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Relationship Between Cognitive Assessment and Balance Measures in Adolescents Referred for Vestibular Physical Therapy After Concussion

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Abstract

Objective—To examine the relationship between cognitive and balance performance in adolescents with concussion.

Design—Retrospective case series.

Setting—Tertiary.

Patients—Sixty patients.

Interventions—Correlation analyses were performed to describe the relationship between symptoms, cognitive measure, and balance measure at the time of initiation of vestibular physical therapy.

Main Outcome Measures—Cognitive performance was assessed using the Immediate Post-concussion Assessment and Cognitive Testing (ImPACT). The dizziness and balance function measures included dizziness severity rating, Activities-specific Balance Confidence scale (ABC), Dizziness Handicap Inventory (DHI), Functional Gait Assessment, gait speed, Timed “UP and GO,” Five Times Sit to Stand, and Sensory Organization Test (SOT). To account for multiple comparisons, the False Discovery Rate method was used.

Results—Performance measures of balance were significantly correlated with cognitive measures. Greater total symptom scores were related to greater impairment in the ABC and DHI (r

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= 0.35-0.39, $P \leq 0.008$) and worse performance in condition 2 of the SOT (r = −0.48, $P = 0.004$). Among the ImPACT composite scores, lower memory scores were correlated with impaired balance performance measures (r = 0.37-0.59, $P \leq 0.012$). Lower visual memory was also correlated with worse ABC scores.

Conclusions—The significant relationships reported between the cognitive performance scores and balance measures may reflect that similar levels of functioning exist across domains in individuals with protracted recovery who receive vestibular physical therapy.

Keywords

mild traumatic brain injury; vestibular rehabilitation; dizziness

INTRODUCTION

The awareness of concussion in adolescents has increased substantially in the last decade. Many studies have noted that high school athletes are more susceptible to concussion compared with older athletes.[1,2] Differences between children and adults in glutamate sensitivity, tolerance to biomechanical changes after injury, and different psychosocial factors have been proposed to explain the different courses of recovery between children and adults who sustain concussion.[3–5] The differential rate of recovery between children and adults led to a consensus that conservative management should be used with children postconcussion.[6,7] A conservative management approach warrants the clinicians to assess a variety of functional domains (eg, cognition and balance) and to track the resolution of symptoms after concussion.[8–12] The diversity in measurements used to assess adolescents with concussion has enhanced our understanding of the multifaceted nature of the sequelae of concussion and improved the sensitivity of the assessment battery available to record functioning in individuals with concussion.[13] However, recovery of the different domains (cognition, balance, and self-reported symptoms) has often been studied in isolation, so it is unclear if recovery trajectories are related. A few studies have concluded that cognitive and motor effects of concussion resolve differently after concussion in adults.[14,15] For example, Parker et al[14] found no relationship between cognitive testing and gait performance.

The low correlation between measures of different domains during recovery has been a subject of debate.[8,13,16–18] Although some view the low correlation between performance measures and self-report symptoms as an indication for the lack of sensitivity in performance measures[16] or an indication for the inaccuracy of self-report symptoms,[8] others speculate that they may represent fundamentally different neurobehavioral processes. The low correlation could also be related to different recovery trajectories.[13,14,17,18] Lovell[18] has concluded that post-concussion symptoms (PCSS) are a result of combinations of cognitive deficits and other factors (eg, vestibular dysfunction), which may explain the low correlation between symptoms and cognitive testing. Despite the conceptual debate about the reasons behind the low correlation between measurements from different domains, examining the relationship between measurements may enhance our understanding about the multifaceted nature of concussion effects and recovery.

Posttraumatic headache, dizziness, and balance problems are frequent symptoms after concussion.[19–23] Dizziness is associated with prolonged clinical recovery.[24] A small percentage of individuals with concussion exhibit protracted recovery and present with persistent headache and dizziness beyond what is considered normal window of recovery.[23,25–27] Therefore, an increasing number of adolescents with prolonged dizziness and/or balance problems are being referred for vestibular physical therapy.[28] Although studies that have examined vestibular physical therapy after concussion demonstrated equally beneficial outcomes to adolescents and adults,[29] the relationship between balance outcomes obtained during vestibular rehabilitation and cognitive performance has not been examined. Therefore, the purpose of this study is to examine the relationship between self-reported symptoms, cognitive performance, and balance performance in adolescents with protracted recovery referred to vestibular physical therapy after concussion. We hypothesize that a significant relationship exists between symptoms, cognitive, and balance performance.

METHODS

Participants and Outcome Measures

A retrospective case series was performed of 60 consecutive participants (40 females and 20 males; mean age = 15 years, SD = 1.8) who were referred to a tertiary balance center for vestibular physical therapy after being diagnosed with a concussion by a physician. The vestibular physical therapy intervention consisted of a customized program that was tailored to each patient's impairments and functional limitations that are related to dizziness, ocular motor function, and gait and balance function.[29] The categories of exercises most frequently provided included gaze stabilization exercises in sitting and standing positions, standing balance, and walking with balance challenge.[30] Self-report and balance performance measures were administered during the first physical therapy visit as well as at weekly and monthly intervals. The outcomes improved after discharge from the vestibular physical therapy program and are reported elsewhere.[29] The selection of the self-report and performance measures was based on their wide use in vestibular physical therapy clinics.[29,31,32] The study was approved by the institutional review board of University of Pittsburgh.

Self-report Measures

Participants were asked to rate their current dizziness severity on a verbal scale from 0 to 100, where 0 means no dizziness and 100 means maximum dizziness. Verbal anchors relating to severity of dizziness (eg, slight, mild, moderate, severe) were provided for the scale.

The Activities-specific Balance Confidence scale (ABC) was used to assess the respondent's level of confidence that he/she would not lose his/her balance while performing 16 functional activities. The highest possible score of 100 suggests maximum confidence and a score of 0 suggests no confidence.[33] The minimal detectable change for the ABC scale is reported to be 13 points in individuals with neurologic diseases.[34,35]

The Dizziness Handicap Inventory (DHI) assesses the individual's handicap because of his/her dizziness using 25 items relating to physical, emotional, and functional domains. The highest overall score on the test is 100, and higher scores indicate greater handicap resulting from dizziness.[36] An 18-point change in DHI is considered clinically meaningful.[36]

Balance Performance Measures

The Functional Gait Assessment (FGA) is a 10-item test based on the Dynamic Gait Index. The 3 new items introduced in the FGA are gait with a narrow base of support, gait with eyes closed, and ambulating backward. The maximum score is 30. Higher scores indicate better performance.[37] The minimal detectable change for the FGA is reported to be 6 points in persons with balance and vestibular disorders.[38]

Although participants were asked to walk at their comfortable speed, gait speed was timed over 6-m course using a stopwatch. A change in gait speed that is ≥0.21 m/s is considered a reliable change in adolescents.[39]

The Timed “UP & GO” (TUG) is a timed test during which participants stand from a chair, walk 3 m at their normal walking speed, and return to the chair.[40] A change in the TUG score that is ≥0.9 seconds is considered a reliable change in adolescents.[39]

The Five Times Sit to Stand (FTSTS) requires participants to stand-up and sit-down from a standard height chair 5 times as quickly as possible. The participants were asked to complete the task with their hands crossed on their chest.[41] A change in FTSTS scores that is ≥0.4 seconds is considered a reliable change in adolescents.[39]

Participants also performed the Sensory Organization Test (SOT; Neurocom Inc, Clackamas, Oregon) under 6 different sensory conditions: (1) eyes open, fixed support; (2) eyes closed, fixed support; (3) sway-referenced vision, fixed support; (4) eyes open, sway-referenced support; (5) eyes closed, sway-referenced support; and (6) sway-referenced vision and support surface. Three 20-second trials were performed for each condition. The highest theoretical equilibrium score is 100, which indicates no sway; losses of balance were graded as zero. Average scores for each condition were recorded, and the composite score was calculated using a weighted average of the individual trials. A change that is greater than or equal to 10 points in the composite score is considered clinically meaningful.[42]

Cognitive and Symptom Measures

Around the time, participants were seen for vestibular physical therapy, and they performed a computerized cognitive assessment that included the Immediate Post-concussion Assessment and Cognitive Testing (ImPACT).[43] The ImPACT test comprises a cognitive testing battery and PCSS.[43] The cognitive portion of ImPACT measures attention, processing speed, reaction time, and memory. A detailed description of the individual test modules and composite scores is provided elsewhere.[44–46] The individual modules are aggregated into 4 composite scores consisting of verbal and visual memory, visual motor processing speed and reaction time. The PCSS includes 22 items and is designed to quantify the severity of symptoms in the acute phase of recovery after concussion, using a 7-point (0 = none to 6 = severe) Likert-type scale. The PCSS yields a total symptom score by adding the scores obtained for the 22 items. The PCSS has been evaluated for its psychometric properties, clinical interpretation, and normative scores.[12,22,47]

Statistical Analysis

Descriptive statistics were used to describe the participants' demographic characteristics, and the time between concussion and the start of vestibular physical therapy. A χ^2 test was used to examine whether there was a difference in outcome measures between male and female participants. Correlation analysis was performed to examine the relationship between the measures of dizziness severity rating, ABC, DHI, FGA, gait speed, TUG, FTSTS, and SOT to the composite scores of ImPACT and PCSS total symptom score at the start of vestibular physical therapy. The normality of the distribution was examined for all measures. The dizziness rating, ABC, DHI, FGA, GS, FTSTS, and the 6 conditions of SOT were normally distributed. All ImPACT and PCSS variables were normally distributed except reaction time. For the variables that were not normally distributed (reaction time, SOT composite score, and the TUG scores), Spearman rho correlation analysis was performed. A total of 70 correlation analyses were conducted. The level of significance was $\alpha = 0.05$. To account for multiple comparisons, the False Discovery Rate (FDR) method described by Benjamini and Hochberg[48] was used. False discovery rate is the expected proportion of erroneous rejections among all rejections.

RESULTS

Participants were seen at a median of 46 days after concussion, and the cognitive testing was administered within an average of 1.8 days (SD = 11 days) around the start of their vestibular physical therapy. At the time of cognitive evaluation postconcussion, 39 (65%) participants exhibited impairment (ie, below median) in at least 1 cognitive domain compared with age- and sex-matched norms. A closer inspection of the individual domains revealed that more participants exhibited impairments with visual memory (n = 31) compared with verbal memory (n = 27), reaction time (n = 26), and processing speed (n = 23). A detailed inspection of the total symptom score revealed that 45 participants experienced increased symptoms beyond normal (ie, greater than 6 and 8 for males and females, respectively). The total symptom score in 39 of these participants was very high (ie, greater than 22 and 44 for males and females, respectively).

Patients exhibited with reduced balance confidence, increased complaints of dizziness, and impaired balance performance in clinical tests for balance (Table 1). The χ^2 test revealed no significant differences between male and female participants on any of the obtained measures.

Using the FDR method to adjust for multiplicity of analyses, 17 of 70 correlations were significant (Table 2). Greater total PCSS scores were significantly related to greater impairment in 2 of the self-report measures and the performance of the second condition of SOT. The strongest correlation for the PCSS was with the self-reported DHI score (r = 0.39). Among the cognitive composite scores, worse visual memory scores were correlated with the self-report ABC and most clinical performance measures (ie, FGA, GS, and FTSTS). Lower visual memory scores were associated with greater sway in 3 of the 6 SOT conditions. In particular, visual memory was related to postural sway with eyes closed ($r = 0.59$, $P <$, 0.001, and $r = 0.47$, $P = 0.005$) for conditions 2 and 5, respectively. Additionally, visual memory was related to the condition of sway-referenced vision with fixed support ($r = 0.53$, $P = 0.001$). Verbal memory was related to 3 of the clinical measures and conditions 2 and 3 of the SOT (Table 2). Reaction time was significantly related to the ABC ($r_s = -0.35$, $P = 0.007$) and FTSTS ($r_s = 0.38$, $P = 0.010$). In all cases, worse cognitive performance was associated with worse self-report ABC score and worse balance performance. There was no significant relationship between processing speed to any of the measures collected during vestibular physical therapy.

DISCUSSION

Visual and verbal memory exhibited stronger correlations to balance and gait measures compared with reaction time. The visual memory score is based on the average percent correct scores for 2 tasks; a recognition memory task that requires the discrimination of a series of abstract line drawings, and a memory task that requires the identification of a series of illuminated X's or O's after an intervening task (mouse clicking a number sequence from 25 to 1).[43] These tasks may require spatial navigation and memory. Although spatial memory seems to be primarily a cognitive task, researchers have demonstrated that patients with vestibular impairments have impaired spatial memory independent of otherwise normal cognitive performance.[49–51] Therefore, the role of the vestibular system in spatial perception and spatial memory has been supported by many studies.[52–56] This involvement of vestibular system in spatial memory may explain the stronger correlation of visual memory to balance measures compared with other composite scores that do not require spatial abilities. Evidence of vestibular connections to the hippocampus, which is thought to play a prominent role in spatial navigation and spatial memory, may explain the mechanism by which vestibular inputs affect spatial memory.[52,57,58] The verbal memory score is based on the average percentage correct for a word recognition paradigm, a symbol–number match task and a letter memory task with an accompanying interference task.[43] It is unclear why verbal memory exhibited a number of significant relationships with measurements of vestibular physical therapy. A possible explanation would be that verbal memory was the second most affected score after visual memory in this sample. Additionally, the tests of verbal memory are being visually presented to the patient on the screen; the visual (ie, not auditory) presentation of the tasks may have influenced the scores because the visual presentation may have also required spatial perception and spatial memory. It is unclear why processing speed did not correlate with any of the measures administered during vestibular physical therapy. However, it is reasonable to believe that outcome variability associated with concussion may have resulted in processing speed being the least affected domain in this cohort.

The PCSS total score is a global measure of 22 symptoms that are commonly reported in the acute phase after concussion. Previous studies suggested that concussion symptoms become better defined and delineated (eg, vestibular, migraine, etc.) over time (ie, >10 days after injury).[59] Therefore, the impaired balance performance of participants in this study who were referred after the acute phase of concussion may have not been consistent with their overall symptoms, and therefore the association between PCSS and balance performance measures was not significant. Additionally, previous studies reported that adolescents tend to minimize and underreport concussion symptoms, which may have resulted in a lack of association with the performance of balance tasks.[60] Clinicians working with adolescents postconcussion should carefully examine the presence of clusters of symptoms (eg, vestibular, migraine, etc.) to help direct different clinical management approaches rather than relying on the total symptom score. Additionally, PCSS should always be used in conjunction with balance and neuro-cognitive performance measures.[6]

Barlow et al[61] reported that no relationship existed between changes in Balance Error Scoring System and ImPACT scores in adolescents after concussion. However, the authors are unaware of any previous research studies that have examined the relationship between computerized cognitive performance and the balance outcomes used in this study. Therefore, the comparison of the findings to others is unattainable.

The strength of associations observed in this study may have also been affected by the psychometric properties of the measures; extensive research was used in developing, validating, and reporting psychometric properties for the cognitive assessments related to concussion,[47,62,63] whereas the balance performance tests were not developed specifically for use in adolescents with concussion. Alsalaheen et al[39] reported a ceiling effect for the vestibular rehabilitation measures (eg, ABC and FGA) in adolescents. Because of the differential sensitivity between cognitive testing and balance testing, cognitive tests may produce a higher sensitivity to concussion's deleterious effects than the balance measures used in this article.[13,64] The relationship between cognition and balance might be different (ie, stronger) if the balance measures were developed to detect specific effects of concussion on balance. It is noteworthy to mention that despite the ceiling effects anticipated for some of the vestibular rehabilitation measures, patients in this group exhibited with reduced gait speed (median = 1.1 m/s) compared with their age-referenced values (1.44 m/s) and worse FTSTS performance (median = 9.5 seconds) compared with a median of 7.5 seconds in normal healthy adolescents.[39] The presence of impairments in gait and balance measures after a median of 46-day postconcussion may support the clinical utility of gait and balance measures as ancillary measures in adolescents with concussion. Because of the ceiling effect reported for FGA in adolescents, timed measures including TUG, FTSTS, and gait speed are recommended over FGA to quantify balance impairments and recovery after concussion.[39] A direct comparison of postconcussion scores to baseline scores (if available) or age-referenced norms is recommended.[39] Additionally, the timed measurements are practical to administer in clinical settings (eg, physician's office) because they do not require additional equipment and take approximately 5 minutes to be completed. A comparison to baseline scores or age referenced normative scores may quantify gait and balance impairments and recovery after concussion.[39]

This study had some limitations. The participants included in this study were obtained from a clinical population of patients referred by 1 practice for vestibular physical therapy where the referral process was solely based on clinical judgment. The participants were referred after the acute phase of concussion, and therefore this sample does not represent the majority of individuals with concussion who will typically recover within the first 7 to 10 days of injury.[65–67] The relationship between cognitive functioning and balance functioning may have been different if examined in the acute phase of injury. Because this was a retrospective study, the time points considered for the correlation analyses were variable between participants. A prospective design that allows for concurrent cognitive and gait/balance evaluations may provide a better understanding of the relationship between cognitive and gait/balance impairment after concussion. Despite these limitations, we believe that this study serves as a preliminary starting point for future research on the interrelationships between different assessment domains after concussion in adolescents. Future areas of exploration should include assessment of changes in cognitive and balance function during vestibular rehabilitation to examine whether recovery in these outcomes has similar trajectories.

REFERENCES

1. Reddy CC, Collins MW, Gioia GA. Adolescent sports concussion. Phys Med Rehabil Clin N Am. 2008; 19:247–269. [PubMed: 18395647]
2. Reddy CC, Collins MW. Sports concussion: management and predictors of outcome. Curr Sports Med Rep. 2009; 8:10–15. [PubMed: 19142074]
3. McCrory P, Collie A, Anderson V, et al. Can we manage sport related concussion in children the same as in adults? Br J Sports Med. 2004; 38:516–519. [PubMed: 15388528]
4. Kirkwood MW, Yeates KO, Wilson PE. Pediatric sport-related concussion: a review of the clinical management of an oft-neglected population. Pediatrics. 2006; 117:1359–1371. [PubMed: 16585334]
5. Cohen JS, Gioia G, Atabaki S, et al. Sports-related concussions in pediatrics. Curr Opin Pediatr. 2009; 21:288–293. [PubMed: 19390439]
6. McCrory P, Meeuwisse W, Johnston K, et al. Consensus statement on concussion in sport 3rd International Conference on Concussion in Sport held in Zurich, November 2008. Clin J Sport Med. 2009; 19:185–200. [PubMed: 19423971]
7. Guskiewicz KM, Bruce SL, Cantu RC, et al. National Athletic Trainers' Association position statement: management of sport-related concussion. J Athl Train. 2004; 39:280–297. [PubMed: 15514697]
8. Broglio SP, Sosnoff JJ, Ferrara MS. The relationship of athlete-reported concussion symptoms and objective measures of neurocognitive function and postural control. Clin J Sport Med. 2009; 19:377–382. [PubMed: 19741309]
9. Collins MW, Grindel SH, Lovell MR, et al. Relationship between concussion and neuropsychological performance in college football players. JAMA. 1999; 282:964–970. [PubMed: 10485682]
10. Collins MW, Iverson GL, Lovell MR, et al. On-field predictors of neuro-psychological and symptom deficit following sports-related concussion. Clin J Sport Med. 2003; 13:222–229. [PubMed: 12855924]
11. Erlanger D, Saliba E, Barth J, et al. Monitoring resolution of postconcussion symptoms in athletes: preliminary results of a web-based neuro-psychological test protocol. J Athl Train. 2001; 36:280–287. [PubMed: 12937497]
12. Iverson GL, Gaetz M, Lovell MR, et al. Relation between subjective fogginess and neuropsychological testing following concussion. J Int Neuropsychol Soc. 2004; 10:904–906. [PubMed: 15637782]
13. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. Neurosurgery. 2007; 60:1050–1057. [PubMed: 17538379]
14. Parker TM, Osternig LR, van Donkelaar P, et al. Recovery of cognitive and dynamic motor function following concussion. Br J Sports Med. 2007; 41:868–873. [PubMed: 17517857]
15. Guskiewicz KM. Assessment of postural stability following sport-related concussion. Curr Sports Med Rep. 2003; 2:24–30. [PubMed: 12831673]

16. Guskiewicz KM, Ross SE, Marshall SW. Postural stability and neuro-psychological deficits after concussion in collegiate athletes. J Athl Train. 2001; 36:263–273. [PubMed: 12937495]
17. Guskiewicz KM. Postural stability assessment following concussion: one piece of the puzzle. Clin J Sport Med. 2001; 11:182–189. [PubMed: 11495323]
18. Lovell MR. The relevance of neuropsychologic testing for sports-related head injuries. Curr Sports Med Rep. 2002; 1:7–11. [PubMed: 12831641]
19. Gessel LM, Fields SK, Collins CL, et al. Concussions among United States high school and collegiate athletes. J Athl Train. 2007; 42:495–503. [PubMed: 18174937]
20. Lew HL, Lin PH, Fuh JL, et al. Characteristics and treatment of headache after traumatic brain injury: a focused review. Am J Phys Med Rehabil. 2006; 85:619–627. [PubMed: 16788394]
21. Blinman TA, Houseknecht E, Snyder C, et al. Postconcussive symptoms in hospitalized pediatric patients after mild traumatic brain injury. J Pediatr Surg. 2009; 44:1223–1228. [PubMed: 19524745]
22. Lovell MR, Iverson GL, Collins MW, et al. Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. Appl Neuropsychol. 2006; 13:166–174. [PubMed: 17361669]
23. Dischinger PC, Ryb GE, Kufera JA, et al. Early predictors of postconcussive syndrome in a population of trauma patients with mild traumatic brain injury. J Trauma. 2009; 66:289–296. [PubMed: 19204499]
24. Lau BC, Kontos AP, Collins MW, et al. Which on-field signs/symptoms predict protracted recovery from sport-related concussion among high school football players? Am J Sports Med. 2011; 39:2311–2318. [PubMed: 21712482]
25. Faux S, Sheedy J. A prospective controlled study in the prevalence of posttraumatic headache following mild traumatic brain injury. Pain Med. 2008; 9:1001–1011. [PubMed: 18266807]
26. Lannsjo M, af Geijerstam JL, Johansson U, et al. Prevalence and structure of symptoms at 3 months after mild traumatic brain injury in a national cohort. Brain Inj. 2009; 23:213–219. [PubMed: 19205957]
27. Maskell F, Chiarelli P, Isles R, et al. Dizziness after traumatic brain injury: results from an interview study. Brain Inj. 2007; 21:741–752. [PubMed: 17653948]
28. Vidal PG, Goodman AM, Colin A, et al. Rehabilitation strategies for prolonged recovery in pediatric and adolescent concussion. Pediatr Ann. 2012; 41:1–7. [PubMed: 22953976]
29. Alsalaheen BA, Mucha A, Morris LO, et al. Vestibular rehabilitation for dizziness and balance disorders after concussion. J Neurol Phys Ther. 2010; 34:87–93. [PubMed: 20588094]
30. Alsalaheen BA, Whitney SL, Mucha A, et al. Exercise prescription patterns in patients treated with vestibular rehabilitation after concussion. Physiother Res Int. 2013; 18:100–108. [PubMed: 22786783]
31. Whitney, SL.; Herdman, SJ. Physical therapy assessment of vestibular hypofunction.. In: Herdman, SJ., editor. Vestibular Rehabilitation. F. A. Davis; Philadelphia, PA: 2007. p. 272-308.
32. Brown KE, Whitney SL, Marchetti GF, et al. Physical therapy for central vestibular dysfunction. Arch Phys Med Rehabil. 2006; 87:76–81. [PubMed: 16401442]
33. Powell LE, Myers AM. The Activities-specific balance confidence (ABC) scale. J Gerontol A Biol Sci Med Sci. 1995; 50:M28–M34. [PubMed: 7814786]
34. Salbach NM, Mayo NE, Hanley JA, et al. Psychometric evaluation of the original and Canadian French version of the activities-specific balance confidence scale among people with stroke. Arch Phys Med Rehabil. 2006; 87:1597–1604. [PubMed: 17141639]
35. Steffen T, Seney M. Test-retest reliability and minimal detectable change on balance and ambulation tests, the 36-item short-form health survey, and the unified Parkinson disease rating scale in people with parkinsonism. Phys Ther. 2008; 88:733–746. [PubMed: 18356292]
36. Jacobson GP, Newman CW. The development of the dizziness handicap inventory. Arch Otolaryngol Head Neck Surg. 1990; 116:424–427. [PubMed: 2317323]
37. Wrisley DM, Walker ML, Echternach JL, et al. Reliability of dynamic gait index in people with vestibular disorders. Arch Phys Med Rehabil. 2003; 84:1528–1533. [PubMed: 14586922]

38. Marchetti GF, Lin CC, Alghadir A, et al. Responsiveness and minimal detectable change of the dynamic gait index and functional gait index in persons with balance and vestibular disorders. J Neurol Phys Ther. 2014; 38:119–124. [PubMed: 24637931]
39. Alsalaheen BA, Whitney SL, Marchetti GF, et al. Performance of high school adolescents on functional gait and balance measures. Pediatr Phys Ther. 2014; 26:191–199. [PubMed: 24675118]
40. Podsiadlo D, Richardson S. The timed “Up & Go”: a test of basic functional mobility for frail elderly persons. J Am Geriatr Soc. 1991; 39:142–148. [PubMed: 1991946]
41. Lord SR, Murray SM, Chapman K, et al. Sit-to-stand performance depends on sensation, speed, balance, and psychological status in addition to strength in older people. J Gerontol A Biol Sci Med Sci. 2002; 57:M539–M543. [PubMed: 12145369]
42. Broglio SP, Ferrara MS, Sopiarz K, et al. Reliable change of the sensory organization test. Clin J Sport Med. 2008; 18:148–154. [PubMed: 18332690]
43. Maroon JC, Lovell MR, Norwig J, et al. Cerebral concussion in athletes: evaluation and neuropsychological testing. Neurosurgery. 2000; 47:659–669. [PubMed: 10981754]
44. Schatz P, Pardini JE, Lovell MR, et al. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. Arch Clin Neuropsychol. 2006; 21:91–99. [PubMed: 16143492]
45. Lovell MR, Collins MW, Iverson GL, et al. Grade 1 or “ding” concussions in high school athletes. Am J Sports Med. 2004; 32:47–54. [PubMed: 14754723]
46. Iverson GL, Lovell MR, Collins MW. Validity of ImPACT for measuring processing speed following sports-related concussion. J Clin Exp Neuropsychol. 2005; 27:683–689. [PubMed: 16019644]
47. Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. Clin Neuropsychol. 2003; 17:460–467. [PubMed: 15168911]
48. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J R Stat Soc Series B Stat Methodol. 1995; 57:289–300.
49. Smith PF, Zheng Y, Horii A, et al. Does vestibular damage cause cognitive dysfunction in humans? J Vestib Res. 2005; 15:1–9. [PubMed: 15908735]
50. Risey J, Briner W. Dyscalculia in patients with vertigo. J Vestib Res. 1990; 1:31–37. [PubMed: 1670135]
51. Schautzer F, Hamilton D, Kalla R, et al. Spatial memory deficits in patients with chronic bilateral vestibular failure. Ann N Y Acad Sci. 2003; 1004:316–324. [PubMed: 14662471]
52. Hanes DA, McCollum G. Cognitive-vestibular interactions: a review of patient difficulties and possible mechanisms. J Vestib Res. 2006; 16:75–91. [PubMed: 17312336]
53. Berthoz A. The role of inhibition in the hierarchical gating of executed and imagined movements. Brain Res Cogn Brain Res. 1996; 3:101–113. [PubMed: 8713551]
54. Israel I, Fetter M, Koenig E. Vestibular perception of passive whole-body rotation about horizontal and vertical axes in humans: goal-directed vestibulo-ocular reflex and vestibular memory-contingent saccades. Exp Brain Res. 1993; 96:335–346. [PubMed: 8270026]
55. Harris LR, Jenkin M, Zikovitz DC. Visual and non-visual cues in the perception of linear self-motion. Exp Brain Res. 2000; 135:12–21. [PubMed: 11104123]
56. Nakamura T, Bronstein AM. The perception of head and neck angular displacement in normal and labyrinthine-defective subjects. A quantitative study using a “remembered saccade” technique. Brain. 1995; 118:1157–1168. [PubMed: 7496777]
57. Vitte E, Derosier C, Caritu Y, et al. Activation of the hippocampal formation by vestibular stimulation: a functional magnetic resonance imaging study. Exp Brain Res. 1996; 112:523–526. [PubMed: 9007554]
58. Maguire EA, Gadian DG, Johnsrude IS, et al. Navigation-related structural change in the hippocampi of taxi drivers. Proc Natl Acad Sci U S A. 2000; 97:4398–4403. [PubMed: 10716738]
59. Kontos AP, Elbin RJ, Schatz P, et al. A revised factor structure for the post-concussion symptom scale: baseline and postconcussion factors. Am J Sports Med. 2012; 40:2375–2384. [PubMed: 22904209]

60. Register-Mihalik JK, Guskiewicz KM, McLeod TC, et al. Knowledge, attitude, and concussion-reporting behaviors among high school athletes: a preliminary study. J Athl Train. 2013; 48:645–653. [PubMed: 23848520]

61. Barlow M, Schlabach D, Peiffer J, et al. Differences in change scores and the predictive validity of three commonly used measures following concussion in the middle school and high school aged population. Int J Sports Phys Ther. 2011; 6:150–157. [PubMed: 21904694]

62. Collie A, Maruff P, McStephen M, et al. Psychometric issues associated with computerised neuropsychological assessment of concussed athletes. Br J Sports Med. 2003; 37:556–559. [PubMed: 14665603]

63. Schatz P, Putz BO. Cross-validation of measures used for computer-based assessment of concussion. Appl Neuropsychol. 2006; 13:151–159. [PubMed: 17361667]

64. Broglio SP, Puetz TW. The effect of sport concussion on neurocognitive function, self-report symptoms and postural control: a meta-analysis. Sports Med. 2008; 38:53–67. [PubMed: 18081367]

65. Guskiewicz KM, Perrin DH, Gansneder BM. Effect of mild head injury on postural stability in athletes. J Athl Train. 1996; 31:300–306. [PubMed: 16558414]

66. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. JAMA. 2003; 290:2556–2563. [PubMed: 14625332]

67. Lovell MR, Collins MW, Iverson GL, et al. Recovery from mild concussion in high school athletes. J Neurosurg. 2003; 98:296–301. [PubMed: 12593614]

Clinical Relevance

The weak-to-moderate relationships warrant the continuous use of multiple domains of assessment. A better understanding to the relationships between the domains of functioning after concussion may improve the overall management approach for adolescents with concussion.

TABLE 1

Descriptive Statistics for Neurocognitive Testing Scores and Outcome Measures Obtained at the Start of Vestibular Physical Therapy

Outcome Measure (n)	Descriptive Statistic
Measurements obtained at vestibular rehabilitation	
Dizziness rating (58) (maximum score = 100)	22 (21)*
ABC (58) (maximum score = 100)	67 (27)*
DHI (59) (maximum score = 100)	44 (20)*
FGA (54) (maximum score = 30)	25 (5)*
GS (55) (m/s)	1.10 (0.25)*
TUG (47) (s)	7.8 (4.0–15.0)†
FTSTS (46) (s)	9.5 (3.5)*
SOT composite score (34) (maximum score = 100)	63 (4–82)†
SOT condition 1 (34) (maximum score = 100)	85 (13)*
SOT condition 2 (34) (maximum score = 100)	78 (17)*
SOT condition 3 (34) (maximum score = 100)	74 (23)*
SOT condition 4 (34) (maximum score = 100)	53 (26)*
SOT condition 5 (34) (maximum score = 100)	37 (25)*
SOT condition 6 (34) (maximum score = 100)	41 (26)*
ImPACT composite scores	
Total symptom score (60) (maximum score = 132)	43 (26)*
Visual memory (60)	65 (16)*
Verbal memory (60)	80 (16)*
Reaction time (60) (ms)	625 (410–1290)†
Visual motor processing speed (60)	31 (11)*

Condition 1, eyes open, fixed support; condition 2, eyes closed, fixed support; condition 3, sway-referenced vision, fixed support; condition 4, eyes open, sway-referenced support; condition 5, eyes closed, sway-referenced support; condition 6, sway-referenced vision and support surface.

*Values are expressed as mean (SD).

†Values are expressed as median (range).

TABLE 2

Correlation Between ImPACT Composite Scores and Measures Administered at the Start of Vestibular Physical Therapy

	ImPACT Composite Measure				
	Visual Memory	**Reaction Time**	**Verbal Memory**	**Processing Speed**	**Total Symptom Score**
Self-report measures (n)					
Dizziness rating (58)	r = –0.15	r_s = 0.03	r = –0.11	r = 0.11	r = 0.25
ABC (58)	r = 0.39† P = 0.003	r_s = –0.35† P = 0.007	r = 0.32	r = 0.29	r = –0.35† P = 0.008
DHI (59)	r = –0.21	r_s = 0.20	r = –0.23	r = –0.18	r = 0.39† P = 0.002
Balance performance measures (n)					
FGA (54)	r = 0.40† P = 0.003	r_s = –0.23	r = 0.44† P = 0.001	r = 0.31	r = –0.33
GS (55)	r = 0.34† P = 0.012	r_s = –0.06	r = 0.37† P = 0.005	r = 0.22	r = –0.30
TUG (47)	r_s = –0.09	r_s = 0.22	r_s = –0.16	r_s = –0.23	r_s = –0.01
FTSTS (46)	r = –0.38† P = 0.010	r_s = 0.38† P = 0.010	r= –0.50† P < 0.001	r = –0.33	r = 0.30
SOT composite score (34)	r_s = 0.40	r_s = –0.15	r_s = 0.20	r_s = 0.16	r_s = –0.25
SOT condition 1 (34)	r = 0.40	r_s = –0.11	r = 0.32	r = 0.28	r = –0.25
SOT condition 2 (34)	r = 0.59† P < 0.001	r_s = –0.35	r = 0.53† P = 0.001	r = 0.58	r = –0.48† P = 0.004
SOT condition 3 (34)	r = 0.53† P = 0.001	r_s = –0.30	r = 0.58† P < 0.001	r = 0.34	r = –0.37
SOT condition 4 (34)	r = 0.41	r_s = –0.19	r = 0.37	r = 0.23	r = –0.28
SOT condition 5 (34)	r = 0.47† P = 0.005	r_s = –0.12	r = 0.32	r = 0.17	r = –0.27
SOT condition 6 (34)	r = 0.39	r_s = –0.07	r = 0.27	r = 0.12	r = –0.21

n, number of participants; condition 1, eyes open, fixed support; condition 2, eyes closed, fixed support; condition 3, sway-referenced vision, fixed support; condition 4, eyes open, sway-referenced support; condition 5, eyes closed, sway-referenced support; condition 6, sway-referenced vision and support surface, r_s, Spearman rank correlation coefficient, r, Pearson product-moment correlation coefficients.

† Statistically significant.