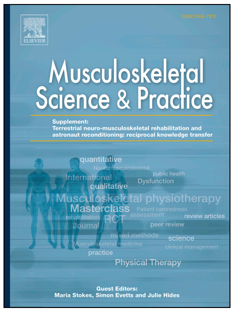

A prospective investigation of changes in the sensorimotor system following sports concussion. An exploratory study

Julie A. Hides, PhD, Melinda M. Franettovich Smith, PhD, M. Dilani Mendis, PhD, Nigel A. Smith, MAppSc (Res), Andrew J. Cooper, MInfSci, Julia Treleaven, PhD, Felix Leung, BPhty (Hons), Andrew J. Gardner, PhD, Paul McCrory, PhD, Nancy L. Low Choy, PhD

PII: S2468-7812(17)30035-8

DOI: 10.1016/j.msksp.2017.02.003

Reference: MSKSP 50

To appear in: *Musculoskeletal Science and Practice*

Received Date: 2 September 2016

Revised Date: 10 February 2017

Accepted Date: 16 February 2017

Please cite this article as: Hides, J.A., Franettovich Smith, M.M., Mendis, M.D., Smith, N.A., Cooper, A.J., Treleaven, J., Leung, F., Gardner, A.J., McCrory, P., Low Choy, N.L., A prospective investigation of changes in the sensorimotor system following sports concussion. An exploratory study, *Musculoskeletal Science and Practice* (2017), doi: 10.1016/j.msksp.2017.02.003.

A prospective investigation of changes in the sensorimotor system following sports concussion. An exploratory study.

Julie A Hides[1], PhD

Melinda M Franettovich Smith[1], PhD

M. Dilani Mendis[1,2], PhD

Nigel A Smith[1], MAppSc (Res)

Andrew J Cooper[1], MInfSci

Julia Treleaven[3], PhD

Felix Leung[1], BPhty (Hons)

Andrew J Gardner [4,5], PhD

Paul McCrory[6], PhD

Nancy L Low Choy[7], PhD

[1]Centre for Musculoskeletal Research, Mary MacKillop Institute for Health Research, Australian Catholic University, Brisbane, QLD, Australia, 4102.

[2]Physiotherapy Department, Mater Health Services, South Brisbane, Australia, 4101.

[3]Division of Physiotherapy, School of Health and Rehabilitation Sciences, The University of Queensland, 4072, Australia.

[4]Priority Research Centre for Stroke and Brain Injury, School of Medicine and Public Health, University of Newcastle, Callaghan, NSW, 2310.

[5] Hunter New England Local Health District Sports Concussion Program, John Hunter Hospital, New Lambton Heights, NSW, 2305

[6] The Florey Institute of Neuroscience and Mental Health, Heidelberg, Victoria, Australia.

[7]School of Physiotherapy, Australian Catholic University, Brisbane, QLD, Australia, 4014.

Corresponding author: Julie A Hides

Level 1, 631 Stanley Street, Woolloongabba, QLD, Australia, 4102

Email: Julie.hides@acu.edu.au Phone: +617 3623 7530

ACKNOWLEDGEMENTS

Funding: This work was funded by a Collaborative Research Network/Australian Catholic University Research Fund [Grant number: 2013000523]. The authors would like to acknowledge the players and medical staff of the participating Football Clubs, funding by the Australian Catholic University Research Fund/ CRN Grant, Professor Jennifer Peat for statistical advice, Sue Lewandowski, Ann Rahmann, Margot Sexton and Tanja Miokovic for assistance with data collection, Dr Hugh Seward for advice and Jazmin Walsh, Christine Sonsearay and Rosemary Parker for assistance with manuscript preparation.

A prospective investigation of changes in the sensorimotor system following sports concussion. An exploratory study.

ABSTRACT

Background: Sports concussion is a risk for players involved in high impact, collision sports. Post-concussion, the majority of symptoms subside within 7-10 days, but can persist in 10-20% of athletes. Understanding the effects of sports concussion on sensorimotor systems could inform physiotherapy treatment.

Objective: To explore changes in sensorimotor function in the acute phase following sports concussion.

Design: Prospective cohort study.

Methods*:* Fifty-four players from elite rugby union and league teams were assessed at the start of the playing season. Players who sustained a concussion were assessed three to five days later. Measures included assessments of balance (sway velocity), vestibular system function (vestibular ocular reflex gain; right-left asymmetry), cervical proprioception (joint position error) and trunk muscle size and function.

Results: During the playing season, 14 post-concussion assessments were performed within 3-5 days of injury. Significantly decreased sway velocity and increased size /contraction of trunk muscles, were identified. Whilst not significant overall, large inter-individual variation of test results for cervical proprioception and the vestibular system was observed.

Limitations: The number of players who sustained a concussion was not large, but numbers were comparable with other studies in this field. There was missing baseline data for vestibular and cervical proprioception testing for some players.

Conclusions: Preliminary findings post-concussion suggest an altered balance strategy and trunk muscle control with splinting / over-holding requiring consideration as part of the development of appropriate physiotherapy management strategies.

Key Words: Motor control; vestibular system; balance; cervical proprioception; trunk muscles; rugby.

Funding: This work was funded by a Collaborative Research Network/Australian Catholic University Research Fund. [Grant number: 2013000523]

Conflicts of interest: none.

INTRODUCTION

Sports concussion is an inherent injury risk for participants involved in collision sports such as rugby league and rugby union (Gardner et al., 2015; Gardner et al., 2014). Following concussion, commonly reported initial symptoms include headache, dizziness, gait unsteadiness, blurred vision, nausea and neck pain (Makdissi et al., 2009). Whilst symptoms resolve in the majority of cases within 7-10 days, 10-20% of post-concussed players report continued symptoms (Benson et al., 2011; Makdissi et al., 2009).

Potential damage to various structures could occur following a concussion injury including the peripheral and central vestibular system and the cervical spine. Accordingly this can lead to deficits in sensorimotor control relating to balance, oculomotor and head movement control and can be related to the above symptoms. Since symptoms of dizziness and headache are predictors of post-concussion syndrome and or prolonged recovery post-concussion, (Faux et al., 2011; Ganti et al., 2014; Ellis et al., 2015; McLeod et al., 2015) it is important to consider deficits in the sensorimotor system post-concussion.

Impairments in static balance have been demonstrated post-concussion, using tests such as the modified Clinical Test of Sensory Interaction (CTSIB) (Guskiewicz et al., 1996), Balance Error Scoring System (BESS) (Alsalaheen et al., 2015; Riemann and Guskiewicz, 2000) and Sensory Organization Test (SOT) (Broglio et al., 2014; McDevitt et al., 2016). These impairments are generally thought to resolve within 3-5 days (Guskiewicz et al., 1996; McCrea et al., 2003; Peterson et al., 2003). Studies of dynamic balance following concussion have revealed mixed results. Post-concussion, conservative gait patterns with less sway and slower sway velocity in the sagittal plane (Catena et al., 2009) have been observed. These deficits may take longer to resolve (Slobounov et al., 2006) with inconsistent patterns of recovery (Parker et al., 2006). Rehabilitation of balance (and mobility) involves addressing deficits in the cervical (Leddy et al., 2016; Leddy et al., 2012) and vestibular systems (Alsalaheen et al., 2010; Leddy et al., 2012), practising balance and mobility tasks with graduated challenges to the base of support (firm to soft surfaces; narrower base of support during stance and mobility activities), actively exercising at the limits of stability, improving reaction times as well as adding secondary (dual) tasks during practice of stance and mobility tasks (Fu et al., 2009; Horak, 2006; Nitz and Choy, 2004).

Impairments of balance are thought to be due to deficits in the vestibular system, which may also lead to deficits in oculomotor control following concussion (Leddy et al., 2015). Dizziness and gaze instability are possible symptoms related to the vestibulo-ocular system (Khan and Chang, 2013). Rehabilitation of the vestibular system has been shown to be effective for people with persistent symptoms post- sports concussion when combined with cervical spine physiotherapy (Schneider et al., 2014).

Cervical spine injury can be caused by the acceleration-deceleration forces of a concussive trauma, and concomitant injuries are common with whiplash mechanisms identified as the cause of 10% of Australian and rugby football related concussions (McIntosh et al., 2000). Furthermore, a strong association between whiplash induced neck injuries and the symptoms of concussion have been demonstrated in other sports such as hockey (Hynes and Dickey, 2006). Assessment of cervical spine proprioception may be of importance post-concussion, and appropriate tests which might have utility in sports concussion have been validated in whiplash patients (Chen and Treleaven, 2013). Cervical joint position sense has been tested in a rugby union population, and results showed that cervical joint position sense was altered in these players (Pinsault et al., 2010). Cervical joint position sense can be improved with rehabilitation

(Revel et al., 1994); however cervical proprioception testing has not been performed pre and post sports concussion.

Postural control is important in physically demanding sports such as rugby league and rugby union, and the relationship between control of the lumbar spine and its influence on the cervical spine has been highlighted in both laboratory and clinical studies (Caneiro et al., 2010; Falla et al., 2007). Given that football involves physical collisions and tackles, adequate proprioception of cervical and lumbar trunk muscles may allow athletes to minimise head/neck injury by enhancing the player's ability to pre-set the head in an optimal position (Pinsault and Vuillerme, 2010). Furthermore, the ability to contract the lumbar multifidus muscle predicted head and neck injury in AFL players (Hides et al., 2016). There are also links between the vestibular system and the trunk muscles. The vestibulo-spinal system is responsible for postural control (Cullen, 2012), preferentially influencing the motor neuronal pool of the deeper cervical and trunk muscles (Hain, 2011). Dysfunction of the vestibulo-spinal system may affect balance (Khan and Chang, 2013) and motor control of cervical and trunk muscles. Trunk muscles have not previously been assessed pre and post sports concussion.

In order to determine whether physiotherapy would be beneficial during the acute post-concussion phase, it is first necessary to explore the deficits typically observed in this period. Previous research has shown that assessing athletes post-concussion injury should incorporate testing of multiple domains rather than rely on one area of measurement (Pearce et al., 2015). The primary aim of this exploratory study was to establish if specific deficits of the sensorimotor systems (balance, peripheral and central vestibular system, cervical spine proprioception and trunk muscle size and function) were present in the acute period post-sports concussion.

MATERIALS AND METHODS

A prospective exploratory cohort study employing a pre-season/baseline and post-concussion assessment model was undertaken. The design of this study allowed those who suffered concussion to act as their own control, by allowing comparison of their pre-concussion test results with those collected in the acute phase post-concussion. STROBE guidelines for reporting observational studies were utilised (von Elm et al., 2008).

Participants

Players aged 18 to 33 years from professional rugby union and rugby league teams were eligible for participation in the study (n=54). Informed consent was obtained and this study was approved by the host institution's Human Research Ethics Committee.

Procedures

All players' assessments were conducted at the respective football clubs prior to the start of their respective playing season (baseline). Club medical staff, along with an independent match-day doctor in Rugby Union, were responsible for diagnosis and referral of players with concussion injuries to the research team for follow-up testing. All post-concussion assessments were conducted within three-to-five days using portable laboratory equipment at the athlete's club.

Materials

1. Self-report questionnaires.

The Dizziness Handicap Inventory (DHI) (Jacobson and Newman, 1990) was administered pre and post-concussion to determine the impact of dizziness on daily life (Whitney et al., 2004). The DHI is a valid and reliable measure of dizziness impact (0-100) with physical (0-28), functional (0-36) and emotional (0-36) sub-categories.

2. Balance assessment.

Each participant completed the Stability Evaluation Test (SET) (VSR^{TM} Sport Portable Balance System, Natus Medical Incorporated, San Carlos, CA 94070 USA) protocol, a measure of postural stability under varying base of support conditions, with moderate reliability (ICC = 0.56-0.66) (Davisson, 2014). Use of the SET enabled portability for testing at the club sites and provided quantitative data (Figure 1a).

The protocol included six stance conditions (20s each) without foot-wear: feet together, single leg stance (standing on non-dominant leg) and tandem stance (non-dominant foot behind) on firm, then foam, surfaces. Each test condition was performed with the participants' hands on their iliac crests, eyes closed. The trial concluded early if the participant stepped off the platform (fall), with fall trials included in the SET output. The output of the VSR^{TM} Sport Portable Balance System computes sway velocity (°/sec) and records time to failure for each of the six testing conditions. The composite score is a weighted average of sway velocity of all six testing conditions. To examine for the possible confounding effects of lower limb injury on balance output, players were questioned regarding the presence of acute lower limb injuries.

3. Vestibular system function testing.

Assessment of oculo-motor and vestibulo-ocular reflex (VOR) function was performed to identify signs of central or peripheral vestibular system function deficits. Active rotation of cervical spine rotation (minimum 45 degrees bilaterally) and sagittal plane movement (30 degrees flexion and extension) were assessed prior to vestibular system and cervical proprioception testing (below) with all players demonstrating a capacity to achieve these ranges without pain or limitation. As Benign Paroxysmal Positioning Vertigo (BPPV) has been reported post-concussion and mild head trauma (Ahn et al., 2011; Fife and Giza, 2013; Hoffer et al., 2004) a screening protocol for BPPV was undertaken. Frenzel Goggles (Interacoustics, Video Frenzel Lens VF405 Unit – Monocular Vision) were worn while the Hallpike-Dix (Bhattacharyya et al., 2008) and Head Roll tests were used to screen for BPPV in the posterior/anterior canals (Furman and Cass, 1999; Lanska and Remler, 1997) and horizontal canals (Baloh et al., 1987) respectively (present/absent).

Oculo-motor dysfunction has also been reported following concussion and mild head trauma (Leddy et al., 2015) with the recommendation that specific testing for vestibular deficits would be required to detect such deficits. Screening for oculo-motor deficits and VOR dys-control was undertaken using standard visual conditions, and then with lighting removed, by wearing Frenzel Goggles (Hall and Herdman, 2006). With standard lighting, the clinical examination identifies overt deficits in smooth pursuit and saccadic eye movements (normal/abnormal), spontaneous and gaze holding nystagmus at 30 degrees from the midline (present/absent) (Hall and Herdman, 2006). The use of Frenzel Goggles enables observation of spontaneous nystagmus, gaze evoked nystagmus and head shaking nystagmus with vision removed, and if identified, is indicative of central dysfunction if suppression of nystagmus does not occur when a light is switched on within the Frenzel Goggles (Hain et al., 1987; Hall and Herdman, 2006).

The clinical Head Impulse (thrust) Test (HIT) identified overt saccadic eye movement (present/absent), indicating decreased unilateral hypofunction of the peripheral vestibular system (Halmagyi and Curthoys, 1988). For those referred for vestibular assessment, the test has an established sensitivity of 41-54% and specificity of 91-100% (Jorns-Häderli et al., 2007; Perez and Rama-Lopez, 2003) but covert saccadic eye movements are difficult to detect. The video head impulse test (vHIT) (EyeSeeCam Interacoustics AS) (Petrak et al., 2013) (Figure 1b) was used to record overt and covert saccadic movement with VOR gain (ms) and left-right Asymmetry (%) recorded (Mossman et al., 2015; Petrak et al., 2013). Vestibular ocular reflex (VOR) gain represents eye movement relative to head movement as an expression of the horizontal VOR. The vHIT software automatically calculates the gain for impulses applied by an assessor in the horizontal plane at 40ms, 60ms and 80ms and identifies any asymmetry between left and right responses (Yang et al., 2016). The range of 'normal responses' for impulses at 60ms is 0.65 to 1.17(Mossman et al., 2015) and at 80ms is 0.76 to 1.18 (Mossman et al., 2015). Recent data from Yang et al (2016) suggests that a gain near 1 and less than 8% asymmetry is consistent for healthy adults aged up to 70 years.

Cervical proprioception was chosen as it has been identified as an important test to differentially diagnose cervicogenic dizziness (L'Heureux-Lebeau et al., 2014). To measure cervical proprioception, a modified joint position error test using neck torsion (trunk movement with stationary head), rather than head rotation, was used to differentiate cervical from vestibular deficits (Chen and Treleaven, 2013). A laser was attached to the mid-sternum, with the beam projecting onto a target 90 cm from the chest (Figure 1c). Participants were blindfolded and seated with their feet and buttocks positioned on soft foam to minimize proprioceptive cues. The examiner lightly held the participant's head in the neutral position. Participants performed one practice movement to each side. For the test, participants crossed their arms, held away from the body. The participant rotated their trunk and returned to their perceived neutral position, and the laser beam position was marked on the target. The test was conducted six times alternately to each side (Swait et al., 2007). Cervical proprioception error was calculated using the mean of absolute errors (AE) for the six left and six right trials. The difference between the start and returning position of the laser beam on the target was measured in degrees using the formula, angle = $\tan^{-1}$ [error distance/90 cm] (Roren et al., 2009). The twelve measures were averaged to give an overall mean score (sensitivity = 78%, ICC = 0.68) (Roren et al., 2009).

4. Trunk muscle ultrasound imaging.

Ultrasound imaging was conducted using LOGIQ e apparatus with a 5 MHz curvilinear transducer (GE Healthcare, Wuxi, China) (Figure 1d). The ultrasound imaging protocol has been published previously (Hides and Stanton, 2016). The multifidus muscles were imaged bilaterally from the L2 to L5 vertebral levels (Hides et al., 1995), and the quadratus lumborum muscle was measured in line with the L3-4 vertebral interspace (Hides and Stanton, 2016). Muscle thickness (mm) was used to indicate the size of the transversus abdominis, internal oblique muscles and multifidus muscles at rest and on contraction. (Hides et al., 2007; Wallwork et al., 2009). Ultrasound images were stored and measured offline using OsiriX medical imaging software (Geneva, Switzerland). Physiotherapists with demonstrated reliability conducted the measurements of quadratus lumborum size (ICC = 0.99) (Hides and Stanton, 2016), multifidus muscle size (ICC mean L2-L5 = 0.94) (Hides et al., 1995), multifidus muscle thickness (ICC = 0.88-0.95, relaxed and contracted) (Wallwork et al., 2007) and abdominal muscle thickness (Transversus abdominis ICC = 0.62-0.98; internal oblique ICC = 0.69-0.99, relaxed and contracted) (Hides et al., 2007). To examine for the possible confounding effects of acute low back pain on trunk muscle size and contraction, players were questioned regarding the presence of low back pain.

Figure 1 (a-d): Measures used in the study.

a) Balance testing (Stability Evaluation Test, SET)

b) Vestibular testing using the Video Head Impulse Test (vHIT)

c) Testing cervical proprioception (trunk torsion test)

d) Ultrasound imaging of trunk muscles

Statistical analysis

The statistical analysis was conducted using SPSS version 22.0 [IBM, USA]. Means and standard deviations (SD) for demographics (age, height, weight), years playing football, and DHI were calculated.

Paired samples t-tests were used to examine differences between pre- and post-concussion measures of balance, vestibular system function, cervical proprioception, and muscle size/

contraction. Because this was an exploratory study aimed at identifying the priority for subsequent research, effect sizes (mean difference / pooled baseline standard deviation) > 0.5 and liberal p-values <0.1, were considered to help identify clinically meaningful effects.

RESULTS

Participants

Fifty-four players completed the baseline assessment. The mean age was 24.4 (SD 3.9) years, mean height was 185.4 (SD 6.2) cm and mean weight was 101.6 (SD 9.2) kg. Participants had been playing professional football for an average of 6 (SD 4) years. Whilst collection of baseline data from all of the 54 players available for testing was required to capture the baseline (pre-concussion) data, 14 post-concussion assessments were requested by the medical team and conducted during the playing season. Multiple concussions occurred in three players, and players were not included twice, providing 11 sets of pre and post-concussion data for analysis. Baseline and post-concussion testing including questionnaires, and ultrasound imaging measures were collected at all post-concussion assessments. Testing of the vestibular system and balance system was performed on eight players and testing of cervical proprioception was tested on seven players due to late arrival of portable testing equipment. Appendix 1 provides a summary of the baseline and post-concussion results of all of the other tests.

Pre- and post-concussion testing

Results of the DHI reflected that the players with concussion presented with very mild symptoms before and after their concussion, with mean values of 3.0 (6.2) pre-concussion and 2.6 (5.3) post-concussion. The differences between pre and post-concussion scores were not statistically significant and the scores from both time points suggest negligible symptoms, with scores up to

10 considered to fall into a category defined as negligible/ normal (Jacobson and Newman, 1990). There were no players at either time point who presented with BPPV.

In the balance system (n=14), (Table 1), reduced sway velocity was observed in the single leg stance (*p=0.07; effect size (ES)=0.9*) and bilateral stance (*p=0.07; ES=0.9*) for the foam conditions post-concussion. The SET composite score (*p=0.02; ES=0.6*) also demonstrated reduced sway velocity post-concussion. Individual player results are provided in Appendix 2. Because the results of the composite score were significant, and reflected reduced sway velocity, this would suggest that the direction of the results was consistent for the individual items of the SET. Inspection of the individual results for the balance system testing presented in Appendix 1 support this conclusion, in that the direction of change for 4 of the 6 conditions tested was consistently a decrease in sway velocity, with little or no change reported for the remaining 2 conditions tested. Only the individual conditions reported above (single leg and bilateral stance on foam) reached individual statistical significance. No acute lower limb injuries, which could have affected balance, were reported at the time of post-concussion testing.

Results for testing of the vestibular system and cervical proprioception (Table 1) showed that there were no significant differences pre- and post-concussion. It was observed post-concussion that individual results for VOR gain from two players moved to outside the normal clinical range (Mossman et al., 2015). In addition, for vHIT asymmetry, three players demonstrated increased asymmetry above the accepted clinical threshold post-concussion (Yang et al., 2016). The clinical implication of these results is that even though a consistent pattern or direction of results was not observed for all players, these systems may still require testing as individual players may demonstrate deficits outside the known range of clinical norms which may be of clinical relevance.

In the neuromuscular system (n=14) (Table 1), significant cross-sectional area (CSA) increases at rest were observed for the multifidus muscle on the right side at L4 (*p=0.02; ES=0.8*) and bilaterally at the L5 vertebral level (*p≤0.05; ES=0.5-0.6*) post-concussion. Individual player results are provided in Appendix 2. While only three measures of the multifidus muscle (at two vertebral levels) were shown to be significantly larger following concussion, examination of the overall pattern of results in Appendix 1 reveals that the direction of change in mean muscle size post-concussion was consistently larger across both sides for each of the four vertebral levels measured (L2-L5). Increased resting thickness of the right internal oblique muscle (*p=0.01; ES=0.5*) was also found. Individual player results are provided in Appendix 2. Inspection of the means in Appendix 1 demonstrates that the mean resting values of the internal oblique and transversus abdominis muscles increased on both sides post-concussion, but only the right internal oblique muscle reached statistical significance. Post-concussion, players also demonstrated an increased ability to contract the left multifidus muscle isometrically at L5 (*p=0.1; ES=0.6*). Individual player results are provided in Appendix 2. The pattern of results for the means in Appendix 1 demonstrates that the direction of change in mean muscle contraction of the multifidus muscle post-concussion was consistently larger on the left side for vertebral levels L2, L4 and L5, with only the difference at the L5 vertebral level reaching statistical significance. None of the players reported acute low back pain, which could have affected muscle size and contraction, at the time of post-concussion testing.

Table 1. Group means (SD) and mean difference (95% CI) pre- and post-concussion for players who suffered a concussion

Measure	Pre-Concussion Mean (SD)	Post-Concussion Mean (SD)	Mean Difference (95% CI)	Effect size	P-value
Stability Evaluation Test (Sway Velocity °/s) (n = 8)					
Bilateral Foam Score	2.1 (0.2)	1.9 (0.3)	-0.2 (0.0, 0.5)	0.9	0.07*
Single Leg Foam Score	5.2 (1.6)	3.8 (1.4)	-1.4 (-0.1, 2.8)	0.9	0.07*
Composite Score	2.4 (0.6)	2.1 (0.4)	-0.3 (0.1, 0.6)	0.6	0.02*
Video Head Impulse Test (n = 8)					
Asymmetry (%)	3.0 (2.3)	4.5 (3.7)	-1.5 (-5.7, 2.7)	0.5	0.42
Cervical Proprioception Test (°) (n = 7)					
Overall average error score	4.3(1.3)	3.6 (1.1)	0.7 (-0.3, 1.6)	0.5	0.14
Multifidus Muscle Cross Sectional Area (cm^2) (n = 11)					
L4 (R) Side	8.2 (1.6)	9.8 (2.5)	-1.6 (-2.9, -0.3)	0.8	0.02*
L5 (L) Side	9.3 (1.4)	10 (1.6)	-0.7 (-1.4, -0.1)	0.5	0.03*
L5 (R) Side	9.5 (1.8)	10.7 (2.1)	-1.2 (-2.5, -0.0)	0.6	0.05*
Muscle Thickness at Rest (mm) (n = 11)					
(R) Internal Oblique muscle	13.2 (2.9)	14.9 (3.7)	-1.7 (-2.6, -0.7)	0.5	0.01*
Multifidus muscle contraction (mm) (n = 11)					
L4 (L) Side	2.4 (2.0)	3.5 (2.3)	-1 (-2.5, 0.4)	0.5	0.15
L5 (L) Side	2.1 (1.3)	3.3 (2.7)	-1.2 (-2.7, 0.3)	0.6	0.10*

* p-values <0.1

DISCUSSION

Our exploratory study demonstrated that rugby league and rugby union players had significant changes within their neuromuscular system, specifically altered sway velocity and trunk muscle size and contraction, 3-5 days post-concussion.

With respect to balance, a large prospective longitudinal cohort study of collegiate footballers (McCrea et al., 2003) showed that balance deficits were most pronounced at the time of the concussion and day-1 post injury when compared with controls. Balance deficits resolved by day 5, but after day 5, players in the sports concussion group continued to improve and by day 90 the direction of results was reversed (indicating improved postural stability) (McCrea et al., 2003). We also observed the unexpected finding of decreased sway velocity (thought to reflect improved postural stability) on balance testing 3-5 days post-concussion. Rather than reflecting improved postural stability, these altered postural control strategies may reflect decreased willingness to use sway to create sensory stimulation and gather information about the environment using the central nervous system (Carpenter et al., 2010; Murnaghan et al., 2011; Murnaghan et al., 2013). Post-concussion players may subconsciously adopt a pattern of splinting or over-holding which is also consistent with increases in CSA of the multifidus and internal oblique muscles seen in the current investigation. Similar results have also been reported in individuals suffering from traumatic neck pain (Field et al., 2008) and low back pain (LBP) (Jacobs et al., 2009; Moseley and Hodges, 2006), where subjects demonstrated less ability to compensate for challenges to the postural system and decreased variability to adapt to different balance strategies. Future research could investigate whether athletic performance could potentially be affected by decreased variability to adapt to different balance strategies.

Concussed players demonstrated *increased* multifidus muscle CSA and *increased* thickness of the right internal oblique muscle post-concussion. These results likely represent true post-concussion sequelae within the neuromuscular system for two reasons. First, the changes exceeded the demonstrated minimal detectable change (MDC) of 0.4cm^2 for the multifidus muscle (Hides et al., 2015). Second, longitudinal studies have demonstrated that multifidus muscle CSA typically decreases across the playing season independent of injury (Hides and Stanton, 2012; Hides et al., 2012), therefore a change in the opposite direction greater than the MDC may represent a clinically meaningful result. While there was also evidence of increased contraction of the multifidus muscle at the L5 vertebral level, this did not exceed the MDC of 1.7 mm (Wallwork et al., 2007).

It is possible that increased multifidus muscle CSA and internal oblique muscle thickness could represent splinting or over-holding possibly leading to increased trunk stiffness in association with an acute injury. Similar altered trunk neuromuscular strategies leading to increased trunk stiffness have been documented in people with acute LBP. Experimentally induced LBP leads to decreased trunk motion during walking (Moe-Nilssen et al., 1999), quiet standing (Smith et al., 2005) and decreased lumbar spine movement relative to the hip during trunk flexion (Dubois et al., 2011). The decreased voluntary trunk/spine motion in these studies is consistent with increased trunk stiffness and may thus represent a central nervous system response to LBP to help minimize pain and further injury (Dubois et al., 2011; Hodges and Moseley, 2003; Smith et al., 2005; van Dieen et al., 2003a). LBP researchers have suggested that higher stiffness among individuals with LBP, even when not experiencing pain, may result from higher baseline electromyographic levels in the trunk musculature (Lee et al., 2006; Radebold et al., 2000; van Dieen et al., 2003b; Wilder et al., 1996). While these compensatory responses may represent appropriate strategies in the acute situation, they may not be optimal long-term strategies, as they may interfere with normal movement (Karayannis et al., 2013) and increase spinal loads (Miller et al., 2013).

There were some limitations associated with the current exploratory study. The number of players who sustained concussions was small, but similar to previous studies in this field (Hynes and Dickey, 2006; Slobounov et al., 2008; Pearce et al., 2015). Second, future studies could consider testing another player from the same team at the same time as the concussed player to act as a matched control. Comparison of results would allow confirmation that the demonstrated changes in sensorimotor function are associated with recent concussion rather than related to the effects of playing contact sport and the stage of the season. Third, there was missing baseline data for vestibular and cervical proprioception testing for some players. Fourth, accuracy and reliability of the medical concussion diagnosis is not clear.

CONCLUSIONS

The current preliminary investigation found that specific deficits of the sensorimotor system were present 3-5 days post-sports concussion when compared with preinjury baseline. Significant findings were not found in the vestibular and cervical spine proprioception systems. These findings highlight a potentially important role for physiotherapeutic interventions following sports concussion.

REFERENCES

Ahn S-K, Jeon S-Y, Kim J-P, Park JJ, Hur DG, Kim D-W, et al. Clinical characteristics and treatment of benign paroxysmal positional vertigo after traumatic brain injury. Journal of Trauma and Acute Care Surgery. 2011;70:442-6.

Alsalaheen BA, Mucha A, Morris LO, Whitney SL, Furman JM, Camiolo-Reddy CE, et al. Vestibular rehabilitation for dizziness and balance disorders after concussion. Journal of Neurologic Physical Therapy. 2010;34:87-93.

Alsalaheen BA, Haines J, Yorke A, Stockdale K, Broglio SP. Reliability and concurrent validity of instrumented balance error scoring system using a portable force plate system. The Physician and Sports Medicine. 2015;43(3):221-226. doi:10.1080/00913847.2015.1040717

Baloh RW, Honrubia V, Jacobson K. Benign positional vertigo Clinical and oculographic features in 240 cases. Neurology. 1987;37:371-.

Benson BW, Meeuwisse WH, Rizos J, Kang J, Burke CJ. A prospective study of concussions among National Hockey League players during regular season games: the NHL-NHLPA Concussion Program. Canadian Medical Association journal. 2011;183:905-11.

Bhattacharyya N, Baugh RF, Orvidas L, Barrs D, Bronston LJ, Cass S, et al. Clinical practice guideline: benign paroxysmal positional vertigo. Otolaryngology-Head and Neck Surgery. 2008;139:S47-S81.

Broglio SP, Cantu RC, Gioia GA, Guskiewicz KM, Kutcher J, Palm M, McLeod TCV. National Athletic Trainers' Association Position Statement: Management of Sport Concussion. Journal of Athletic Training. 2014;49(2):245-265. doi:10.4085/1062-6050-49.1.07

Caneiro JP, O'Sullivan P, Burnett A, Barach A, O'Neil D, Tveit O, et al. The influence of different sitting postures on head/neck posture and muscle activity. Manual therapy. 2010;15:54-60.

Carpenter MG, Murnaghan CD, Inglis JT. Shifting the balance: evidence of an exploratory role for postural sway. Neuroscience. 2010;171:196-204.

Catena RD, van Donkelaar P, Chou L-S. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. Journal of neuroengineering and rehabilitation. 2009;6:1.

Chen X, Treleaven J. The effect of neck torsion on joint position error in subjects with chronic neck pain. Manual therapy. 2013;18:562-7.

Cullen KE. The vestibular system: multimodal integration and encoding of self-motion for motor control. Trends in Neurosciences. 2012;35:185-96.

Davisson C. Test-retest Reliability of the NeuroCom® VSR™ Sport in Division I Collegiate Female Soccer Players. 2014.

Dubois JD, Piche M, Cantin V, Descarreaux M. Effect of experimental low back pain on neuromuscular control of the trunk in healthy volunteers and patients with chronic low back pain. Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology. 2011;21:774-81.

Ellis MJ, Leddy JJ, Willer B. Physiological, vestibulo-ocular and cervicogenic post-concussion disorders: An evidence-based classification system with directions for treatment. Brain Injury. 2015;29(2):238-248. doi:10.3109/02699052.2014.965207

Falla D, O'Leary S, Fagan A, Jull G. Recruitment of the deep cervical flexor muscles during a postural-correction exercise performed in sitting. Manual therapy. 2007;12:139-43.

Faux S, Sheedy J, Delaney R, Riopelle R. Emergency department prediction of post-concussive syndrome following mild traumatic brain injury-an international cross-validation study. Brain Injury. 2011;25(1):14-22. doi:10.3109/02699052.2010.531686

Field S, Treleaven J, Jull G. Standing balance: a comparison between idiopathic and whiplash-induced neck pain. Manual therapy. 2008;13:183-91.

Fife TD, Giza C. Posttraumatic vertigo and dizziness. Seminars in neurology: Thieme Medical Publishers; 2013. p. 238-43.

Fu S, Low Choy N, Nitz J. Controlling balance decline across the menopause using a balance-strategy training program: a randomized, controlled trial. Climacteric. 2009;12:165-76.

Furman JM, Cass SP. Benign paroxysmal positional vertigo. New England Journal of Medicine. 1999;341:1590-6.

Ganti L, Khalid H, Patel PS, Daneshvar Y, Bodhit AN, Peters KR. Who gets post-concussion syndrome? An emergency department-based prospective analysis. International Journal of Emergency Medicine. 2014;7(1):31.

Gardner A, Iverson GL, Levi CR, Schofield PW, Kay-Lambkin F, Kohler RM, et al. A systematic review of concussion in rugby league. British journal of sports medicine. 2015;49:495-8.

Gardner AJ, Iverson GL, Williams WH, Baker S, Stanwell P. A systematic review and meta-analysis of concussion in rugby union. Sports medicine (Auckland, NZ). 2014;44:1717-31.

Guskiewicz KM, Perrin DH, Gansneder BM. Effect of mild head injury on postural stability in athletes. Journal of athletic training. 1996;31:300.

Hain T, Fetter M, Zee D. Head-shaking nystagmus in patients with unilateral peripheral vestibular lesions. American journal of otolaryngology. 1987;8:36-47.

Hain TC. Neurophysiology of vestibular rehabilitation. NeuroRehabilitation. 2011;29:127-41.

Hall CD, Herdman SJ. Reliability of clinical measures used to assess patients with peripheral vestibular disorders. Journal of neurologic physical therapy. 2006;30:74-81.

Halmagyi GM, Curthoys IS. A clinical sign of canal paresis. Archives of Neurology. 1988;45:737-9.

Hides J, Stanton W. Muscle imbalance among elite Australian rules football players: a longitudinal study of changes in trunk muscle size. Journal of athletic training. 2012;47:314-9.

Hides J, Stanton W. Predicting football injuries using size and ratio of the multifidus and quadratus lumborum muscles. Scandinavian Journal of Medicine & Science in Sports. 2016.

Hides JA, Lambrecht G, Stanton WR, Damann V. Changes in multifidus and abdominal muscle size in response to microgravity: possible implications for low back pain research. European spine journal. 2015. doi: 10.1007/s00586-015-4311-5.

Hides JA, Mendis MD, Franettovich Smith MM, Miokovic T, Cooper A, Low Choy N. Association between altered motor control of trunk muscles and head and neck injuries in elite footballers - An exploratory study. Manual therapy. 2016;24:46-51.

Hides JA, Miokovic T, Belavy DL, Stanton WR, Richardson CA. Ultrasound imaging assessment of abdominal muscle function during drawing-in of the abdominal wall: an intrarater reliability study. The Journal of orthopaedic and sports physical therapy. 2007;37:480-6.

Hides JA, Richardson CA, Jull GA. Magnetic resonance imaging and ultrasonography of the lumbar multifidus muscle. Comparison of two different modalities. Spine. 1995;20:54-8.

Hides JA, Stanton WR, Mendis MD, Gildea J, Sexton MJ. Effect of motor control training on muscle size and football games missed from injury. Medicine and science in sports and exercise. 2012;44:1141-9.

Hodges PW, Moseley GL. Pain and motor control of the lumbopelvic region: effect and possible mechanisms. Journal of Electromyography and Kinesiology. 2003;13:361-70.

Hoffer ME, Gottshall KR, Moore R, Balough BJ, Wester D. Characterizing and treating dizziness after mild head trauma. Otology & Neurotology. 2004;25:135-8.

Horak FB. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age and ageing. 2006;35:ii7-ii11.

Hynes LM, Dickey JP. Is there a relationship between whiplash-associated disorders and concussion in hockey? A preliminary study. Brain Injury. 2006;20(2):179-188. doi:10.1080/02699050500443707

Jacobs JV, Henry SM, Nagle KJ. People with chronic low back pain exhibit decreased variability in the timing of their anticipatory postural adjustments. Behavioral neuroscience. 2009;123:455-8.

Jacobson GP, Newman CW. The development of the Dizziness Handicap Inventory. Archives of otolaryngology--head & neck surgery. 1990;116:424-7.

Jorns-Häderli M, Straumann D, Palla A. Accuracy of the bedside head impulse test in detecting vestibular hypofunction. Journal of Neurology, Neurosurgery & Psychiatry. 2007;78:1113-8.

Karayannis NV, Smeets RJ, van den Hoorn W, Hodges PW. Fear of Movement Is Related to Trunk Stiffness in Low Back Pain. PloS one. 2013;8:e67779.

Khan S, Chang R. Anatomy of the vestibular system: a review. NeuroRehabilitation. 2013;32:437-43.

Lanska DJ, Remler B. Benign paroxysmal positioning vertigo Classic descriptions, origins of the provocative positioning technique, and conceptual developments. Neurology. 1997;48:1167-77.

Leddy JJ, Baker JG, Merchant A, Picano J, Gaile D, Matuszak J, et al. Brain or Strain? Symptoms Alone Do Not Distinguish Physiologic Concussion From Cervical/Vestibular Injury. Clinical Journal of Sport Medicine. 2015;25:237-42.

Leddy JJ, Baker JG, Willer B. Active Rehabilitation of Concussion and Post-concussion Syndrome. Physical medicine and rehabilitation clinics of North America. 2016;27:437-54.

Leddy JJ, Sandhu H, Sodhi V, Baker JG, Willer B. Rehabilitation of Concussion and Post-concussion Syndrome. Sports health. 2012;4:147-54.

Lee PJ, Rogers EL, Granata KP. Active trunk stiffness increases with co-contraction. Journal of Electromyography and Kinesiology. 2006;16:51-7.

L'Heureux-Lebeau B, Godbout A, Berbiche D, Saliba I. Evaluation of Paraclinical Tests in the Diagnosis of Cervicogenic Dizziness. Otology & Neurotology. 2014;35(10):1858-1865.

Makdissi M, McCrory P, Ugoni A, Darby D, Brukner P. A prospective study of postconcussive outcomes after return to play in Australian football. The American journal of sports medicine. 2009;37:877-83.

McCrea M, Guskiewicz KM, Marshall SW, Barr W, Randolph C, Cantu RC, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. Jama. 2003;290:2556-63.

McDevitt J, Appiah-Kubi KO, Tierney R, Wright WG. Sensitivity and specificity of sub-acute concussion detection may be increased with the addition of balance and visual-vestibular assessments. Brain Injury. 2016;30(5-6):494-494.

McIntosh AS, McCrory P, Comerford J. The dynamics of concussive head impacts in rugby and Australian rules football. Medicine and science in sports and exercise. 2000;32:1980-4.

McLeod TCV, Hale TD. Vestibular and balance issues following sport-related concussion. Brain Injury. 2015;29(2):175-184. doi:10.3109/02699052.2014.965206

Miller EM, Bazrgari B, Nussbaum MA, Madigan ML. Effects of exercise-induced low back pain on intrinsic trunk stiffness and paraspinal muscle reflexes. Journal of biomechanics. 2013;46:801-5.

Moe-Nilssen R, Ljunggren AE, Torebjork E. Dynamic adjustments of walking behavior dependent on noxious input in experimental low back pain. Pain. 1999;83:477-85.

Moseley GL, Hodges PW. Reduced variability of postural strategy prevents normalization of motor changes induced by back pain: A risk factor for chronic trouble? Behavioral neuroscience. 2006;120:474-6.

Mossman B, Mossman S, Purdie G, Schneider E. Age dependent normal horizontal VOR gain of head impulse test as measured with video-oculography. Journal of Otolaryngology-Head & Neck Surgery. 2015;44:1.

Murnaghan CD, Horslen BC, Inglis JT, Carpenter MG. Exploratory behavior during stance persists with visual feedback. Neuroscience. 2011;195:54-9.

Murnaghan CD, Squair JW, Chua R, Inglis JT, Carpenter MG. Are increases in COP variability observed when participants are provided explicit verbal cues prior to COM stabilization? Gait & posture. 2013;38:734-8.

Nitz JC, Choy NLL. The efficacy of a balance strategy training circuit for community based elders who have had a fall. Age and ageing. 2004;33.

Parker TM, Osternig LR, Van Donkelaar P, Chou L. Gait stability following concussion. Medicine and science in sports and exercise. 2006;38:1032.

Pearce AJ, Hoy K, Rogers MA, Corp DT, Davies CB, Maller JJ, Fitzgerald PB. Acute motor, neurocognitive and neurophysiological change following concussion injury in Australian amateur football. A prospective multimodal investigation. Journal of Science and Medicine in Sport. 2015;18(5):500-6. doi: 10.1016/j.jsams.2014.07.010.

Perez N, Rama-Lopez J. Head-impulse and caloric tests in patients with dizziness. Otology & neurotology. 2003;24:913-7.

Peterson CL, Ferrara MS, Mrazik M, Piland S, Elliott R. Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. Clinical Journal of Sport Medicine. 2003;13:230-7.

Petrak MR, Bahner C, Beck DL. Video Head Impulse Testing (vHIT): VOR Analysis of High Frequency Vestibular Activity 2013.

Pinsault N, Anxionnaz M, Vuillerme N. Cervical joint position sense in rugby players versus non-rugby players. Physical therapy in sport. 2010;11:66-70.

Pinsault N, Vuillerme N. Degradation of cervical joint position sense following muscular fatigue in humans. Spine. 2010;35:294-7.

Radebold A, Cholewicki J, Panjabi MM, Patel TC. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. Spine. 2000;25:947-54.

Revel M, Minguet M, Gregoy P, Vaillant J, Manuel JL. Changes in cervicocephalic kinesthesia after a proprioceptive rehabilitation program in patients with neck pain: a randomized controlled study. Archives of physical medicine and rehabilitation. 1994;75:895-9.

Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. Journal of athletic training. 2000;35:19.

Roren A, Mayoux-Benhamou MA, Fayad F, Poiraudeau S, Lantz D, Revel M. Comparison of visual and ultrasound based techniques to measure head repositioning in healthy and neck-pain subjects. Manual therapy. 2009;14:270-7.

Schneider KJ, Meeuwisse WH, Nettel-Aguirre A, Barlow K, Boyd L, Kang J, et al. Cervicovestibular rehabilitation in sport-related concussion: a randomised controlled trial. British journal of sports medicine. 2014;48:1294-8.

Slobounov S, Cao C, Sebastianelli W, Slobounov E, Newell K. Residual deficits from concussion as revealed by virtual time-to-contact measures of postural stability. Clinical Neurophysiology. 2008;119(2):281-9. DOI: 10.1016/j.clinph.2007.10.006

Slobounov S, Tutwiler R, Sebastianelli W, Slobounov E. Alteration of postural responses to visual field motion in mild traumatic brain injury. Neurosurgery. 2006;59:134-9.

Smith M, Coppieters MW, Hodges PW. Effect of experimentally induced low back pain on postural sway with breathing. Experimental brain research. 2005;166:109-17.

Swait G, Rushton AB, Miall RC, Newell D. Evaluation of cervical proprioceptive function: optimizing protocols and comparison between tests in normal subjects. Spine. 2007;32:E692-701.

van Dieen JH, Cholewicki J, Radebold A. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. Spine. 2003a;28:834-41.

van Dieen JH, Selen LP, Cholewicki J. Trunk muscle activation in low-back pain patients, an analysis of the literature. Journal of electromyography and kinesiology. 2003b;13:333-51.

von Elm E, Altman DG, Egger M, Pocock SJ, Gotzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Journal of clinical epidemiology. 2008;61:344-9.

Wallwork TL, Hides JA, Stanton WR. Intrarater and interrater reliability of assessment of lumbar multifidus muscle thickness using rehabilitative ultrasound imaging. Journal of orthopaedic & sports physical therapy. 2007;37:608-12.

Wallwork TL, Stanton WR, Freke M, Hides JA. The effect of chronic low back pain on size and contraction of the lumbar multifidus muscle. Manual therapy. 2009;14:496-500.

Whitney SL, Wrisley DM, Brown KE, Furman JM. Is perception of handicap related to functional performance in persons with vestibular dysfunction? Otology & Neurotology. 2004;25:139-43.

Wilder DG, Aleksiev AR, Magnusson ML, Pope MH, Spratt KF, Goel VK. Muscular response to sudden load. A tool to evaluate fatigue and rehabilitation. Spine. 1996;21:2628-39.

Yang CJ, Lee JY, Kang BC, Lee HS, Yoo MH, Park HJ. Quantitative analysis of gains and catch-up saccades of video-head impulse testing by age in normal subjects. Clinical otolaryngology. 2016;41(5):532-8. doi: 10.1111/coa.12558.

Appendix 1. Group means (SD) and mean difference (95% CI) pre- and post-concussion for all measures (DHI, vestibular system, balance, cervical proprioception and muscle system) for players who suffered a season concussion

Measure	Pre-Concussion Mean (SD)	Concussion Mean (SD)	Mean Difference (95% CI)	Effect Size	P-Value
DHI (n=11)					
Score Total	3.0 (6.2)	2.6 (5.3)	0.4 (-3.6, 4.4)	0.1	0.82
Stability Evaluation Test (Sway Velocity °/s) (n=8)					
Bilateral Firm Score	0.6 (0.1)	0.7 (0.1)	-0.1 (-0.2, 0.1)	0.4	0.45
Single Firm Score	1.8 (0.4)	1.6 (0.2)	0.1 (-0.1, 0.4)	0.4	0.26
Tandem Firm Score	1.9 (1.3)	1.4 (0.6)	0.5 (-0.2, 1.3)	0.0	0.15
Bilateral Foam Score	2.1 (0.2)	1.9 (0.3)	0.2 (-0.0, 0.5)	0.9	0.07*
Single Foam Score	5.2 (1.7)	3.8 (1.4)	1.4 (-0.1, 2.8)	0.9	0.07*
Tandem Foam Score	3.1 (1.1)	3.1 (1.8)	-0.1 (-1.2, 1.0)	0.1	0.88
Composite Score	2.4 (0.6)	2.1 (0.4)	0.3 (0.1, 0.6)	0.6	0.02*
vHIT (n=8)					
(L) Gain	1.0 (0.1)	1.1 (0.2)	-0.1 (-0.3, 0.1)	0.6	0.30
(R) Gain	1.0 (0.1)	1.0 (0.1)	-0.0 (-0.2, 0.1)	0.4	0.50
(L) 40ms	1.0 (0.1)	1.1 (0.1)	-0.1 (-0.2, 0.1)	0.6	0.30
(R) 40ms	1.1 (0.2)	1.0 (0.1)	0.1 (-0.1, 0.3)	0.7	0.33
(L) 60ms	0.9 (0.1)	1.0 (0.3)	-0.0 (-0.3, 0.2)	0.1	0.83
(R) 60ms	0.9 (0.1)	0.9 (0.1)	0.0 (-0.1, 0.1)	0.0	1.00
(L) 80ms	0.9 (0.1)	1.0 (0.1)	-0.1 (-0.2, 0.0)	0.9	0.13
(R) 80ms	0.9 (0.1)	1.0 (0.2)	-0.0 (-0.2, 0.2)	0.3	0.66

Asymmetry	3.0 (2.3)	4.5 (3.7)	-1.5 (-5.7, 2.7)	0.5	0.42
Cervical Proprioception Test (°) (n=7)					
(L) average error score	4.6 (2.6)	3.6 (1.5)	1.0 (-0.9, 2.9)	0.5	0.24
(R) average error score	4.0 (1.7)	3.7 (1.2)	0.3 (-1.5, 2.2)	0.2	0.67
Overall average error score	4.3(1.3)	3.6(1.1)	0.7 (-0.3, 1.6)	0.5	0.14
Muscle Cross Sectional Area (cm^2) (n=11)					
L2 (L) Multifidus muscle	3.4 (0.8)	3.5 (1.2)	-0.2 (-1.0, 0.7)	0.2	0.66
L2 (R) Multifidus muscle	3.4 (0.9)	3.6 (1.0)	-0.2 (-1.0, 0.6)	0.2	0.59
L3 (L) Multifidus muscle	5.8 (1.9)	6.4 (2.8)	- 0.6 (-1.5, 0.4)	0.2	0.21
L3 (R) Multifidus muscle	5.9 (1.8)	6.5 (2.5)	-0.6 (-1.6, 0.4)	0.3	0.19
L4 (L) Multifidus muscle	8.7 (1.6)	8.9 (2.0)	-0.1 (-1.2, 1.0)	0.1	0.79
L4 (R) Multifidus muscle	8.2 (1.6)	9.8 (2.5)	-1.6 (-2.9, -0.3)	0.8	0.02*
L5 (L) Multifidus muscle	9.3 (1.4)	10 (1.6)	-0.7 (-1.4, -0.1)	0.5	0.03*
L5 (R) Multifidus muscle	9.5 (1.8)	10.7 (2.1)	-1.2 (-2.5, -0.0)	0.6	0.05*
(L) Quadratus Lumborum	11.1 (1.7)	11.3 (1.7)	-0.2 (-1.9, 1.5)	0.1	0.81
(R) Quadratus Lumborum	10.5 (1.5)	10.3 (1.1)	0.2 (-0.9, 1.3)	0.1	0.69
Muscle Thickness at Rest (mm) (n=11)					
(L) Transversus Abdominis	4.4 (1.0)	4.7 (1.2)	-0.4 (-1.0, 0.3)	0.3	0.23
(R) Transversus Abdominis	4.5 (0.9)	4.8 (1.0)	-0.4 (-1.1, 0.4)	0.4	0.29
(L) Internal Oblique muscle	13.2 (2.8)	13.7 (3.1)	-0.5 (-1.6, 0.6)	0.2	0.36
(R) Internal Oblique muscle	13.2 (2.9)	14.9 (3.7)	-1.7 (-2.6, -0.7)	0.5	0.01*
L2 (L) Multifidus muscle	26.4 (3.9)	26.1 (4.1)	0.3 (-2.5, 3.1)	0.1	0.81
L2 (R) Multifidus muscle	27.0 (5.0)	25.9 (3.3)	1.1 (-1.8, 4.0)	0.3	0.42
L3 (L) Multifidus muscle	30.1 (5.2)	28.9 (4.5)	1.2 (-2.6, 5.0)	0.3	0.49
L3 (R) Multifidus muscle	31.5 (3.9)	29.4 (4.5)	2.1 (-0.3, 4.5)	0.5	0.07*

L4 (L) Multifidus muscle	34.3 (4.2)	35.3 (3.5)	-1.0 (-3.5, 1.6)	0.3	0.43
L4 (R) Multifidus muscle	34.0 (4.0)	35.6 (4.0)	-1.6 (-3.0, -0.2)	0.4	0.03*
L5 (L) Multifidus muscle	35.6 (2.3)	34.9 (2.9)	0.8 (-0.6, 2.1)	0.3	0.24
L5 (R) Multifidus muscle	35.0 (3.4)	34.9 (3.7)	0.2 (-1.1, 1.4)	0.0	0.79
Size of Muscle Contraction (mm) (n=11)					
(L) Transversus Abdominis	2.4 (0.9)	2.6 (1.4)	-0.3 (-0.9, 0.4)	0.2	0.37
(R) Transversus Abdominis	2.6 (1.3)	3.0 (0.9)	-0.4 (-1.6, 0.9)	0.3	0.53
(L) Internal Oblique muscle	3.3 (1.8)	2.3 (2.2)	1.0 (-0.6, 2.6)	0.5	0.20
(R) Internal Oblique muscle	3.4 (2.2)	2.5 (2.1)	1.0 (-1.0, 3.0)	0.5	0.30
L2 (L) Multifidus muscle	2.4 (1.5)	3.5 (3.2)	-1.0 (-2.9, 0.7)	0.5	0.19
L2 (R) Multifidus muscle	3.2 (2.6)	2.0 (1.8)	1.2 (-0.5, 2.9)	0.5	0.16
L3 (L) Multifidus muscle	2.9 (1.7)	2.8 (2.7)	0.1 (-1.4, 1.6)	0.0	0.88
L3 (R) Multifidus muscle	2.9 (3.2)	2.2 (1.7)	0.7 (-1.2, 2.7)	0.3	0.43
L4 (L) Multifidus muscle	2.4 (2.0)	3.5 (2.3)	-1 (-2.5, 0.4)	0.5	0.15
L4 (R) Multifidus muscle	3.2 (2.2)	2.6 (1.7)	0.7 (-0.8, 2.2)	0.3	0.36
L5 (L) Multifidus muscle	2.1 (1.3)	3.3 (2.7)	-1.2 (-2.7, 0.3)	0.6	0.10*
L5 (R) Multifidus muscle	3.0 (2.0)	2.8 (1.6)	0.1 (-1.1, 1.4)	0.1	0.80

* $p < 0.1$

DHI= Dizziness Handicap Inventory

vHIT= Video Head Impulse Test

Appendix 2.

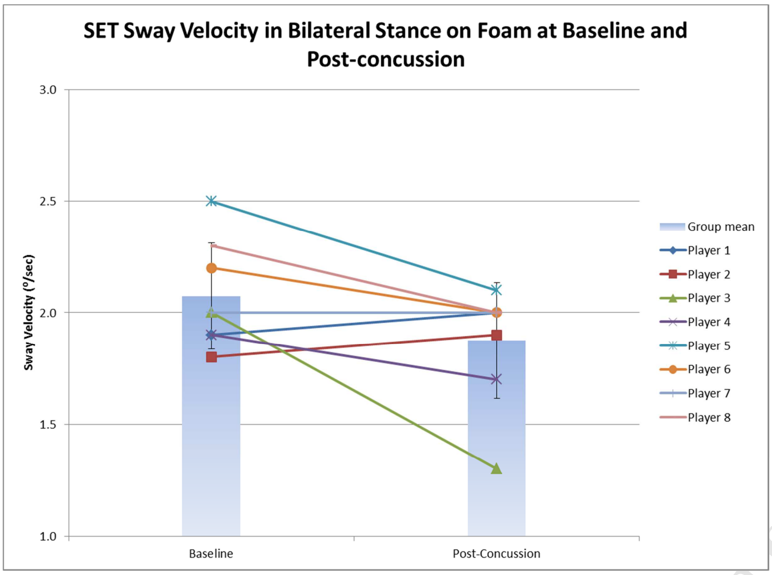

Figure 1. Results for Stability Evaluation Test (SET) for the Bilateral Foam condition pre and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

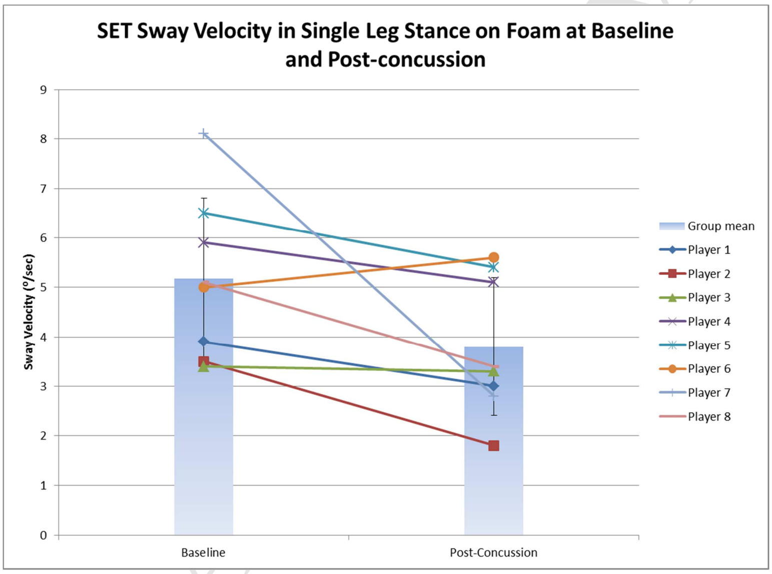

Figure 2. Results for the Stability Evaluation Test (SET) for the Single Leg Foam condition pre and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

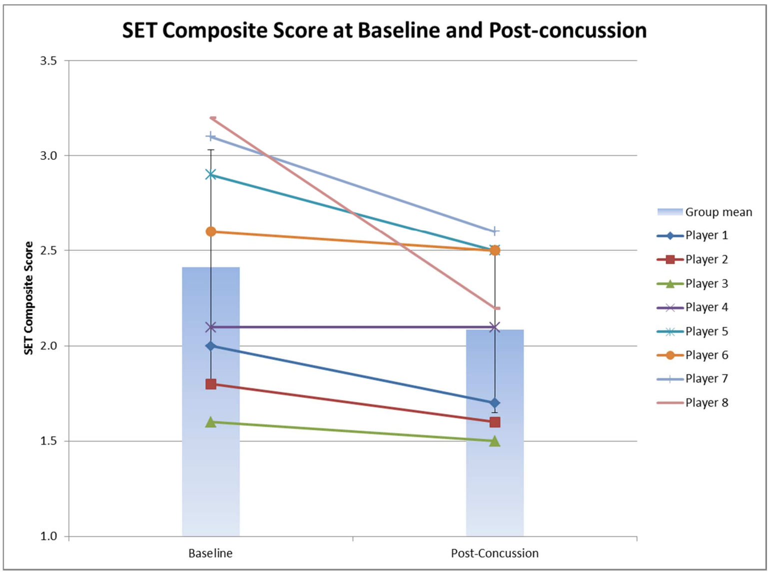

Figure 3. Results for the Stability Evaluation Test (SET) for the composite score (mean of 6 conditions tested) pre and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

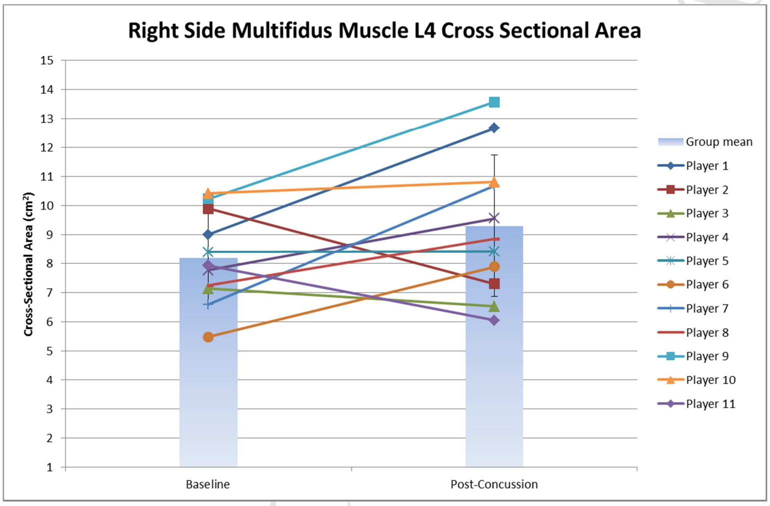

Figure 4. Results for the cross-sectional area of the multifidus muscle at the L4 vertebral level on the right side pre- and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

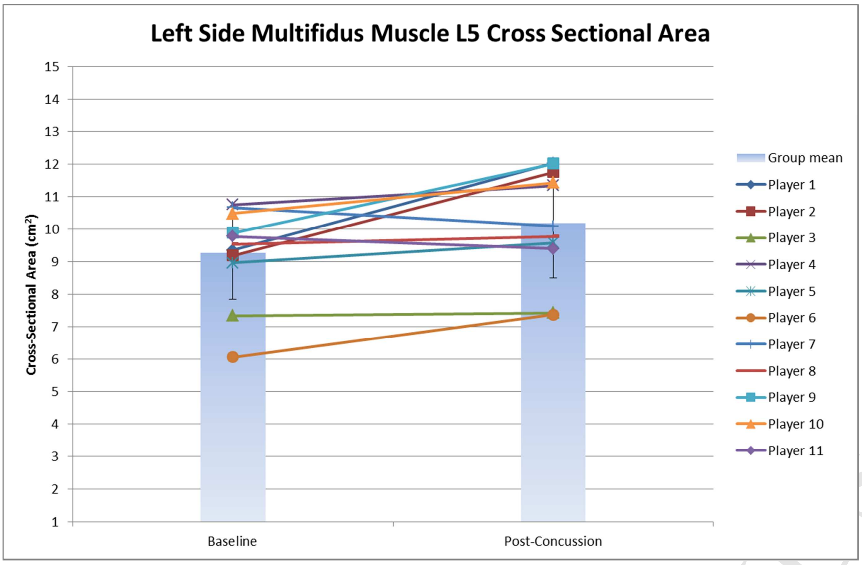

Figure 5. Results for the cross-sectional area of the multifidus muscle at the L5 vertebral level on the left side pre- and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

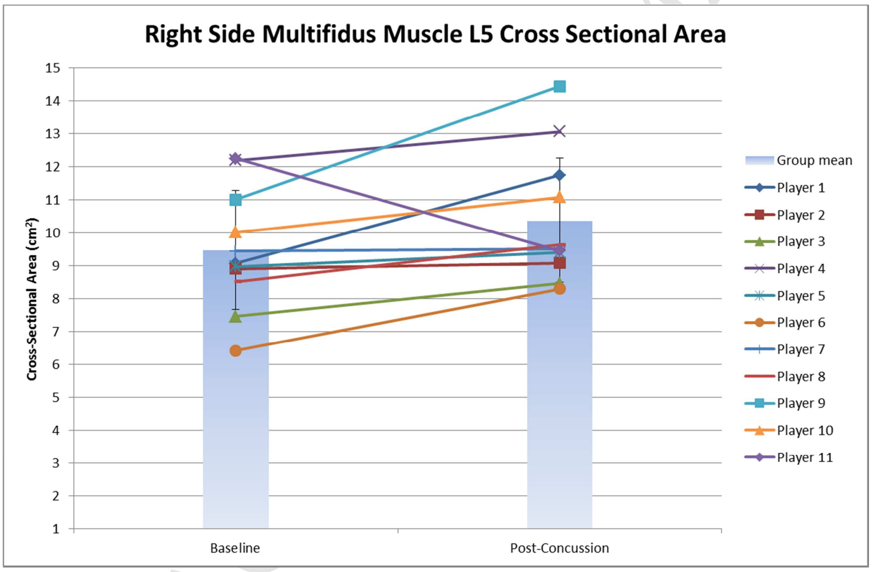

Figure 6. Results for the cross-sectional area of the multifidus muscle at the L5 vertebral level on the right side pre- and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

Figure 7. Results for the thickness of the internal oblique muscle on the right side pre- and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

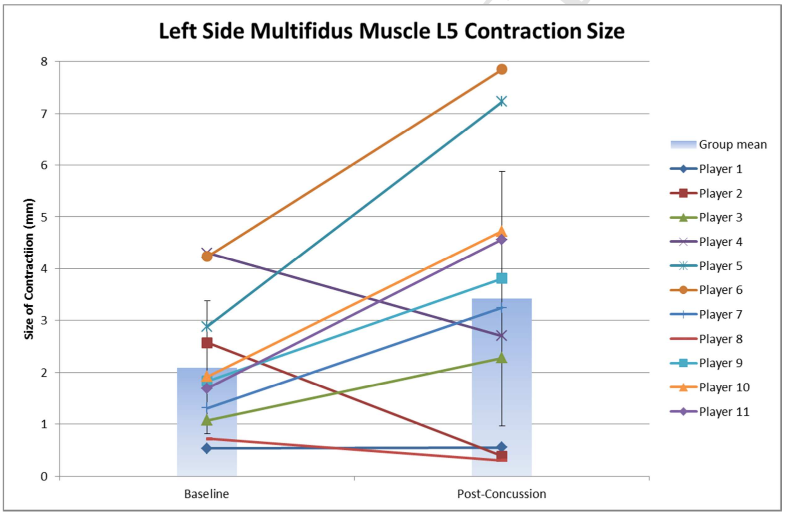

Figure 9. Results for the contraction of the multifidus muscle at the L5 vertebral level on the left side pre- and post-concussion. Bars and error bars denote group means and SD. Sloping solid lines denote individual cases.

HIGHLIGHTS

- Deficits in sensorimotor systems were detected following sports concussion.
- These systems are modifiable and amenable to management by physiotherapists.
- This is the first step towards planning trials of physiotherapy post-concussion.