება, შეგილიათ დაუკავშირდეთ UCL კვლევის კომიტეტის თავმჯდომარეს - ethics@ucl.ac.uk

8. იქნება თუ არა კონფიდენციალური პროექტში ჩემი მონაწილეობის მიღება**?**
ნებისმიერი ინფორმაცია, რასაც თქვენზე შევაგროვებთ კვლევის განმავლობაში, იქნება კონფიდენციალური. ვერ ამოგიცნობენ ვერც ერთ მოხსენებასა თუ პუბლიკაციაში. გარდა ამისა, ყველა თქვენი მონაცემები თუ შედეგები იქნება ანონიმური. არავითარ შემთხვევაში არ გაზიარდება თქვენი პირადი მონაცემები მესამე პირთან.

9. კონფიდენციალობის ლიმიტები

გთხოვთ გაითვალისწინოთ, რომ კონფიდენციალობა იქნება მკაცრად დაცული იმ შემთხვევაში, თუ არ იქნება აღმოჩენილი დანაშაული ან პოტენციური ზიანის მტკიცებულება. ამ შემთხვევებში უნივერსიტეტი ვალდებულია დაეკონტაქტოს შესაბამის ნორმატიულ ორგანოებს / სააგენტოს.

10. რა ელის კვლევის პროექტის შედეგებს**?**
ამ კვლევის პროექტის შედეგები შეგროვდება შედარებითი გამოკვლევების ჟურნალში გამოქვეყნების მიზნით. თუ გსურთ გამოქვეყნებული კვლევის ასლის მიღება, დაუკავშირდით მთავარ მკვლევარს და ის სიამოვნებით უზრუნველყოფს თქვენთვის ასლის გადმოცემას.

11. მონაცემთა დაცვის კონფიდენციალურობის შეტყობინება
შენიშვნა**:**
ამ პროექტის მონაცემთა კონტროლი იქნება ლონდონის უნივერსიტეტის კორპორაცია (UCL). UCL მონაცემთა დაცვის სამსახური უზრუნველყოფს UCL- ის საქმიანობას, რომელიც მოიცავს პირადი მონაცემების დამუშავებას. შეგიძლიათ დაუკავშირდეთ შემდეგ მისამართზე: data-protection@ucl.ac.uk. UCL-ის მონაცემთა დაცვის ოფიცერი არის ლი შეილერი (Lee Shailer) და მასთან დაკავშირებაც ამ მისამართზეა შესაძლებელი:data-protection@ucl.ac.uk**.**

თქვენი პირადი მონაცემები დამუშავდება ამ განცხადებაში აღწერილი მიზნებისათვის.
იურიდიული საფუძველი, რომელიც გამოყენებული იქნება თქვენი პირადი მონაცემების დამუშავებისათვის იქნება [თქვენი თანხმობის უზრუნველყოფა.] თანხმობის ფორმის შევსებით, რომელიც უკვე გადმოგეცათ, შეგიძლიათ დაადასტუროთ ამ პროექტში თქვენი პირადი მონაცემების გამოყენების თანხმობა.

თქვენი პირადი მონაცემების დამუშავება გაგრძელდება მანამ, სანამ ამას კვლევის პროექტი მოითხოვს. ჩვენ აუცილებლად დავიცავთ თქვენს მიერ მოწოდებული მონაცემების ანონიმურობას და შევეცდებით შევამციროთ პირადი მონაცემების დამუშავების პროცესი მინიმუმამდე.
თქვენი პირადი მონაცემების დამუშავების პროცესთან დაკავშირებით დაინტერესების შემთხვევაში, გთხოვთ პირველ რიგში დაუკავშირდეთ UCL-ს შემდეგ მისამართზე: data-protection@ucl.ac.uk. თუ ინფორმაცია არ იქნება დამაკმაყოფილებელი, შეგიძლიათ დაუკავშირდეთ საინფორმაციო კომისიის ოფისს (ICO). საკონტაქტო ინფორმაცია და მონაცემთა უფლებების დეტალები შეგიძლიათ იხილოთ ICO-ს ვებსაიტზე: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

16. დამატებითი ინფორმაციისთვის დაკავშირება

დამატებითი ინფორმაციისათვის გთხოვთ დაუკავშირდით თეო ფარლის t.farley@ucl.ac.uk, ISEH, 170N Tottenham Court Road, London, W1T 7HA.

სურვილის შემთხვევაში შეგიძლიათ საინფორმაციო ფურცელი წაიღოთ სახლში და გადახედოთ/განიხილოთ

მადლობას გიხდით ინფორმაციის წაკითხვისა და კვლევაში მონაწილეობის მიღების განხილვისათვის

C3: Participant consent form: Study 1

****This is a template form and must be tailored to meet the needs of your study and should be displayed on departmental headed paper.**

CONSENT FORM FOR Didi 10 RUGBY PLAYERS IN RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study: Is neck strength a risk factor to concussion in rugby union players
Department: Department of Surgery and Interventional Sciences
Name and Contact Details of the Researcher(s: Theo Farley
Name and Contact Details of the Principal Researcher: Theo Farley
Name and Contact Details of the UCL Data Protection Officer: Lee Shailer data-protection@ucl.ac.uk
This study has been approved by the UCL Research Ethics Committee: Project ID number: 11785/004

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

I confirm that I understand that by ticking/initialling each box below I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes means that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

		Tick Box
1.	I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction	
2.	I understand that I will be able to withdraw my data at any time during the intervention period	
3.	I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with all applicable data protection legislation. Personal data that will be collected includes: Age Weight Height Sex Injury history: History of neck trauma/pain History of concussion History of headache Test data: Neck strength Cognetivity Ltd assessment Incidence of concussion Minutes played through season	

4.	**Use of the information for this project only** I understand that all personal information will remain confidential and that all efforts will be made to ensure I cannot be identified I understand that my data gathered in this study will be stored anonymously and securely. It will not be possible to identify me in any publications.	
5.	I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason, [*without the care I receive or my legal rights being affected*]. I understand that if I decide to withdraw, any personal data I have provided up to that point will be deleted unless I agree otherwise.	
6.	I understand the potential risks of participating and the support that will be available to me should I become distressed during the course of the research.	
7.	I understand the direct/indirect benefits of participating.	
8.	I understand that the data will not be made available to any commercial organisations but is solely the responsibility of the researcher undertaking this study.	
9.	I understand that I will not benefit financially from this study or from any possible outcome it may result in in the future.	
10.	I agree that my anonymised research data may be used by others for future research. [No one will be able to identify you when this data is shared.]	
11.	I understand that the information I have submitted will be published as a report and I wish to receive a copy of it. (please circle relevant statement)	Yes No
12.	I hereby confirm that I understand the inclusion criteria as detailed in the Information Sheet and explained to me by the researcher.	
13.	I hereby confirm that: (a) I understand the exclusion criteria as detailed in the Information Sheet and explained to me by the researcher; and (b) I do not fall under the exclusion criteria.	
14.	I agree that my doctor may be contacted if any unexpected results are found in relation to my health.	
15.	I have informed the researcher of any other research in which I am currently involved or have been involved in during the past 12 months.	
16.	I am aware of who I should contact if I wish to lodge a complaint.	
17.	I voluntarily agree to take part in this study.	
18.	Use of information for this project and beyond: The personal data that you provide will be used within the research study only and will be reported on anonymously within the published research. Your data will be stored on an encrypted laptop and stored for the duration of the research project only.	

If you would like your contact details to be retained so that you can be contacted in the future by UCL researchers who would like to invite you to participate in follow up studies to this project, or in future studies of a similar nature, please tick the appropriate box below.

	Yes, I would be happy to be contacted in this way	
	No, I would not like to be contacted	

_____	_____	_____
Name of participant	Date	Signature
_____	_____	_____
Researcher	Date	Signature

C4: Participant consent form: Study 1 (Georgian Translation)

კვლევაში მონაწილეობის თანხმობის ფორმა მორაგბეებისთვის

გთხოვთ, შეავსოთ ეს ფორმა ინფორმაციის წაკითხვისა და კვლევის განმარტების მოსმენის შემდეგ.

სწავლის სათაური: არის თუ არა მორაგბეებში კისრის სიძლიერე რისკის ფაქტორი ტვინის შერყევისთვის?

განყოფილება: ქირურგიისა და ინტერვენციული მეცნიერების განყოფილება

მკვლევარის სახელი და საკონტაქტო ინფორმაცია: თეო ფარლი

მთავარი მკვლევარის სახელი და საკონტაქტო ინფორმაცია: თეო ფარლი

UCL მონაცემების დაცვის ოფიცერის სახელი და საკონტაქტო ინფორმაცია: ედვარდ ჩარნლი **e.charnley@ucl.ac.uk**

აღნიშნული სწავლება დამტკიცებულია **UCL** კვლევის ეთიკის კომიტეტის მიერ: პროექტის ID ნომერი:

მადლობას გიხდით კვლევაში მონაწილეობის მიღებისათვის. პირი, რომელიც ორგანიზებას უწევს კვლევას, ვალდებულია აგიხსნათ პროექტი, სანამ დაეთანხმებით მონაწილეობის მიღებაზე. თუ რაიმე შეკითხვა გაგიჩნდათ ინფორმაციის წაკითხვისა თუ მოსმენის შემდეგ, გთხოვთ ჰკითხოთ მკვლევარს, სანამ გადაწყვეტთ მონაწილეობის მიღებას. თქვენ გადმოგეცემათ თანხმობის ფორმის ასლი.

ვადასტურებ, რომ ყოველი აღნიშვნის ყუთის მონიშვნით, ვეთანხმები სწავლების ამ ელემენტს. მესმის, რომ მოუნიშნავი ყუთები ნიშნავს, რომ არ ვეთანხმები კვლევის აღნიშნულ ნაწილს. მესმის, რომ არც ერთი ელემენტის მონიშვნის შემთხვევაში ვიქნები არაუფლებამოსილი კვლევისთვის.

		აღნიშვნის გრაფა
1.	ვადასტურებ, რომ გავეცანი ინფორმაციას კვლევასთან დაკავშირებით. მქონდა შესაძლებლობა გამეაზრებინა ინფორმაცია და ჩემთვის მოსალოდნელი ფაქტორები. ასევე, მქონდა შესაძლებლობა დამესვა კითხვები, რომლებზეც დამაკმაყოფილებელი პასუხები მივიღე	
2.	ვიცი, რომ შემიძლია გავაუქმო ჩემი მონაცემები ნებისმიერ დროს პროცესის მსვლელობისას	

3.	ვეთანხმები ჩემი პირადი ინფორმაციის დამუშავებას ახსნილი მიზეზებისთვის. მესმის, რომ ასეთი ინფორმაცია იქნება დაცული ყველა მოქმედი მონაცემთა დაცვის კანონმდებლობის შესაბამისად. შეგროვებული პიროვნული მონაცემები მოიცავს: ასაკი წონა სიმაღლე სქესი ტრავმების ისტორია: კისრის ტრავმის/ტკივილის ისტორია ტვინის შერყევის ისტორია თავის ტკივილის ისტორია შემოწმების მონაცემები: კისრის სიძლიერის ქულა ტვინის შერყევის სიხშირე კოგნიტური ტესტის ქულა	
4.	ინფორმაციის მხოლოდ ამ პროექტისთვის გამოყენება. შევიტყვე, რომ ნებისმიერი პირადი ინფორმაცია დარჩება კონფიდენციალური ყველანაირი ძალისხმევის გამოყენებით შევიტყვე, რომ ამ კვლევაში დაგროვებული ჩემი მონაცემები შეინახება ანონიმურად და იქნება დაცული. შეუძლებელი იქნება ჩემი იდენტიფიცირება ნებისმიერ გამოცემაში	
5.	მესმის, რომ ვარ მოხალისე და შემიძლია ნებისმიერ დროს, ახსნის გარეშე შევწყვიტო მონაწილეობის მიღება, [*თუ კი ვიგრძენი უპატივცემულობა ან ჩემი კანონიერი უფლებები დაზარალდა*]. ვიაზრებ, რომ თუ გადავწყვეტ შევწყვიტო მონაწილეობა, ნებისმიერი პირადი მონაცემები, რაც მანამდე შეგროვდა, წაიშლება ჩემი სურვილის შესაბამისად.	

6.	ვიაზრებ მონაწილეობის მიღების პოტენციურ რისკს და მხარდაჭერას, თუ კი რაიმე გამირთულდება კვლევის მსვლელობისას.	
7.	ვიაზრებ მონაწილეობის მიღების პირდაპირ და ირიბ სარგებელს.	
8.	ვიაზრებ, რომ მონაცემები არ გახდება ხელმისაწვდომი არც ერთი კომერციული ორგანიზაციისათვის. მკვლევარი არის პასუხისმგებელი ამ კვლევის ჩატარებაზე	
9.	ვიაზრებ, რომ ამ კვლევისგან ან მომავალში მისი შესაძლო შედეგებისგან არ მივიღებ ფინანსურ სარგებელს	
10.	ვეთანხმები, რომ ჩემი ანონიმური კვლევის მონაცემები შეიძლება სხვებმა გამოიყენონ მომავალი კვლევებისთვის [ამ მონაცემების გაზიარებით ვერავინ შეძლებს თქვენს იდენტიფიცირებას.]	
11.	ვიაზრებ, რომ ჩემს მიერ წარდგენილი ინფორმაცია გამოქვეყნდება, როგორც მოხსენება და მსურს მივიღო მისი ასლი. (გთხოვთ შემოხაზეთ შესაბამისი პასუხი)	დიახ არა
12.	ამით ვადასტურებ, რომ ვიაზრებ მკვლევარის მიერ განმარტებულ და საინფორმაციო ფურცელზე თანდართულ კრიტერიუმებს დეტალურად	
13.	ამით ვადასტურებ, რომ: (ა)ვიაზრებ მკვლევარის მიერ განმარტებულ და საინფორმაციო ფურცელზე გამონაკლის კრიტერიუმებს დეტალურად; (ბ)მე არ გამოვრიცხავ გამონაკლის კრიტერიუმებს.	
14.	ვეთანხმები, რომ ჩემს ორგანიზაციას შეუძლია გაუზიაროს ჩემი ტრავმების მონაცემები კვლევაში მონაწილე გუნდს.	
15.	მკვლევარს მივაწოდე ინფორმაცია სხვა ნებისმიერ კვლევაში ამჟამად ან ბოლო 12 თვის განმავლობაში ჩემი ჩართულობისა.	
16.	ვიცი ვის უნდა მივმართო, თუ საჩივრის დაწერა ვისურვე	
17.	ნებაყოფლობით ვეთანხმები ამ კვლევაში მონაწილეობას.	

18.	ინფორმაციის გამოყენება ამ პროექტსა და მის ფარგლებს გარეთ: თქვენს მიერ მოწოდებული პირადი მონაცემები გამოიყენება მხოლოდ კვლევის ფარგლებში და გამოქვეყნდება ანონიმურად. თქვენი მონაცემები ინახება დაშიფრულ ლეპტოპში და ინახება მხოლოდ კვლევის პროექტის განმავლობაში.	

თუ გსურთ, რომ თქვენი საკონტაქტო ინფორმაცია იქნეს შენახული, რათა UCL მკვლევარები დაგიკავშირდნენ მომავალში იგივე ან განსხვავებულ კვლევებში მონაწილეობის მისაღებად, გთხოვთ მონიშნეთ შესაბამისი გრაფა.

	დიახ, მსურს დამიკავშირდნენ	
	არა, არ მსურს დამიკავშირდნენ	

_____ _____ _____

მონაწილის სახელი თარიღი ხელმოწერა

_____ _____ _____

მკვლევარი თარიღი ხელმოწერა

C5: Participant information form: Study 2

Participant Information Sheet- rugby players

UCL Research Ethics Committee Approval ID Number: 11785/007

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study:
Is neck proprioception a risk factor to concussion injur y in rugby players
Department: Department of surgery and interventional sciences
Name and Contact Details of the Principal Researcher: Theo Farley. t.farley@ucl.ac.uk

1. **Invitation Paragraph**
   You are being invited to take part in a research project. Before you decided it is important for you to understand why the research is being done and what participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

   Thank you for reading this.

2. **What is the project's purpose?**
   We are investigating whether a neck proprioception is a risk factor to concussion injury in rugby players.

3. **Why have I been chosen?**
   You have been asked to participate because you are part of the rugby team. We are aiming to recruit 140 rugby players to this study.
   To be included in this study you must be a rugby player and have no medical condition that would exclude you from playing rugby or conducting a neck proprioception assessment. You will be required to complete a medical screening form prior to starting the study to ensure that there is no medical reason that you are unable to take part.

4. **Do I have to take part?**
   It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and asked to sign a consent form). You can withdraw at any time without giving a reason and without it affecting any benefits that you are entitled to.

   If you decide to withdraw you will be asked what you wish to happen to the data you have provided up that point.

5. **What will happen to me if I take part?**
   Involvement in this study will include the researcher taking a measurement of your neck proprioception.

   Alongside your neck proprioception assessment we ask that you report any injuries to the researcher so that we may monitor your injury incidence. This includes concussion and any other injuries that you sustain while playing rugby or prevents you from playing rugby.

   The observational period will last the whole season and the research project will last for two seasons so that the research may gather sufficient numbers for analysis.

6. **What are the possible disadvantages and risks of taking part?**
   You will be required to report your injuries to the research team. This will be confidential and no information will be relayed to anyone, either within your organisation or external to it.

7. **What if something goes wrong?**
   Should you wish to make a complaint about the conduct of the researcher or the research process you may contact Dr Courtney Kipps the head of department for the MSc in Sport and Exercise Medicine.

   Should you wish to report a serious problem with anything to do with the research process, please also contact Dr Courtney Kipps.

   At c.kipps@ucl.ac.uk

   If you feel the need to escalate your concerns you may contact the Chair of the UCL Research Ethics Committee – ethics@ucl.ac.uk

8. **Will my taking part in this project be kept confidential?**
   All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any ensuing reports or publications. Furthermore all of your data and results will be anonymised upon data entry so will not be traceable at any time.

   At no point will your personal data be shared with any third party or outside organisation.

9. **Limits to confidentiality**

Please note that assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

10. **What will happen to the results of the research project?**

    The results of this research project will be collected for the purpose of publication in a peer reviewed journal. Should you wish to attain a copy of this published research you are encouraged to contact the principle researcher who will be happy to provide it to you. At present there is not fixed date for publication.

    No individual will be mentioned within the reporting of this paper however your university will be credited with taking part.

11. **Data Protection Privacy Notice**

    Notice:
    The data controller for this project will be University College London (UCL). The UCL Data Protection Office provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk. UCL's Data Protection Officer is Lee Shailer and he can also be contacted at data-

protection@ucl.ac.uk**.**

Your personal data will be processed for the purposes outlined in this notice. The legal basis that would be used to process your personal data will be [the provision of your consent.] You can provide your consent for the use of your personal data in this project by completing the consent form that has been provided to you.

Your personal data will be processed so long as it is required for the research project. We will anonymise the personal data you provide and will endeavour to minimise the processing of personal data wherever possible.

If you are concerned about how your personal data is being processed, please contact UCL in the first instance at data-protection@ucl.ac.uk. If you remain unsatisfied, you may wish to contact the Information Commissioner's Office (ICO). Contact details, and details of data subject rights, are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

16. Contact for further information

For further information please contact Theo Farley at t.farley@ucl.ac.uk, ISEH, 170N Tottenham Court Road, London, W1T 7HA.

Please feel free to take this information sheet home for review and discussion should you feel the need.

Thank you for reading this information sheet and for considering taking part in this research study.

C6: Participant consent form: Study 2

CONSENT FORM FOR RUGBY PLAYERS IN RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and listened to an explanation about the research.
Title of Study: Is neck proprioception a risk factor to concussion injury in rugby players
Department: Department of Surgery and Interventional Sciences
Name and Contact Details of the Researcher: Theo Farley
Name and Contact Details of the Principal Researcher: Theo Farley
Name and Contact Details of the UCL Data Protection Officer: Lee Shailer data-protection@ucl.ac.uk
This study has been approved by the UCL Research Ethics Committee: Project ID number: 11785/007
Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.
I confirm that I understand that by ticking each box below I am consenting to this element of the study. I understand that it will be assumed that unticked boxes means that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

		Tick Box
1.	I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction	
2.	I understand that I will be able to withdraw my data at any time during the intervention period	
3.	I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with all applicable data protection legislation. Personal data that will be collected includes: Age Weight Height Sex Injury history: History of neck trauma/pain History of concussion History of headache Test data: Neck proprioception scores Match minutes played Incidence of concussion	
4.	**Use of the information for this project only** I understand that all personal information will remain confidential and that all efforts will be made to ensure I cannot be identified I understand that my data gathered in this study will be stored anonymously and securely. It will not be possible to identify me in any publications.	
5.	I understand that my participation is voluntary and that I am free to withdraw at any	

	time without giving a reason, [*without the care I receive or my legal rights being affected*]. I understand that if I decide to withdraw, any personal data I have provided up to that point will be deleted unless I agree otherwise.	
6.	I understand the potential risks of participating and the support that will be available to me should I become distressed during the course of the research.	
7.	I understand the direct/indirect benefits of participating.	
8.	I understand that the data will not be made available to any commercial organisations but is solely the responsibility of the researcher undertaking this study.	
9.	I understand that I will not benefit financially from this study or from any possible outcome it may result in in the future.	
10.	I agree that my anonymised research data may be used by others for future research. [No one will be able to identify you when this data is shared.]	
11.	I understand that the information I have submitted will be published as a report and I wish to receive a copy of it. (please circle relevant statement)	Yes No
12.	I hereby confirm that I understand the inclusion criteria as detailed in the Information Sheet and explained to me by the researcher.	
13.	I hereby confirm that: (a) I understand the exclusion criteria as detailed in the Information Sheet and explained to me by the researcher; and (b) I do not fall under the exclusion criteria.	
14.	I agree that my organisation may share my injury data with the research team.	
15.	I have informed the researcher of any other research in which I am currently involved or have been involved in during the past 12 months.	
16.	I am aware of who I should contact if I wish to lodge a complaint.	
17.	I voluntarily agree to take part in this study.	
18.	Use of information for this project and beyond: The personal data that you provide will be used within the research study only and will be reported on anonymously within the published research. Your data will be stored on an encrypted laptop and stored for the duration of the research project only.	

If you would like your contact details to be retained so that you can be contacted in the future by UCL researchers who would like to invite you to participate in follow up studies to this project, or in future studies of a similar nature, please tick the appropriate box below.

	Yes, I would be happy to be contacted in this way	
	No, I would not like to be contacted	

_____	_____	_____
Name of participant	Date	Signature
_____	_____	_____
Researcher	Date	Signature

C7: Participant information form: Study 3

Participant Information Sheet- University rugby players
UCL Research Ethics Committee Approval ID Number: 11785/001

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study:
The difference in Vestibular-Oculomotor Screening assessment (VOMS) pre-exercise and at three different time points post exercise in elite and recreational athletes and sedentary individuals

Department: Department of surgery and interventional sciences
Name and Contact Details of the Principal Researcher: Theo Farley. t.farley@ucl.ac.uk

1. **Invitation Paragraph**
   You are being invited to take part in a research project. Before you decided it is important for you to understand why the research is being done and what participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

   Thank you for reading this.

2. **What is the project's purpose?**
   We are investigating whether the vestibular system (inner ear) and the oculomotor system (eye) work as effectively after a moderate intensity treadmill run as they do when people are at rest.

3. **Why have I been chosen?**
   You have been asked to participate because you are part of a sports team at your university or a student that does not take part in any exercise. We are aiming to recruit 100 student athletes to this study and 100 sedentary students.
   To be included in this study you must be a university student and have no medical condition that would exclude you from playing your chosen sport or conducting a treadmill run.

4. **Do I have to take part?**
   It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and asked to sign a consent form). You can withdraw at any time without giving a reason and without it affecting any benefits that you are entitled to.

   If you decide to withdraw you will be asked what you wish to happen to the data you have provided up that point.

5. **What will happen to me if I take part?**
   Involvement in this study will include the researcher making an assessment of your vestibular and oculomotor systems. When this is complete you will be asked to complete a treadmill run for 5 minutes. The assessment of your oculomotor system will then be repeated immediately post run and then at 2 minutes post run and 4 minutes post run. The vestibular and oculomotor assessment is a non invasive assessment that involves you actively moving your head and eyes in a controlled manor.

   This is a one off assessment that will last approximately 20 minutes. After this you will not be required to do anything further. This study will be active for nine months which is the amount of time that your data will be stored

.

6. **What are the possible disadvantages and risks of taking part?**
   This study will involve the commitment of your time (20 minutes) to complete the assessment.

7. **What are the possible benefits of taking part?**
   You will be offered a copy of your test results that will inform you whether you have any dysfunction in your vestibular or oculomootor systems. Based on these results the researcher will offer you a set of self led exercises that you can use to train these systems to improve their efficiency.

8. **What if something goes wrong?**
   Should you wish to make a complaint about the conduct of the researcher or the research process you may contact Dr Courtney Kipps the head of department for the MSc in Sport and Exercise Medicine.

   Should you wish to report a serious problem with anything to do with the research process, please also contact Dr Courtney Kipps.

   At c.kipps@ucl.ac.uk

   If you feel the need to escalate your concerns you may contact the Chair of the UCL Research Ethics Committee – ethics@ucl.ac.uk

9. **Will my taking part in this project be kept confidential?**
   All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any ensuing reports or publications. Furthermore all of your data and results will be anonymised upon data entry so will not be traceable at any time.

   At no point will your personal data be shared with any third party or outside organisation.

10. **Limits to confidentiality**
    - Please note that assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.
    - Please note that confidentiality will be maintained as far as it is possible, unless during our conversation I hear anything which makes me worried that someone might be in danger of harm, I might have to inform relevant agencies of this.
    - Confidentiality will be respected subject to legal constraints and professional guidelines.
    - Confidentiality will be respected unless there are compelling and legitimate reasons for this to be breached. If this was the case we would inform you of any decisions that might limit your confidentiality.
    - Confidentiality may be limited and conditional and the researcher has a duty of care to report to the relevant authorities possible harm/danger to the participant or others.

C8: Participant consent form: Study 3

CONSENT FORM FOR RESEARCH STUDIES

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study: The difference in Vestibular-Oculomotor Screening assessment (VOMS) pre-exercise and at three different time points post exercise in elite and recreational athletes and sedentary individuals

Department: Department of Surgery and Interventional Sciences
Name and Contact Details of the Researcher(s: Theo Farley
Name and Contact Details of the Principal Researcher: Theo Farley
Name and Contact Details of the UCL Data Protection Officer: Edward Charnley e.charnley@ucl.ac.uk
This study has been approved by the UCL Research Ethics Committee: Project ID number: 11785/001

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

I confirm that I understand that by ticking/initialling each box below I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes means that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

		Tick Box
1.	I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction	
2.	I understand that I will be able to withdraw my data at any time during the intervention period	
3.	I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with all applicable data protection legislation. Personal data that will be collected includes: Age Weight Sex Injury history: History of neck trauma/pain History of concussion History of headache Test data: Vestibular Oculomotor Screening (VOMS) assessment results	

4.	**Use of the information for this project only** I understand that all personal information will remain confidential and that all efforts will be made to ensure I cannot be identified I understand that my data gathered in this study will be stored anonymously and securely. It will not be possible to identify me in any publications.	
5.	I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason, [*without the care I receive or my legal rights being affected*]. I understand that if I decide to withdraw, any personal data I have provided up to that point will be deleted unless I agree otherwise.	
6.	I understand the potential risks of participating and the support that will be available to me should I become distressed during the course of the research.	
7.	I understand the direct/indirect benefits of participating.	
8.	I understand that the data will not be made available to any commercial organisations but is solely the responsibility of the researcher undertaking this study.	
9.	I understand that I will not benefit financially from this study or from any possible outcome it may result in in the future.	
10.	I agree that my anonymised research data may be used by others for future research. [No one will be able to identify you when this data is shared.]	
11.	I understand that the information I have submitted will be published as a report and I wish to receive a copy of it. (please circle relevant statement)	Yes No
12.	I hereby confirm that I understand the inclusion criteria as detailed in the Information Sheet and explained to me by the researcher.	
13.	I hereby confirm that: (a) I understand the exclusion criteria as detailed in the Information Sheet and explained to me by the researcher; and (b) I do not fall under the exclusion criteria.	
14.	I agree that my GP may be contacted if any unexpected results are found in relation to my health.	
15.	I have informed the researcher of any other research in which I am currently involved or have been involved in during the past 12 months.	
16.	I am aware of who I should contact if I wish to lodge a complaint.	
17.	I voluntarily agree to take part in this study.	
18.	Use of information for this project and beyond: The personal data that you provide will be used within the research study only and will be reported on anonymously within the published research. Your data will be stored on an encrypted laptop and stored for the duration of the research project only.	

If you would like your contact details to be retained so that you can be contacted in the future by UCL researchers who would like to invite you to participate in follow up studies to this project, or in future studies of a similar nature, please tick the appropriate box below.

	Yes, I would be happy to be contacted in this way	
	No, I would not like to be contacted	

_____	_____	_____
Name of participant	Date	Signature
_____	_____	_____
Researcher	Date	Signature

C9: Medical screening form: Studies 1, 2 and 3

General Medical History

Please check the following that you have experienced

You suffer from headaches	Yes	No
Do you have neck pain	Yes	No
Have you ever been hospitalised with a neck problem	Yes	No
Have you ever had surgery to your head neck or spine	Yes	No
Do you have a history of concussion	Yes	No
If yes, when did the most recent concussion resolve	Yes	No
Do you ever experience dizziness, fainting or blackouts	Yes	No
Do you experience shortness of breath at rest	Yes	No
Do you have a history of cardiac issues that would prevent you from playing rugby	Yes	No

Appendix D: Data collection aids

D1: Graduated Return to Play protocol: Study 2

D2: Borg scale 1-20: Study 3

EXERTION: how do you feel?

6	No effort at all (REST)
7	Very Very Light
8	
9	Very Light
10	
11	Fairly Light
12	
13	Somewhat Hard
14	
15	Hard
16	
17	Very Hard
18	
19	Very Very Hard
20	Maximal Effort