Retrospective Review: Effectiveness of Cervical Proprioception Retraining for Dizziness After Mild Traumatic Brain Injury in a Military Population With Abnormal Cervical Proprioception

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Abstract

Objective: This study aimed to assess the outcomes of 2 treatments for patients with dizziness after mild traumatic brain injury (mTBI) who demonstrate abnormal cervical spine proprioception (CSP).

Methods: A retrospective records review was conducted on the medical charts of patients treated for dizziness after mTBI who received either standard care (vestibular rehabilitation therapy [VRT]) or cervical spine proprioceptive retraining (CSPR) from 2009 to 2013. All patients included in the analysis were active-duty military with recurring dizziness after mTBI who had at least 1 abnormal CSP test. Patients were excluded for dizziness with a clear peripheral vestibular or central symptom origin, incomplete data, or no CSP assessment, or if both treatments were administered. Forty-eight total patients were included in the final dataset (22 VRT; 26 CSPR). Traditional VRT was compared with CSPR when abnormal CSP tests were present, regardless of the presence or absence of neck pain. A clinician review of records was used to determine improvement of dizziness based on patient reports of symptoms at discharge evaluation (ie, no symptoms for at least 2 weeks).

Results: Patients who received CSPR were 30 times more likely to report improvement in dizziness symptoms compared with those who received VRT (adjusted odds ratio: 30.12; 95% confidence interval 4.44-204.26, $P < .001$) when abnormal CSP tests were present. Patients with dizziness over 1 year were significantly less likely to improve.

Conclusion: These results suggest that patients with dizziness after mTBI and who had abnormal CSP assessments responded better to CSPR compared with those who received VRT. (J Manipulative Physiol Ther 2019;42:399-406)

Key Indexing Terms: *Dizziness; Brain Concussion; Neck Pain; Cervicalgia; Vertigo; Postural Balance; Kinesthesis*

Introduction

Mild traumatic brain injury (mTBI) makes up 86% of brain injuries that US military personnel have sustained between 2000 and 2018.[1] Although most symptoms after mTBI resolve within 2 weeks, several can persist, including dizziness.[2]

Dizziness that occurs after mTBI is not heterogeneous, presenting with varied characteristics and several potential sources and mechanisms, including the inner ear, the brain, the cervical spine, and/or the integration of afferent input and tuning within the sensorimotor control system.[3,4]

Traditionally, vestibular rehabilitation therapy (VRT) aimed at central or peripheral vestibular origins has been used to treat persistent dizziness after mTBI,[5,6] but recent attention has examined the possible role of the cervical spine in postconcussive dizziness.[7-9] Dizziness after mTBI has been shown to improve when manual therapy and specific sensorimotor control exercises for the cervical spine were added to standard care VRT.[7-9] Further, a growing body of

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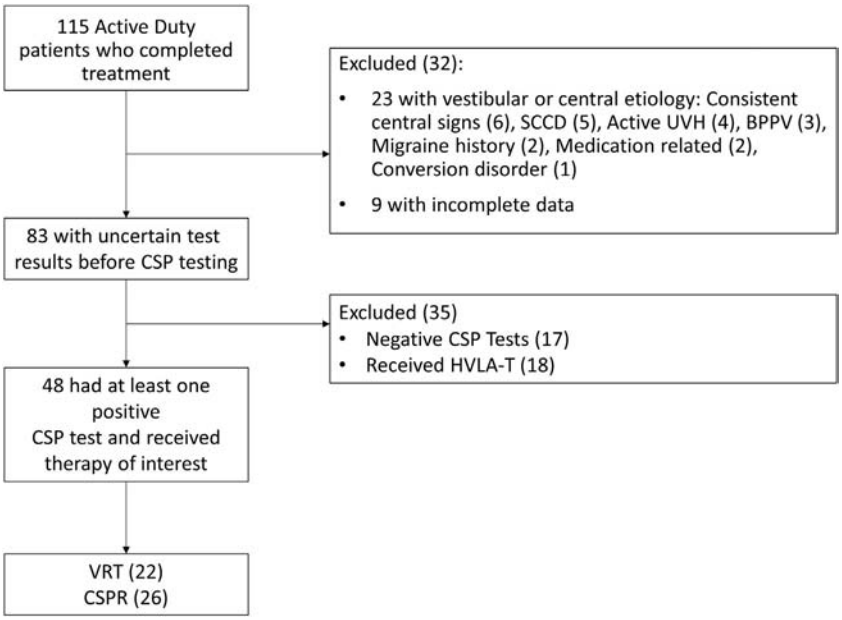

Fig 1. *Selection of charts included in the review.* BPPV, *benign paroxysmal positional vertigo;* CSP, *cervical spine proprioception;* CSPR, *cervical spine proprioceptive retraining;* HVLA-T, *high-velocity, low-amplitude thrust;* SCCD, *superior semicircular canal dehiscence;* UVH, *unilateral vestibular hypofunction.*

research indicates that symptoms such as dizziness and sensorimotor and balance dysfunctions regularly occur in those with both traumatic and nontraumatic neck pain.[10-14] This is thought to be due to abnormal cervical proprioception or afferent input to the sensorimotor control system as evidenced by improvement of signs and symptoms after specific cervical spine proprioception (CSP) training in those with neck pain.[15,16]

A recent Delphi study demonstrated a lack of agreement on the tests used for the assessment of CSP.[3] Cervical joint position error (JPE) is a traditional measure of cervical proprioception.[17] Although tests such as the smooth pursuit neck torsion test (SPNT) measures change in eye movement control when the head is held still and the trunk turned compared with a neutral head position and thus looks at the specific effect of altering cervical afferent input on eye movement.[18-20] It is possible, then, that some patients after mTBI with abnormal JPE or SPNT, which may reflect altered cervical proprioceptive input to and/or integration within the sensorimotor control system, may benefit from management directed toward improving CSP.[15,21]

Further, it was noted clinically that when cervical spine proprioceptive retraining (CSPR) was initiated in a specific group of our patients who demonstrated at least 1 positive JPE or SPNT test and no obvious peripheral or central vestibular signs, outcomes regarding dizziness seemed to improve. Thus, this retrospective chart review endeavored to assess whether CSPR resulted in greater odds of recovery of dizziness than treatment with traditional vestibular therapy in this specific group.

Methods

Study Sample

The Brooke Army Medical Center institutional review board approved this study. A comprehensive retrospective chart review was performed on all charts of patients seen from 2009 to 2013 who were treated for dizziness after mTBI in the Brooke Army Medical Center Brain Injury Rehabilitation Service physical therapy clinic. The review was performed on all active-duty military patients seen between 2009 and 2013 for dizziness after mTBI who completed a full course of treatment.

All charts of patients with mTBI who reported dizziness did not have a known vestibular or central pathology (eg, benign paroxysmal positional vertigo, superior semicircular canal dehiscence, unilateral vestibular hypofunction; see Fig 1) and demonstrated abnormal SPNT or JPE were reviewed (Table 1).[22-26] Mild TBI was defined consistent with Department of Defense parameters as a loss or alteration of consciousness for no longer than 30 minutes, post-traumatic amnesia of no longer than 24 hours, and normal imaging of the brain, if taken.[1] Other inclusion criteria included patients diagnosed with an mTBI who had received VRT only or CSPR only with no other confounding treatments, although both groups received physical therapy

Table 1. *Descriptions of Special Tests*

Test name	Descriptor of techniques as used during the period of this study
Cervical Proprioception Tests	
JPE, a test of CSP	An light-emitting diode device attached to the head of a standing patient and a calibrated target were used to identify accuracy of head position sense in neutral with eyes closed after actively moving the head from a position of slight discomfort or stretch without pain following right and left rotation and flexion/extension. Stabilization of the patient was attained through placement of the hand on a cabinet to their right. Inaccuracy of more then 4.5° from the bull's-eye as identified by a yellow stripe on the target when the patient's ears are 90 cm from the wall in any direction was considered an abnormal finding on this test. If the patient had normal tests in all 4 directions on the first trial, they were asked to perform the test again for a second trial in all directions.[16,22]
SPNT, a test believed to measure effects of the cervical spine on ocular control	Quality of smooth pursuit by visual inspection and/or patient sensation was compared in neutral and with the patient's head torsioned statically to the left and to the right. Variability of sense or observed quality of motion received an abnormal test finding.[20,23]
Tests Used for Exclusion Criteria	
Smooth pursuit	Therapist observes the quality of smooth pursuit in all directions. Consistent saccadic intrusions were deemed to be central in nature; inconsistent were considered questionable.[24,25]
Gaze-evoked nystagmus	Therapist observes stability of eye at a point short of end gaze abnormal test indicated by nystagmus. Direction changing gaze-evoked nystagmus was indicative of a central sign; however, end gaze evoked is not considered abnormal. Gaze evoked in one direction is indicative of unilateral vestibular hypofunction.[25,26]
Dix-Hallpike testing	Used in the event of the description of vertigo that occurs when moving from sitting to or from supine. Video goggles are applied to the patient and head is turned; the patient's head is stabilized with the therapist's hands as the patient is in long sitting. The patient is then taken back into supine rapidly so that the head is in a position of extension and rotation over the downward-placed headrest of the mat table. A positive test demonstrates an up or down beating torsional nystagmus of seconds to minutes duration. Seconds duration denotes canalithiasis, minutes duration cupulolithiasis. The direction of torsion denotes the affected ear and up or down beat denotes posterior or anterior canal, respectively.[25]
Roll test	Used in the event of the description of visual vertigo that occurs when one rolls over in bed. The patient is supine on the bed with video goggles on and head elevated on headrest. The patient rotates the head rapidly to one direction and holds. Geotropic or ageotropic nystagmus denotes horizontal canal issue and time of nystagmus denotes cupulolithiasis vs canalithiasis as in Dix-Hallpike above.[25]
VOR cancellation	The patient sits in a rotating office chair and clasps both hands together with their thumb in front of them. The chair is rotated quickly back and forth while the patient focuses on the thumbs. An abnormal test result is the inability to keep the eyes on the target. It indicates an abnormality in the central nervous system or an imbalance in the peripheral vestibular system. A sharp change in direction of chair motion was used in lieu of the head thrust test to identify UVH as it eliminates any input the neck might have on the test and to not exacerbate neck pain.[25]

CSP, cervical spine proprioception; *JPE*, joint position error; *SPNT*, smooth pursuit neck torsion test; *UVH*, unilateral vestibular hypofunction; *VOR*, vestibulo-ocular reflex.

for musculoskeletal pain as indicated, per standard treatment in the clinic.

Exclusion criteria included any patients who had clear peripheral vestibular or consistent central signs on clinical vestibulo-ocular testing with or without visual suppression. Charts of patients who demonstrated saccadic intrusion on smooth pursuit and hyper- or hypometric saccade that were not consistent were not excluded. This was done under the logical assumption that aberrant cervical proprioceptive input could potentially cause intermittent saccadic eye movements. Table 1 describes the tests used to make these determinations during a targeted vestibular evaluation by a physical therapist.

The beginning date was chosen as the period when comprehensive physical therapy vestibular testing started (March 2009-2011), when a treatment plan change was initiated, and ending in 2013 when a second treatment plan change introduced an exclusionary criterion of high-velocity

low-amplitude thrust manipulation. The full breakdown of chart selection is shown in Figure 1. There was no statistical basis used to determine sample size. Thus all patients who met the criteria during this period were examined.

Interventions

Standard Care—VRT. The Brooke Army Medical Center Brain Injury Rehabilitation Service VRT standard treatment for dizziness after mTBI consisted of vestibular ocular reflex retraining and balance exercises as deemed appropriate by the clinician. A home exercise program consisted of common vestibular ocular reflex retraining exercise progressions (ie, gaze stabilization with horizontal and vertical head motion advancing in difficulty with tolerance) to be completed 3 to 5 times per day and 1-time-daily substitutive balance exercises using combinations of 5 variables to customize the challenge for each individual (hard to soft surface, wider to smaller base of support, arm position changes from abducted to at side to crossed, and eyes open or closed).

Cervical Spine Proprioceptive Retraining. This treatment is structured as a game designed to improve cervical proprioception using a standard assessment measure.[16,17] Patients practiced head relocation to neutral with feedback from the light-emitting diode beam attached to the head and projected onto a target.[16,17] The patients performed CSPR at least twice per day as a home exercise program, once each in the morning and evening. Patients were tested the following week to verify proper technique and were instructed to stop the CSPR exercise when they were free of dizziness for 2 weeks and thereafter use CSPR as needed.

All patients in either the VRT or CSPR group also received soft tissue and joint mobilization tailored to the needs of the patient, per standard treatment in the clinic.

Outcome Measure

Dizziness improvement was determined from patient self-report of symptoms on discharge re-evaluation or through weekly questioning. Patients who reported resolution of dizziness symptoms for at least 2 weeks before discharge were scored as "improved," with any dizziness in the last 2 weeks being scored "no improvement." The outcome variable was dichotomous: no improvement = 0, improvement = 1.

Characterization of the Sample

To better understand the sample, we examined age, sex (male or female), branch of service (Army, Air Force, and Navy), military rank (enlisted or officer), injury type (blunt, blast, motor vehicle accident, and multiple), time since injury (TSI), and number of treatments by intervention. Data regarding secondary gain, psychiatric concerns, anxiety, and the presence or severity of neck pain were not retrospectively available.

Statistical Analysis

Descriptive statistics of the sample were first generated. Although we describe the intervention groups by sex, branch of service, military rank, and injury type, we did not include these in the logistic regression owing to a limited sample size. We opted instead to prioritize clinical characteristics deemed by the clinical authors to be most relevant. These factors included age, TSI (more or less than 1 year), and number of treatments received. Age and TSI violated the assumption of linearity and log odds and were thus categorized. Age was divided into 2 equally sized categories (younger than 34, 35 and older). The TSI was categorized into either less than or more than a year to evenly divide the sample to assess for any difference in outcomes after care. Number of treatments received was categorized into 9 or fewer and 10 or more (Table 2). We then ran a standard logistic regression using Statistical Packages for Social Sciences software version 14 (SPSS Inc, Chicago, Illinois), including the following factors: treatment (CSPR or VRT), age, TSI, and number of treatments received.

To assess multicollinearity among the factors in the regression, we examined variance inflation factors among all the variables, finding that none met the criteria for possible multicollinearity (variance inflation factors ≥ 3; all values <2.22). The results of the logistic regression analysis are reported using adjusted odds ratios with their associated 95% CIs. The level of statistical significance was set to $P < .05$.

Results

The resultant sample consisted of 48 participants with a mean age of 33.48 years (standard deviation 8.88), with 6 women and 42 men. Overall, the sample was predominantly composed of enlisted personnel (83.3%) in the Army (87.5%). Descriptive statistics of the sample for each treatment group are shown in Table 2.

The logistic regression analysis indicated treatment as a significant predictor of dizziness improvement, indicating that those who received the CSPR treatment were approximately 30 times more likely to report improved dizziness relative to those who received usual care. Further, those for whom it had been more than a year since injury were less likely to report dizziness improvement relative to those for whom it had been less than a year. The results of the regression analysis are shown in Table 3.

Discussion

This study examined subjective improvement of dizziness in patients with mTBI who had signs of altered cervical proprioception, with no accounting for absence or presence of neck pain. This subgroup of patients was 30 times more likely to report relief of dizziness if they had treatment directed toward improving CSP rather than the clinic's standard care,

Table 2. *Characteristics of the Sample*

n (%)	VRT	CSPR	Total
Outcome			
Dizziness not improved	18 (81.8)	4 (15.4)	22 (45.8)
Dizziness improved	4 (18.2)	22 (84.6)	26 (54.2)
Age			
Younger than 34	10 (45.5)	14 (53.8)	24 (50%)
35 and older	12 (54.5)	12 (46.2)	24 (50%)
Time since injury			
Less than a year	10 (45.5)	19 (73.1)	29 (60.4)
More than a year	12 (54.5)	7 (26.9)	19 (39.6)
Number of treatments			
9 or fewer	10 (45.5)	15 (57.7)	25 (52.1)
10 or more	12 (54.5)	11 (42.3)	23 (47.9)
Sex			
Male	20 (90.9)	22 (84.6)	42 (87.5)
Female	2 (9.1)	4 (15.4)	6 (12.5)
Branch of service			
Army	19 (86.4)	23 (88.5)	42 (87.5)
Air Force	2 (9.1)	3 (11.5)	5 (10.4)
Navy	1 (4.5)	0	1 (2.1)
Rank			
Enlisted	17 (77.3)	23 (88.5)	40 (83.3)
Officer	5 (22.7)	3 (11.5)	8 (16.7)
Injury type			
Blunt	6 (27.3)	9 (34.6)	15 (31.3)
Blast	10 (45.5)	12 (46.2)	22 (45.8)
Motor vehicle accident	2 (9.1)	3 (11.5)	5 (10.4)
Multiple	4 (18.2)	2 (7.7)	6 (12.5)

CSPR, cervical spine proprioceptive retraining; *VRT*, vestibular rehabilitation therapy.

which was directed toward the vestibular and central nervous system. Further, 85% of the individuals in the CSPR group and only 18% in the usual care group had dizziness improvement (Table 2). These findings suggest that treatment directed toward cervical proprioception may be important for individuals with dizziness after mTBI where signs of altered CSP are demonstrated and no clear peripheral vestibular or consistent central signs are present. The results also suggest that treatment may be more effective if delivered within a year after injury and supports early, appropriate management in this subgroup. We hypothesize that a large proportion of the patients with mTBI experiencing dizziness may have had underappreciated cervicogenic dysfunction or sensorimotor integration deficit,[9,11,21,27] which may respond well to treatments targeting cervical spine proprioception, especially if identified early. It is also possible that this type of training assists with sensorimotor compensation regarding other systems within the sensorimotor control system.[9,11,21,27] This may be regardless of the presence of neck pain or subtle vestibular dysfunction. Future studies should consider if the presence of neck pain is an important factor in the outcome in this population. Other studies incorporating this type of therapy in mTBI have combined this with vestibular management with success in sporting individuals.[9,27] Further research could consider additional benefits of using a combined cervical vestibular approach. Other studies have shown improvement following isolated CSPR treatment, but this has been in those with neck pain with different outcome measures and thus comparison to the results of the current study is limited.[17,28]

Limitations

This was a retrospective records review evaluating a perceived improvement in subjective symptoms realized after a treatment plan change was initiated and thus lacks many of the rigorous methodological controls of a prospective study. Further, by design the study selected patients with abnormal findings on the CSP tests and excluded those with active, uncompensated vestibular pathology and consistent central signs. For this reason, the results should not be generalized to all mTBI patients with dizziness.

Further, our sample was too small for statistical analysis of the impact of time since injury (eg, in the VRT group [n = 22] 4 had improved dizziness, while 18 did not). It is likely that the limited number of those who experienced improved dizziness among those treated with VRT (4) and those who did not experience dizziness improved among those treated by CSPR (4) contributed to the large 95% CI generated for the intervention factor. Further study on this point is warranted.

It is possible that those with subtle vestibular or central pathology were not excluded, as those with intermittent central signs were not excluded. Although, we would argue, this should have negatively affected any potential positive findings of the study. It could be argued that the clinical tests used to identify CSP were not specifically validated or reliable; however, the fact that treatment directed toward these impairments improved dizziness in 85% of the participants may suggest that the tests were able to identify those who are likely to respond to CSPR treatment.

Table 3. *Results of the Logistic Regression on Dizziness Outcome*

Factor N = 48 n (%)	Dizziness Not Improved n = 22	Dizziness Improved n = 26	Adjusted Odds Ratio (95% CI)
Treatment			
VRT	18 (81.8)	4 (18.2)	Ref
CSPR	4 (15.4)	22 (84.6)	30.12 (4.44-204.26) [a]
Age			
Younger than 34	8 (33.3)	16 (66.7)	Ref
35 and older	14 (58.3)	10 (41.7)	0.48 (0.07-3.55)
Time since injury			
Less than a year	8 (27.6)	21 (72.4)	Ref
More than a year	14 (73.7)	5 (26.3)	0.08 (0.01-0.69) [a]
Number of treatments			
9 or fewer	9 (36.0)	16 (64.0)	Ref
10 or more	13 (56.5)	10 (43.5)	0.21 (0.03-1.74)

CSPR, cervical spine proprioceptive retraining; *Ref*, reference group; *VRT*, vestibular rehabilitation therapy.
[a] Statistically significant at the $P < .05$ level.

Owing to the retrospective nature of the study, treatments provided may not have been consistent, of similar dose, or standardized. It is possible that manual therapy treatment was not similar between the groups; however, this is unlikely as this had always been part of standard treatment. Because dizziness was the focus of the treatment of these individuals, physical therapy intervention for pain was limited to occasional soft tissue and low-grade joint mobilization and no other modalities. Similarly, compliance to the home program might not have been equal. In fact, the possibility that CSPR was better adhered to is likely as it was less intensive and time-consuming compared with VRT. We do not have data on compliance to treatment, however. Future research should consider the effect of CSPR treatment in those with normal results on these CSP tests.

Another limitation is that a single therapist performed all assessments and oversaw all treatments for the patients. The same therapist collected all data for the review. Although this created an opportunity for bias as there was no blinding, it potentially created greater consistency in the administration of assessments and delivery of treatments. However, the authors acknowledge that the evidence would be stronger if there had been another therapist available for data collection or review.

Further, this was a study of active-duty military personnel who are more likely to have sustained multiple orthopedic injuries than the general population, and therefore results may not be directly translatable to other populations with mTBI.

Finally, although we are assuming somewhat that CSPR retrains cervical proprioception, it is also possible that this type of training assists with sensorimotor integration or compensation with respect to other systems within the sensorimotor control system. No data were collected on presence or absence of neck pain or headaches; however, it was treated with standard-of-care physical therapy as appropriate for each patient and was consistent between groups.

This was a retrospective review and lacks methodological rigor; however, the improvements in patients' subjective dizziness outcomes would appear noteworthy. Future research should explore the efficacy of CSPR in a prospective manner in addition to which factors or diagnostic tests best delineate patients who may respond to CSPR.

Conclusion

The study results demonstrated that active-duty military patients after mTBI with dizziness, abnormal CSP tests, no active vestibular pathology, and no consistent central signs who had treatment directed toward CSP seem to improve in their dizziness symptoms more than the patients who had the usual care (consisting of VRT).

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Contributorship Information

Concept development (provided idea for the research): M.H.
Design (planned the methods to generate the results): M.H., A.A.S., J.T.N., J.M.T.
Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): M.H., A.A.S., J.T.N., J.M.T.
Data collection/processing (responsible for experiments, patient management, organization, or reporting data): M.H., A.A.S., J.T.N.
Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): M.H., A.A.S., J.T.N., J.M.T.
Literature search (performed the literature search): M.H., J.M.T.
Writing (responsible for writing a substantive part of the manuscript): M.H., A.A.S., J.T.N., J.M.T.
Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): A.A.S., J.T.N., J.M.T.

Practical Applications

- Some studies indicate adding manual therapy to the treatment of patients with dizziness after concussion.
- The findings of this chart review suggest that treatment directed toward proprioceptive retraining of the cervical spine may be more beneficial than manual therapy and standard vestibular rehabilitation.
- This indicates investigation into whether there is more cervical then central input as the source of error causing the dizziness.

References

1. Department of Defense. DoD Numbers on traumatic brain injury worldwide totals. Available at: http://dvbic.dcoe.mil/dod-worldwide-numbers-tbi. Accessed August 9, 2018.
2. Ellis MJ, Leddy JJ, Willer B. Physiological, vestibulo-ocular and cervicogenic post-concussion disorders: an evidence-based classification system with directions for treatment. *Brain Inj.* 2015;29(2):238-248.
3. Reneker JC, Moughiman MC, Cook CE. The diagnostic utility of clinical tests for differentiating between cervicogenic and other causes of dizziness after a sports-related concussion: an international Delphi study. *J Sci Med Sport.* 2014;18(4):366-372.
4. Shumway-Cook A. Assessment and management of the patient with traumatic brain injury and vestibular dysfunction. In: Herdman SJ, ed. *Vestibular Rehabilitation*. 3rd ed. Philadelphia, PA: F. A. Davis Co; 2007.
5. Alsalaheen BA, Mucha A, Morris LO, et al. Vestibular rehabilitation for dizziness and balance disorders after concussion. *J Neurol Phys Ther.* 2010;34(2):87-93.
6. Gottshall K. Vestibular rehabilitation after mild traumatic brain injury with vestibular pathology. *Neurorehabilitation.* 2011;29(2):167-171.
7. Reneker JC, Cook CE. Dizziness after sports-related concussion: Can physiotherapists offer better treatment than just 'physical and cognitive rest'? *Br J Sports Med.* 2015;49(8):491-492.
8. Schneider KJ, Meeuwisse WH, Nettel-Aguirre A, et al. Cervicovestibular rehabilitation in sport-related concussion: a randomised controlled trial. *Br J Sports Med.* 2014;48(17):1294-1298.
9. Schneider KJ. Sport-related concussion: optimizing treatment through evidence-informed practice. *J Orthop Sports Phys Ther.* 2016;46(8):613-616.
10. Treleaven J. Dizziness, unsteadiness, visual disturbances, and postural control: implications for the transition to chronic symptoms after a whiplash trauma. *Spine (Phila Pa 1976).* 2011;36(25S):S211-S217.
11. Treleaven J. Dizziness, unsteadiness, visual disturbances, and sensorimotor control in traumatic neck pain. *J Orthop Sports Phys Ther.* 2017;47(7):492-502.
12. Treleaven J, Clamaron-Cheers C, Jull G. Does the region of pain influence the presence of sensorimotor disturbances in neck pain disorders? *Man Ther.* Dec 2011;16(6):636-640.
13. Treleaven J, Jull G, Sterling M. Comparison of sensorimotor disturbances between subjects with persistent whiplash-associated disorder and subjects with vestibular pathology associated with acoustic neuroma. *Arch Phys Med.* 2008;89(3):522-530.
14. Treleaven J, Jull G, Sterling M. Dizziness and unsteadiness following whiplash injury: characteristic features and relationship with cervical joint position error. *J Rehabil Med.* 2003;35(1):36-43.
15. Revel M, Minguet M, Gergory P, Vaillant J, Manuel J. Changes in cervicocephalic kinesthesia afer a proprioceptive rehabilitation program in patients with neck pain: a randomized controlled study. *Arch Phys Med Rehabil.* 1994;75(8):895-899.
16. Jull G, Falla D, Treleaven J, Hodges P, Vicenzino B. Retraining cervical joint position sense: the effect of two exercise regimes. *J Orthop Res.* 2007;25(3):404-412.
17. Revel M. Andre-DeShays C, Minguet M. Cervicocephalic kinesthetic sensibility in patients with cervical pain. *Arch Phys Med Rehabil.* 1991;72(5):288-291.
18. Tjell C, Rosenhall U. Smooth pursuit neck torsion test: a specific test for cervical dizziness. *Am J Otolaryngol.* 1998;19(1):76-81.
19. Tjell C, Tenenbaum A, Sandstrom S. Smooth pursuit neck torsion test: a specific test for whiplash associated disorders? *J Whiplash Relat Disord.* 2002;1(2):9-24.
20. Treleaven J, Jull G, LowChoy N. Smooth pursuit neck torsion test in whiplash-associated disorders: relationship to self-

reports of neck pain and disability, dizziness and anxiety. *J Rehabil Med.* 2005;37(4):219-223.
21. Treleaven J. Sensorimotor disturbances in neck disorders affecting postural stability, head and eye movement control. *Man Ther.* 2008;13:2-11.
22. L'Heureux-Lebeau B, Godbout A, Berbiche D, Saliba I. Evaluation of paraclinical tests in the diagnosis of cervicogenic dizziness. *Otol Neurotol.* 2014;35(10):1858-1865.
23. Daley L, Giffard P, Thomas LC, Treleaven J. Validity of clinical measures of smooth pursuit eye movement control in patients with idiopathic neck pain. *Musculoskelet Sci Pract.* 2018;33:18-23.
24. Whitney SL, Herdman SJ. Physical therapy assessment of vestibular hypofunction. In: Herdman SJ, ed. *Vestibular Rehabilitation*. 3rd ed. Philadelphia, PA: F. A. Davis Co; 2007.
25. Herdman SJ. Physical therapy diagnosis for vestibular disorders. In: Herdman SJ, ed. *Vestibular Rehabilitation*. 3rd ed. Philadelphia, PA: F. A. Davis Co; 2007.
26. Fetter M. Assessing vestibular function: which tests, when? *J Neurol.* 2000;247(5):335-342.
27. Schneider KJ, Meeuwisse WH, Barlow KM, Emery CA. Cervicovestibular rehabilitation following sport-related concussion. *Br J Sports Med.* 2018;52:100-101.
28. 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. *Arch Phys Med Rehabil.* 1994;75(8):895-899.